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REVIEW

Small instream infrastructure: Comparative methods and evidence of environmental and ecological responses

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Abstract

1. Around the globe, instream infrastructures such as dams, weirs, and culverts associated with roads are wide-spread and continue to be constructed. There is limited documentation of smaller infrastructure because of mixed regulation and laws related to instream construction, as well as difficulty in documentation because of their size and frequency in waterscapes.
2. We reviewed evidence of different methods used to quantify environmental and ecological responses (positive, negative, or neutral) to dams, weirs, and culverts.
3. Most studies (78% of 87) in our review evaluated dams or weirs, and more than half evaluated environmental or ecological responses at more than one of these structures. More than half of the studies used spatial (disturbed–undisturbed in the same or a different catchment) rather than temporal (before–after construction or before–after destruction) comparative methods. Evaluations also tended to focus on ecological variables, most specifically on fish community responses (just over a quarter) to infrastructure.
4. More than half (58%) of the evaluations at dams, weirs, or culverts reported negative environmental or ecological responses. Discrepancies in responses recorded for different infrastructure types could be partially explained by the focus on ecological responses in reviewed studies and related metrics used for evaluations (e.g. biotic groups, richness, and abundance), the imbalance of studies at different infrastructure types, and discrepancies in spatial and temporal scales of evaluations compared to those at which the variables respond to infrastructure.

5. Despite the abundance of road culverts greatly exceeding the number of small or large dams worldwide, they were evaluated in only 22% of studies that we reviewed. Our findings underscore the need for studies to not only better understand local but also cumulative impacts of these smaller infrastructure, as these could be greater than those caused by large infrastructure depending on their location, density, and type, among other factors. Such studies are needed to inform infrastructure planning and watershed management.

KEYWORDS
dams, evaluation, freshwater ecosystems, rivers, roads, weirs

1 | INTRODUCTION

Instream infrastructures such as dams, weirs, and culverts are widespread, and in many parts of the world continue to be constructed at unprecedented rates (Grill et al., 2019; Ibisch et al., 2016; Zarfl, Lumsdon, Berlekamp, Tydecks, & Tockner, 2015). Built for varied reasons, dams and weirs capture water and modify the magnitude and timing of its movement downstream, whereas culverts are constructed to facilitate the movement of water under roads and railways. Smaller infrastructures such as dams <15 m in height, weirs, and culverts are more prevalent and diverse in size than larger dams, yet are commonly neglected in environmental policy (e.g. Couto & Olden, 2018; Lange et al., 2019). It is estimated that there are 11 small dams for each large dam globally (Couto & Olden 2018), and the abundance of road culverts greatly exceeds the number of small dams (Fuller, Doyle, & Strayer, 2015; Januchowski-Hartley et al., 2013).

Instream infrastructure of all sizes can transform river ecosystems (McIntyre et al., 2016; Olden, 2016). Smaller dams, weirs, and culverts can impede movement of species, river flows, sediments, nutrients, and materials (McIntyre et al., 2016; Oele, Gaeta, Rypel, & McIntyre, 2018). Despite recent attention given to smaller instream infrastructure, the diversity and pervasiveness of their environmental and ecological alterations across broad geographies remain poorly understood. A core limiting factor to enhance this knowledge is mixed regulation and laws for in-stream construction of infrastructure. There are notable regional-scale examples, such as Washington State in the United States, where rules are being put into place to monitor and ensure anything built in-stream allows water and species to move as freely as possible. Equally, there remains largely incomplete documentation of small infrastructure occurrences, and that is in-part due to mixed regulations, as well as difficultly in documentation because of limited visibility on ground and in satellite imagery and their ubiquity across the landscape (Couto & Olden 2018; Fuller et al., 2015).

How we evaluate and compare the distribution of small instream infrastructure (hereafter called infrastructure) influences our understanding about how ecosystems respond to different types of structures as well as our capacity to respond to related changes. We are not aware of any comprehensive syntheses of different methods used to quantify environmental (abiotic factors, such as water quantity or quality) or ecological (biotic factors, such as fish, macrophyte, and macroinvertebrate communities) responses to different infrastructure, or of the effects reported. To address this knowledge gap, we collate evidence from 87 peer-reviewed publications over the last half century. Based on our findings, we propose possible directions for future research to meet information needs and better understand the diversity of infrastructure effects on freshwater ecosystems.

