A global review of the downstream effects of small impoundments on stream habitat conditions and macroinvertebrates

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REVIEW

A global review of the downstream effects of small impoundments on stream habitat conditions and macroinvertebrates

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Abstract: The downstream ecological effects of large impoundments have previously been reviewed; however, little is known about the downstream ecological effects of small man-made impoundments. In this review, we examine 94 papers focusing on the effects of small impoundments on stream habitat conditions and macroinvertebrates. Most studies (89.3%) address the effects of small impoundments on physical and chemical habitat conditions, while fewer studies (48.9%) address the effects on macroinvertebrates. In general, most studies report no significant downstream effects of small impoundments on physico-chemical variables, whereas macroinvertebrates richness and abundance increased or decreased. Mean effect sizes (as Cohen's *d*) for physico-chemical variables range from –0.82 to 0.68 (small weir: –0.21 to 0.35; run-of-river dam: –0.82 to 0.64; low head dam: –0.49 to 0.68), and from –0.03 to 0.63 for macroinvertebrates abundance and richness. Our assessment of the published literature demonstrates the advantage of combining qualitative and quantitative analyses, and that, while small impoundments may have minimal significant effects on most physico-chemical variables, macroinvertebrates' richness and density may be affected. This review is relevant for management and scientific communities to identify potential alterations of stream habitats and biota by small impoundments.

Key words: impoundments, stream invertebrates, river, environment, ecological effects, physico-chemical variables.

Résumé : On a déjà révisé les effets écologiques en aval des grands bassins de rétention. Cependant, on connaît peu de choses sur les effets écologiques en aval des petites retenues construites par l'homme. Dans cette revue, les auteurs examinent 94 publications examinant les effets des petits ouvrages sur le statut des conditions des habitats et sur les macro-invertébrés. La plupart des études (89.3 %) se préoccupent des effets des petites retenues sur les conditions physico-chimiques des habitats, mais moins nombreuses (48.9 %) sont celles qui s'occupent des effets sur les macro-invertébrés. En général, la plupart des études consultées ne perçoivent pas d'effets significatifs en aval des petites retenues sur les variables physico-chimiques, alors qu'on observe une augmentation ou une diminution de l'abondance et de la richesse en macro-invertébrés. Les valeurs moyennes des effets (indice *d* de Cohen) vont de 0.82 à 0.68 (petits barrages, de 0.21 à 0.35; barrages au fil de l'eau, de 0.82 à 0.64; barrages de basse chute, de 0.49 à 0.68), et de 0.03 et 0.63 pour l'abondance et la richesse en macro-invertébrés, respectivement. Les auteurs considèrent que la littérature démontre l'avantage de combiner les analyses qualitatives et quantitatives et que, alors que les petites retenues peuvent exercer des effets minimaux significatifs sur les variables physico-chimiques, la richesse et la densité en macro-invertébrés peuvent être affectées. Cette revue est pertinente en aménagement et pour les communautés scientifiques cherchant à identifier les altérations des habitats des cours d'eau et du biote des petites retenues. [Traduit par la Rédaction]

Mots-clés : retenues, invertébrés des cours d'eau, environnement, effets écologiques, variables physico-chimiques.

1. Introduction

The Millennium Ecosystem Assessment (MEA) considers habitat change as a major driver of biodiversity and ecosystem change (MEA 2005). Modification of the natural flow of rivers through impoundment is one of the most widespread habitat changes caused by humans on rivers worldwide (Dynesius and Nilsson 1994; Nilsson et al. 2005; Van Looy et al. 2014). Impoundments are constructed for many purposes, including water supply, water storage for irrigation and electricity generation, and flood control (Altinbilek 2002); however, impoundments also alter the structure and functioning of rivers in many ways including: (*i*) flooding the surrounding terrestrial habitats; (*ii*) reducing water velocity; (*iii*) retention of sediments, organic debris, chemical pollutants, and nutrients; (*iv*) modificaton of water temperature, and dissolved oxygen content; and (*v*) changing channel geomorphology (Goldman 1976; Baxter 1977; Graf 2006). Consequently, these changes affect the abundance and diversity of biotic communities, such as invertebrates, particularly in the downstream impacted reaches (Mackay and Waters 1986; Mueller et al. 2011; Martínez et al. 2013).