2 | METHODS

2.1 | Types of infrastructure

Our study focused on dams or weirs <15 m high and culverts. Dams refer to infrastructure constructed along rivers by positioning a wall (spanning the channel cross section) intended to hold water back in a reservoir for different human purposes (e.g. water supply and hydroelectric power), and where flows are released downstream via different methods in a controlled manner (Richter & Thomas, 2007; Figure 1a). Weirs are like dams in that a structure is built across a waterway to transform conditions for different societal purposes (e.g. navigation and measuring water discharge; Figure 1b). But unlike dams, weirs often allow water to flow over the top of the structure. Culverts are structures whereby water from a river or other waterbody is diverted under a road, railway, or some other built structure (Truhlar et al., 2020; Figure 1c).

2.2 | Literature review

We conducted a comprehensive search of ISI Web of Science (WoS) for articles published between 1972 and November 2017, with the following two sets of keywords: (a) (weir* OR low-head dam* OR run-of-river OR culvert* OR small dam) AND (impact* OR effect*) AND (enviro* OR eco*) and (b) (weir* OR low-head dam* OR run-of-river OR culvert* OR small dam) AND (water qual* OR water quan*). We used WoS because it references articles over a longer period compared to other databases such as Scopus (limited to articles since 1995) and returns more consistent results than Google Scholar (Nash & Graham, 2016). In using this

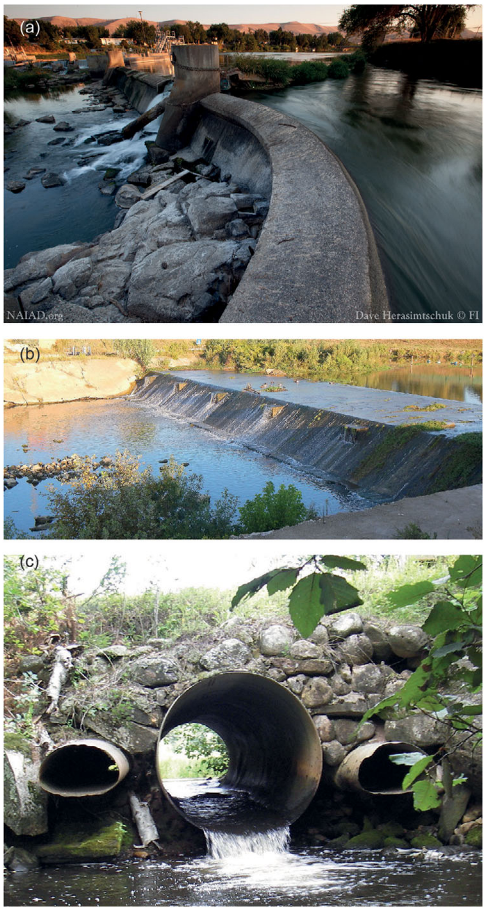

FIGURE 1 Examples of small instream infrastructure: (a) dam, (b) weir, and (c) culvert that were the focus in reviewed studies. Shown are a low head diversion dam on Yakima River, Washington, D.C. (photo by David Herasimtschuk); a weir on Lez River, France (photo by Stephanie Januchowski-Hartley); and a culvert at the intersection of a road and stream in Chequamegon-Nicolet National Forest, USA (photo by Dale Higgins)

method, we omitted studies published outside the focus of WoS such as projects lead by non-government organizations or government agencies that are either internal reports or grey literature. We also removed conference proceedings, books, and book chapters returned from our WoS search, which meant our review was based only on peer-reviewed scientific literature. Our search returned 1,060 publications, all of which were randomly assigned to six of the authors of this manuscript. The six authors reviewed abstracts from all 1,060 publications and retained 327 studies that were written in English, included a description of the infrastructure, and evaluated environmental or ecological responses in freshwater ecosystems. During the initial abstract review, the six authors noted environmental and ecological variables reported in study abstracts. From this, we created a worksheet of environmental and ecological variables to be completed, and refined as needed, during detailed reviews. The worksheet included a list of broadly defined environmental (abiotic factors) and ecological (biotic factors) response variables (Table S1). The 327 studies were then reviewed to determine (a) whether the study considered infrastructure (dams or weirs <15 m high or road culverts) specifically and (b) if the study was comparative in nature, evaluating environmental or ecological responses to infrastructure in reference to another system or condition. In total, 87 studies fit these criteria and were retained for detailed review.

Of the 87 studies we retained for detailed review, most were carried out in the United States (41), Australia (10), and the United Kingdom (8). From each of the 87 studies, we determined the types of infrastructure evaluated, how many, and the comparison method used. In terms of comparison methods, we documented whether studies used spatial, temporal, or spatial and temporal comparative methods to evaluate environmental and ecological responses to infrastructure, and in two cases studies focused on modelling approaches that were spatially explicit and comparative. Specifically, we considered spatial comparisons as those that evaluated environmental and ecological variables in disturbed (infrastructure present) and undisturbed (no infrastructure present) waterways within the same or separate catchments, and temporal comparisons were considered as those that compared waterways before or after construction or destruction. We also determined when a study used any combination of spatial or temporal comparative methods.

We also documented the frequencies of the different environmental or ecological variables evaluated in the 87 studies, where those were measured in relation to infrastructure (above or below), and documented the reported responses (positive, negative, and neutral) observed above or below different structures relative to the control areas. Controls varied by study, relating to the comparative methods used to evaluate environmental and ecological responses to infrastructure. For example, in the case of disturbed and undisturbed comparison, the control would be the undisturbed area evaluated in the study. We also note that while we documented all responses evaluated in the 87 studies (Tables S2–S4), given the inconsistencies of the variables examined between studies, we primarily report overall environmental and ecological responses (i.e. positive, negative, or neutral) to infrastructure.

2.3 | A note on infrastructure characteristics

A primary obstacle encountered through this review was a lack of both data on characteristics and reporting within studies; this influenced which studies were retained for further review. For example at least half of the 327 study publications that we initially reviewed were evaluations of dams or weirs, and of those roughly 80% did not report structure height. Some studies did include context or descriptive information that enabled us to make an assumption that dams or weirs were <15 m in height, but that was only the case for a small number of those included in our detailed reviews. Height, which we used as a characteristic for inclusion or exclusion from our analysis, is only one of several characteristics of infrastructure; it is also likely to be one of the more commonly reported. Explicit inclusion of these characteristics would allow representation of more studies in reviews such as ours and improve our understanding about how different typologies of infrastructure can alter and change freshwater ecosystems.

TABLE 1 Summary of reviewed studies ($N = 87$) that considered single or multiple structures. All studies focused on a single type of infrastructure (e.g. dams), but could have conducted evaluations at more than one structure. We report the frequency (number of studies) that evaluated a single or multiple infrastructure type

Infrastructure type	Single structure	Multiple structures
Dam	12	19
Weir	13	24
Culvert	2	17

TABLE 2 Summary of comparative methods used to evaluate effects of dams, weirs, or culverts in reviewed studies ($N = 87$). We report the frequency (number of studies) of each method used for the different infrastructure types

Comparison method	Dam	Weir	Culvert
Spatial			
Disturbed-–undisturbed (same catchment; DIR)	13	19	4
Disturbed–undisturbed (separate catchment; DIS)	4	4	6
Temporal			
Before–after construction (BAC)	5	6	4
Before–after destruction (BAD)	9	2	0
Spatial and temporal			
Both BAC and BAD in same study	0	0	1
Both BAC and DIR in same study	0	4	2
Both BAC and DIS in same study	0	1	1
Both BAD and DIS in same study	0	0	1
Both BAD and DIR in same study	0	0	0
Both DIS and DIR in same study	0	1	0

3 | RESULTS

3.1 | Methods of evaluation

Most studies in our review evaluated responses at weirs ($n = 37$; 43%) or dams ($n = 31$; 36%). More than half ($n = 43$; 63%) of those evaluations at weirs and dams included more than a single structure (Table 1), meaning that a study focused on weirs could have evaluated multiple representatives of such infrastructure. We also found that nearly half ($n = 36$; 41%) of the studies evaluated between two and 10 structures.

Of the 87 studies that we reviewed, 10 different comparative methods were employed, 21% ($n = 18$) of which used multiple methods (Table 2). Spatial comparisons were used in 57% ($n = 50$) of studies, and within-catchment comparisons of disturbed versus undisturbed sites were most common ($n = 36$; 72% of spatial comparisons). Ten percent ($n = 9$) of studies used both spatial and temporal comparisons of environmental or ecological responses to infrastructure (Table 2).