To date, much of the research on the effects of impoundments on rivers has been conducted on large impoundments (e.g., Baxter 1977; Ward and Stanford 1979; Stanford and Ward 2001), and relatively few empirical studies (e.g., Cortes et al. 1998; Xiaocheng et al. 2008; Käiro et al. 2011) have assessed the ecological effects of small impoundments (<15 m in height; WCD 2000; Poff and Hart 2002). There is need for more investigations on the effects of small impoundments on rivers because of their high abundance (WCD 2000; Chin et al. 2008) and potential for relatively high cumulative effects on river habitats (Kibler and Tullos 2013). Moreover, the

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generalisations (e.g., serial discontinuity concept; Ward and Stanford 1983) on the effects of impoundments on lotic ecosystems are primarily based on studies dealing with the effects of large impoundments (>15 m; e.g., Ward 1976). Millions of small impoundments exist worldwide (WCD 2000), and some watersheds have high numbers of small impoundments (e.g., Van Looy et al. 2014), resulting in severe negative consequences on habitats and biota (Cortes et al. 1998; Sharma et al. 2005; Wang et al. 2013). Moreover, assessments of the effects of impoundments on stream invertebrates is important because invertebrates participate in nutrient cycling processes through breakdown of coarse particulate organic matter (Graça 2001; Raposeiro et al. 2014; David and Boonsoong 2014), facilitating the cycling of organic carbon in microbial food webs, and downstream transport of fine particulate organic matter (Whiles and Wallace 1997; Poepperl 2003; Patrick 2013). Stream invertebrates constitute a crucial food source for some birds and fish (Ward and Stanford 1995; Wong et al. 1998), and the sensitivity of some taxa, relatively low mobility, and direct association with stream bed substrates enables site specific assessment of in-stream habitat conditions (Bae et al. 2005; Li et al. 2010; Chang et al. 2014). Importantly, invertebrates are useful in the assessment of the effects of impoundments on lotic ecosystems in the presence of multiple stressors that characterise freshwater ecosystems (Ormerod et al. 2010; Statzner and Bêche 2010). For example, Colas et al. (2013) evaluated the effects of multiple stressors on the ecological conditions of dammed rivers and found invertebrates to identify chemical contamination as a main influencing factor. Wang et al. (2011) assessed the effects of natural and human-induced variations on physico-chemical conditions and biota in dammed streams and suggested that natural and human-induced variations, in addition to dams, should be incorporated in bioassessments.

Literature reviews exist for the downstream ecological effects of large impoundments (e.g., Ward 1976; Ligon et al. 1995), but little is known about the ecological effects of small impoundments. Furthermore, reviews to date have focused on specific regions, organisms, and stream types. For example, Watters (1996) and Cumming (2004) found small impoundments to reduce the abundance and richness of freshwater mussels and fish in streams in the USA. In this review, one of our objectives is to perform a comprehensive synthesis of case studies to improve our understanding of the ecological impacts of different types of small impoundments. In addition, we extract information from the published literature to determine if qualitative or quantitative patterns can be discerned in the downstream effects of small impoundments on biotic and abiotic response metrics.

2. Approach

2.1. Literature search and calculation of the effect sizes

We conducted an examination of the peer-reviewed literature published between 1986 and 2013 that addressed the effects of small impoundments on stream habitat conditions and macroinvertebrates. The search terms used in the Web of Science database were (small dam OR low head dam OR weir OR small reservoir OR small pond OR run-of-river dam OR small impoundment) AND (zoobentho OR invertebrate) AND (habitat OR environment) AND (stream OR river). A total of 106 papers that matched these search criteria were found. Twelve of these papers were excluded from further analysis because the downstream reach was not sampled, or because these studies focused on the effects of small dams removal. From the remaining 94 papers, small dams were further divided into the following size categories: (*i*) dams whose height does not exceed the elevation of river banks upstream and water flows entirely over the dam (i.e., run-of-river dam; Csiki and Rhoads 2010); (*ii*) dams that are <5 m in height and create small impoundments upstream (i.e., small weirs); and (*iii*) dams that are 5–15 m in height and create impoundments upstream (i.e., low head dams). Information on the study design and the physical (e.g., fine sediment), chemical (e.g., alkalinity) and biological (i.e., macroinvertebrates) variables were extracted (Table S1 in the supplementary data file[1]). The variables were divided into three categories based on positive, negative, and neutral effects. Positive and negative effects indicate significant increases and decreases, respectively, in physico-chemical variables and macroinvertebrates whereas neutral effects indicate no significant downstream effect of impoundment.

A quantitative analysis of the downstream effects of small impoundments on habitat conditions and macroinvertebrates was done using established methods (Cohen 1992), enabling comparisons across studies. The data for calculation of effect sizes were obtained from 25 papers (out of 94), and were standardized by selecting those papers that reported mean values of macroinvertebrates abundance and richness, and physico-chemical variables, or that had enough data to enable their computation. These papers also reported standard deviations and errors. Effect size was calculated using Cohen's d (Cohen 1988); the difference in mean values between reference and experimental sites, divided by the pooled standard deviation or error, depending on the measure of dispersion provided (see Thalheimer and Cook 2002 for detailed equations). The studies used in this review compared downstream reaches to reference conditions.

3. Literature search findings

3.1. Qualitative analysis

Our literature search resulted in 94 peer-reviewed papers that met our criteria (Table S2 in the supplementary data file[1]) reporting the effects of small impoundments on stream habitat conditions and macroinvertebrates. The vast majority of studies were conducted in America (57.4%), with good representation from Europe (20.2%) and Asia (13.8%); however, data were sparse for Africa (3.19%), Australia (3.19%), and the UK (2.13%). Most studies (89.3%) assessed the responses of physical and chemical habitat conditions, while fewer studies (48.9%) reported downstream responses of macroinvertebrates to small impoundments. Analysis of the effect of impoundments on streams was mainly conducted through comparison of sites located in the upstream and downstream reaches, whereas fewer studies compared pre- versus post-impoundment habitat conditions. The duration of the majority of studies was less than 5 years, despite some dams being over 100 years old.

A summary of the reported downstream responses of habitat conditions and macroinvertebrates to small impoundments is presented in Table 1. Most studies (49.2%) assessed small weirs and fewer assessed run-of-river dams (18.4%) and low head dams (32.4%). Most studies found impoundments to have no significant downstream effect on physico-chemical variables (run-of-river dams, 84.7%; small weirs, 54.5%; low head dams, 51.7%). Small weirs mainly caused a significant downstream increase or decrease in macroinvertebrate richness and density (>70% of studies). Similarly, low head dams mainly caused macroinvertebrate density to significantly increase or decrease (74.9% of studies), whereas run-of-river dams had mainly no significant downstream effect on macroinvertebrate richness and abundance (Table 1).

3.2. Quantitative analysis

Results of analysis of the effect sizes of physico-chemical habitat variables and macroinvertebrates are presented in Table 2. The mean effect sizes (r) for chemical variables (e.g., nutrients) ranged from –0.54 to 0.59 (range: small weir, –0.12 to 0.35; run-of-river

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[1] Supplementary data are available with the article through the journal Web site at http://nrcresearchpress.com/doi/suppl/10.1139/er-2014-0080.

Table 1. Studies that reported the downstream effects of small impoundments on stream habitat conditions and macroinvertebrates.