3.2 | Environmental and ecological responses to infrastructure

We found variable environmental and ecological responses (positive, negative, and neutral) both above and below different types of infrastructure, but there were several patterns that emerged (Figure 2a–f). Notably, some studies evaluated more than one environmental or ecological response as well as responses above or below structures, resulting in 92 evaluations of environmental or ecological responses for dams in our study, 80 for weirs, and 43 for culverts (Figure 2; Tables S2–S4).

Overall, there were more evaluations of ecological ($n = 111$; 52%) compared to environmental ($n = 104$; 48%) responses to infrastructure in the studies that we reviewed (Figure 2a–f). Just over a quarter ($n = 58$; 27%) of all evaluations were on fish community responses to infrastructure (Tables S2–S4). The greatest number of environmental and ecological responses were recorded below dams ($n = 51$; 24%) and weirs ($n = 45$; 21%) (Figure 2; Tables S2–S4).

More than half ($n = 125$; 58%) of all evaluations that we reviewed reported negative environmental or ecological responses above or below infrastructure compared to controls (Figure 2). A remaining 24% ($n = 52$) of evaluations found neutral environmental and ecological responses, whereas 18% ($n = 38$) reported positive responses compared to the controls.

Of the evaluations above and below dams, more than half ($n = 53$; 58%) found negative environmental and ecological responses relative to controls (Figure 2a and 2b; Table S2). Of the remaining evaluations above and below dams, nearly a quarter found positive ($n = 21$; 23%) responses. the majority of which were ecological variables such as macroinvertebrate and fish communities ($n = 14$; 67%) (Figure 2a and 2b; Table S2).

We found that nearly half ($n = 39$; 49%) of evaluations at weirs reported negative environmental or ecological responses, as did the majority ($n = 33$; 78%) of the studies evaluating culverts (Figure 2c–f). Fewer environmental and ecological responses above ($n = 14$; 40%) than below ($n = 25$; 56%) weirs were negative compared to controls (Figure 2c and 2d; Table S3). Less than a quarter of evaluations above or below weirs found positive environmental or ecological responses relative to controls (Figure 2c–f). There were no positive or neutral environmental responses found above or below culverts (Figure 2e and 2f).

4 | DISCUSSION

The widespread proliferation of infrastructure constructed along rivers calls for the need to develop a more robust understanding of associated impacts. Most studies in our review evaluated environmental or ecological responses at multiple dams or weirs and employed spatial comparative methods. We found that more than half of the evaluations that we reviewed reported negative environmental or ecological responses at dams, weirs, or culverts. Study evaluations also tended to focus on ecological responses to infrastructure, specifically on fish communities (just over a quarter). We discuss the implications of these findings below and outline recommendations for future studies, with

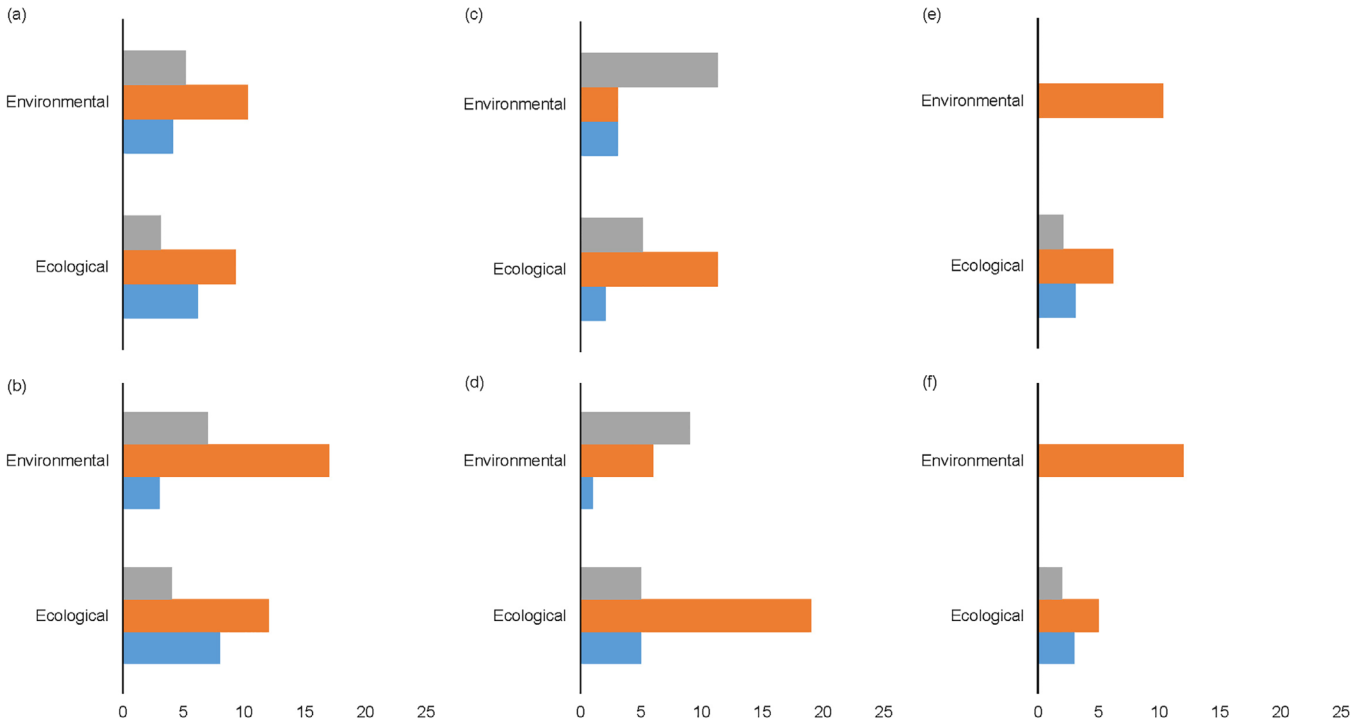

FIGURE 2 Summary of environmental and ecological variable responses (positive (blue), negative (orange), and neutral (grey)) above and below small instream infrastructure. Shown are frequency of variable responses (a) above and (b) below dams; (c) above and (d) below weirs, and (e) above and (f) below culverts. We report the frequency (number of evaluations) of environmental and ecological variables

the goal to explore gaps in current knowledge and inform best practice for future evaluations.

Most evaluations in our review focused on dams or weirs, whereas culverts received less attention. This finding underscores that we have a limited understanding about the impact of culverts on freshwater ecosystems, and that there is a need for studies that include both large and small infrastructure (Grill et al., 2019). The scientific community should seek a more comprehensive, system-wide understanding about how infrastructure can influence and change freshwater ecosystems, especially because of their potentially large cumulative impact (Januchowski-Hartley et al., 2013). It was encouraging to find that studies in our review tended to evaluate environmental and ecological responses to multiple structures. However, our findings also suggest that there has been a tendency for studies to evaluate multiple larger infrastructure such as dams, but not necessarily multiple smaller infrastructure such as culverts. This could be the result of culverts not tending to occur in sequence along rivers, but that seems unlikely given their frequency along our waterways. It could also be that fewer studies focused on culverts is a result of historical focus on larger dams and weirs, and assumptions about the permeability of smaller structures. Regardless of the reason, there is a clear need for improved approaches to inventorying, characterising, and quantifying impacts of smaller infrastructure, such as culverts, on freshwater ecosystems.

More than half of the studies that we reviewed deployed only spatial comparisons to estimate environmental or ecological responses to infrastructure. To better understand the diversity of responses to infrastructure, there is a need for both spatial and temporal comparisons. Our findings indicate a need and opportunity to expand temporal comparisons, potentially to establish sampling multiple years before or after infrastructure destruction or construction. With some forward planning, sampling and comparison across time could be scheduled alongside ongoing and expanding efforts to remove aging infrastructure, such as weirs (Birnie-Gauvin et al., 2018) and dams, and in conjugation with dam operations releasing environmental flows (Olden et al., 2014), particularly in areas of Europe and the United States. Equally, in many areas of the tropics, where infrastructure is expanding, there could be an opportunity to also expand sampling, particularly ahead of emerging projects (Carvajal et al. 2016) that are still in the planning stages.