	Small weir			Run-of-river dam			Low head dam		
Variable	Increase	Decrease	No change	Increase	Decrease	No change	Increase	Decrease	No change
Velocity	6	3	8	1	2	1	5	5	4
Depth	5	5	2	—	1	2	8	1	—
Width	5	1	4	—	1	—	3	—	6
Temperature	5	1	15	—	—	6	6	—	10
Dissolved oxygen	4	1	10	—	—	8	—	2	6
Fine sediment	—	20	11	1	1	7	—	12	4
pH	2	1	15	—	—	4	3	—	8
Chlorophyll a	2	—	3	1	—	4	2	—	—
Phosphate	3	—	5	2	—	8	2	1	4
Nitrate	3	2	4	—	—	6	2	—	4
Ammonia	1	—	4	1	—	4	2	—	2
Conductivity	3	2	10	—	—	4	3	1	8
Turbidity	5	—	4	—	—	2	—	—	3
Alkalinity	4	—	4	—	—	3	—	—	3
Hardness	1	—	3	—	—	2	—	—	—
Invertebrate abundance	5	5	4	1	—	4	1	8	3
Invertebrate richness	4	10	4	—	2	3	1	5	6

Table 2. Cohen's *d* and effect size correlation (*r*) mean values, and ranges, for the downstream effects of small impoundments on stream habitat conditions and macroinvertebrates.

		Small weir			Run-of-river dam			Low head dam		
		r		*d*	*r*		*d*	*r*		*d*
Variable	*n*	Mean	Range	Mean	Mean	Range	Mean	Mean	Range	Mean
Velocity	13	0.07	–0.82 to 0.99	6.70	–0.47	—	1.10	–0.40	–0.86 to 0.15	–1.40
Depth	11	–0.21	–0.75 to 0.49	–0.66	–0.60	—	–1.51	0.59	–0.36 to 0.91	2.45
Width	7	0.08	–0.24 to 0.40	0.19	–0.82	—	–2.94	0.68	0.29 to 0.83	2.22
Temperature	14	0.02	–0.28 to 0.51	0.06	0.09	0 to 0.17	0.17	0.35	0.09 to 0.92	1.19
Oxygen	12	0.28	–0.27 to 0.89	0.95	–0.44	—	–0.99	–0.49	–0.69 to 0.28	–1.19
Fine sediment	3	–0.08	–0.40 to 0.35	–0.17	—	—	—	—	—	—
pH	10	0.16	–0.16 to 0.48	0.37	–0.43	–0.44 to 0.42	–0.97	0.15	0.05 to 0.32	0.33
Chlorophyll a	5	0.27	–0.11 to 0.91	1.41	–0.54	—	–1.29	0.59	—	1.47
Phosphates	6	0.30	–0.09 to 0.82	1.02	0.17	0 to 0.34	0.37	0.40	—	0.89
Nitrates	5	–0.01	–0.97 to 0.94	–1.50	0.30	0.25 to 0.35	0.64	—	—	—
Ammonia	4	0.35	0 to 0.91	1.60	0.38	—	0.83	—	—	—
Conductivity	10	0.06	–0.48 to 0.82	0.30	—	—	—	0.21	–0.10 to 0.52	0.47
Turbidity	6	0.33	–0.05 to 0.98	2.70	0.64	—	1.68	–0.27	—	–0.56
Alkalinity	5	0.12	–0.02 to 0.36	0.26	0	—	0	—	—	—
Hardness	3	–0.12	–0.25 to 0.02	–0.24	–0.08	—	–0.16	—	—	—
Invertebrate abundance	12	–0.001	–0.09 to 0.81	–0.05	0.29	–0.07 to 0.65	0.80	–0.03	—	–0.01
Invertebrate richness	4	0.63	—	1.64	–0.60	–0.77 to 0.43	–1.73	–0.29	—	–0.61

Note: *n*, number of studies.

dam, –0.54 to 0.38; low head dam, –0.49 to 0.59). The mean effect sizes for the physical variables ranged from –0.82 to 0.68 (range: small weir, –0.21 to 0.33; run-of-river dam, –0.82 to 0.64; low head dam, –0.40 to 0.68). With regard to macroinvertebrates, the mean effect sizes for abundance ranged from –0.03 (low head dam), –0.001 (small weir) to 0.29 (run-of-river dam), whereas for richness they ranged from –0.60 (run-of-river dam), –0.29 (low head dam) to 0.63 (small weir).