In addition, more than half of the evaluations in studies that we reviewed reported negative environmental or ecological responses to infrastructure relative to controls. However, both above and below the three types of infrastructure, responses of ecological variables (e.g. fishes, invertebrates, and other biotic communities) were more likely to be positive than responses of environmental variables when compared to controls. Discrepancies in environmental or ecological responses in evaluations that we reviewed could be partially explained by several factors, including the low number of studies that focused on culverts, and differences in number of variables evaluated for the three types of infrastructure. Equally, the creation of different habitats upstream of infrastructure, such as water pooling, could have translated into positive responses, particularly because of the high proportion of evaluations focused on ecological variables. There is a tendency to use single metrics such as taxonomic richness to assess ecological response, and in isolation these metrics can overlook changes to biodiversity (Mueller, Pander, & Geist, 2011). We suggest there is a need to move beyond examining such metrics in isolation to better understand ecological responses to infrastructure, and to measure taxonomic, functional, and phylogenetic properties for different biotic groups. Such investigations should explicitly account for non-native species that are often found in higher diversity and abundance in reservoirs above dams (Johnson, Olden, & Vander Zanden, 2008). In relation to sampling, there could have also been differences in spatial and temporal scales at which evaluations were carried out, and those at which variables respond to infrastructure and associated changes in habitat and connectivity (Fullerton et al., 2010; Ganio, Torgersen, & Gresswell, 2005). While it is challenging to quantify environmental and ecological responses to infrastructure at all relevant spatial and temporal scales, there are methods (e.g. sensors, remote sensing, and machine learning) that can assist researchers with identifying the scales over which connectivity influences different ecosystem properties (Fullerton et al., 2010). Researchers should consider responses at nested spatial scales in relation to infrastructure along a river network and consider relevant temporal scales; this will depend on the response variable in question but needs to be given more specific consideration in future studies (Campbell, Lowe, & Fagan, 2007; Ward, Malard, & Tockner, 2002).

Roughly a quarter of studies that we reviewed focused on the ecological responses of fish communities to infrastructure. This is possibly why comprehensive reviews exist for fish (e.g. Fullerton et al., 2010) responses to infrastructure (large and small structures included). However, our review identifies gaps in previous studies and outlines other relevant variables that are likely to respond to infrastructure and changes in connectivity but that have rarely been included in such assessments. Variables such as algal communities, sediment toxicity and quantity, and biogeochemical processes such as litter breakdown and nutrient cycling tended to be overlooked by studies we reviewed. These gaps in studies limit our understanding about how ecosystems are responding to infrastructure. Better understanding how biogeochemical processes respond to infrastructure can offer insights into changing spatial and temporal dynamics that influence patterns and movements of fishes and other species. There is a need to move towards methods and studies that allow us to better understand changes in processes and patterns in relation to infrastructure, as well as other human alterations within freshwater ecosystems (Fullerton et al., 2010; Linke, Hermoso, & Januchowski-Hartley, 2019).

5 | CONCLUSIONS

Our review revealed a need to capture and record the characteristics of infrastructure more accurately. Doing so would facilitate our ability to scale up and extrapolate findings from individual studies to other areas (e.g. using results from a study on infrastructure over 5 m to estimate effects of infrastructure of the same height in other systems). In addition, our findings point to a need for studies that evaluate environmental and ecological responses to culverts, and this is particularly important because of common assumptions that these are less impactful on freshwater ecosystems despite occurring in higher densities than larger infrastructure. The relatively few studies that focused on culverts limit our ability to draw conclusions about patterns observed in studies. We see a need to move towards more comprehensive study designs, and we offered several directions that could foster a better understanding about how different variables are responding to infrastructure. Finally, most studies that we reviewed were conducted in three countries (the United States, Australia, and the United Kingdom), and we see that work is needed to understand how findings from well-studied areas can help inform poorly studied areas. This is especially relevant as small infrastructure continues to expand around the globe.

AUTHORS' CONTRIBUTIONS

SRJ, SM, JC, VH, and SB conceived the study. SRJ, SM, JC, and VH designed the review procedure and gathered the literature. SRJ, SM, JC, VH, SB, and JDO reviewed the literature. SRJ, SM, and JCW analysed the data. SRJ wrote the article. All authors contributed to writing and editing and approved the manuscript for publication.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data used to produce the results reported in this study are available for download from Figshare: https://doi.org/10.6084/m9.figshare.12958010 (Januchowski-Hartley et al., 2020).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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