4. Responses of habitat conditions and macroinvertebrates to impoundment

4.1. Impoundment and habitat conditions

Based on our qualitative analysis, most studies (>50%) reported that small impoundments had no statistically significant downstream effects on most physico-chemical habitat variables (e.g., Almeida et al. 2009; Principe 2010; Mendoza-Lera et al. 2012); however, quantitative analysis showed that the impoundments had small (r = –0.10 to 0.30; small weir), small-medium (r = –0.50 to 0.30; run-of-river dam) and small-large (r = –0.50 to 0.60; low head dam) effects on chemical variables. With regard to the physical variables, the impoundments had small (r = –0.20 to 0.30; small weir) and small–large (r = –0.80 to 0.60; low head and run-of-river dams) effects. This finding suggests that small weirs (<5 m) may generally have small effects on physico-chemical variables and that, although most tests of statistical significance showed no downstream effects, effect sizes showed that small impoundments (e.g., run-of-river and low head dams) had small to large effects on physico-chemical habitat variables. With an adequately large sample size, statistical tests of signifcance (p values) will most likely show significant differences, even when the effect size itself is very low; however, it should be noted that very small differences, which are deemed statistically significant, are usually not ecologically meaningful. Thus, it is important to report both the statistical significance and effect sizes for readers to fully understand the results (Sullivan and Feinn 2012).

The downstream effects of impoundments on river habitat conditions depend on factors, such as the depth from which water is released to the downstream reaches, water retention time, and the volume of impoundment (denHeyer 2007; Poff and Hart 2002). These factors could be responsible for the observed differences between impoundments, given that small weirs are typically small in size (i.e., height and volume) and release surface water (Csiki and Rhoads 2010). Ménendez et al. (2012) reported that the mean water temperature and dissolved inorganic nitrogen were significantly increased below a small impoundment that released deep water, whereas these two variables were not significantly affected by impoundments that released surface water. Santucci et al. (2005) and Principe (2010) also reported no significant downstream effects of small surface release impoundments on physico-chemical variables whereas Camargo et al. (2005) reported increased nutrient concentrations below small impoundments releasing deep water. It is important to consider the synergistic effects of natural variations (e.g., season) as well as other man-made stressors on the habitat conditions of streams (Nelson and Roline, 2003). Maxted et al. (2005) and Lessard and Hayes (2003) found water temperature to increase significantly below small surface release impoundments during summer, and not to recover to upstream temperatures at the most downstream site. Theodoropoulos et al. (2015) assessed the effect of land use on freshwater invertebrates in impounded streams and found that land use and flow regulation had a negative influence on invertebrates. The authors suggested that both land use and flow regulation stressors should be given equal importance in affecting invertebrates as local instream factors.

4.2. Impoundment and macroinvertebrates

Most studies (>70%; small weir and low head dam) from qualitative analysis found impoundments to affect macroinvertebrates positively or negatively (e.g., Mueller et al. 2011; Martínez et al. 2013; Wang et al. 2013). The mean effect sizes for macroinvertebrates ranged from small (abundance: $r = -0.03$, low head dam; $r = -0.001$, small weir; $r = 0.29$, run-of-river dam) to small–large (richness: $r = -0.60$, run-of-river dam; $r = -0.29$, low head dam; $r = 0.63$, small weir) effects. The impoundments caused downstream increases or decreases in the abundance and richness of macroinvertebrates, although richness was found to be more sensitive to small impoundments than was abundance. Tiemann (2002) found mean macroinvertebrate abundance to decrease by half in the downstream reaches compared to reference reaches. In Spain, there was a greater decrease in mean macroinvertebrate abundance in downstream compared to reference reaches (Martínez et al. 2013). The authors suggested that, because stream physicochemistry was minimally affected by impoundments, downstream change in the ratio of coarse and fine particulate organic matter (CPOM:FPOM) could have adversely affected the abundance of invertebrates. Camargo et al. (2005) reported that small impoundments had a negative effect on some sensitive macroinvertebrate taxa, such as the plecopterans, reducing macroinvertebrate richness at the downstream reaches, whereas taxa abundances tended to be highest at the downstream sites as a result of high abundances of tolerant taxa, such as dipterans. The abundance of organisms in populations is variable over time, and a potential anthropogenic influence, such as impoundment, is not always the cause of change in abundance (Underwood 1992). Freshwater systems are affected by multiple stressors and macroinvertebrates may be affected differently by these stressors (Wagenhoff et al. 2012). Moreover, macroinvertebrate abundance at downstream sites may be the same as reference reaches because sensitive species are replaced by tolerant species at the downstream reaches (Dean et al. 2002). Brandimarte et al. (2005) found macroinvertebrate richness to be more sensitive than species abundance to discharge regulation by small impoundments.

Given that most studies found invertebrates to be more responsive than physico-chemical variables to small impoundments, this suggests that invertebrates were a more sensitive measure to identify the downstream effects of small impoundments; however, most studies focused on the analysis of physico-chemical variables rather than on invertebrates. Considering that benthic invertebrates are representative of a river's ecological status over time, they are a more sensitive measure of stream habitat conditions than physico-chemical analysis (Bae et al. 2005; Li et al. 2010). Analyses based on biotic indicators, such as invertebrates, may therefore help to detect the downstream deleterious effects of small impoundments on streams, in contrast to physico-chemical analysis, which may not be sensitive to impoundment (e.g., Principe 2010; Kil and Bae 2012). Additionally, implementation of such anaylses before and after construction of impoundments may help in prevention or mitigation of undesirable downstream ecological effects on both the biotic and abiotic environments (Renöfält et al. 2010). This may help to protect certain freshwater ecosystem services (e.g., leaf litter decomposition), which are mediated by some sensitive invertebrates (e.g., the plecopterans) (Mendoza-Lera et al. 2012; Ménendez et al. 2012).

Analyses of the effects of impoundments on stream invertebrates may employ techniques such as spatial (e.g., upstream versus downstream) or temporal (e.g., pre- versus post-regulation) comparisons (Braatne et al. 2008). In this review, most studies employed the first technique while fewer studies employed the latter. Although knowledge of stream conditions prior to impoundment construction is important and may be an alternative to reference reaches, studies applying this approach are not common (Brandimarte et al. 2005). Knowledge of downstream pre-impoundment conditions may help to identify downstream effects of small impoundments in streams where the choice of reference sites is hampered by other anthropogenic stressors, beside impoundment; however, in many regions of the world streams are affected by different stressors and it may be difficult to find near-pristine reference reaches (Jungwirth et al. 2000).

Most studies were conducted over a relatively short period of time (<5 years) although most impoundments were much older (>100 years). Despite the fact that short-term assessments may help to identify the potential downstream effects of small impoundments, such assessments are not appropriate for long-term planning purposes or for gaining better understanding of the downstream biotic and abiotic responses to small impoundments. Long-term data are needed to predict and mitigate the potential downstream effects of impoundments throughout their lifespan because short-term studies may fail to detect long-term effects of impoundments on stream habitats and biota (Fjellheim and Raddum 1996).

The construction of small impoundments is increasing globally (Downing 2010) and it is important to take into consideration the potential impacts on habitats and biota through improved construction and to enhance connectivity of reaches located in the upstream and downstream regions of rivers. Despite the various economic and ecological (e.g., reduction of pollutant loads) benefits provided by small impoundments, they may fail to fulfil the targeted uses and affect stream habitat and biota. In conclusion, it is prudent to conduct environmental impact assessments before the construction of small impoundments and to follow with auditing throughout their lifespan, to better detect and prevent possible negative effects over time, as well as for mitigation of already affected systems.

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