

SHORT COMMUNICATION

Utility of artificial river reef structures to enhance fish habitat below a hydropeaking dam

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Abstract

Large-scale modification of river ecosystems for navigation, power generation, flood control, and irrigation has largely homogenized benthic habitats and altered fish assemblages. Although riverine habitat rehabilitation and enhancement techniques are well-studied for wadable streams and small rivers, relatively little is known about the potential utility of artificial fish habitat installation in large rivers impacted by hydropeaking. Lightweight artificial fish habitat structures composed of wood or plastic have demonstrated effects on fish populations in static environments; however, these structures are not able to withstand the high discharge and dynamic flows of a large river system. The Colorado River below the Davis Dam is a representative ecosystem impacted by hydropeaking, where water release can range from 2000 to 23,000 ft³/s (56.6–651.3 m³/s) in a single day. In coordination with multiple state and federal government agencies, we deployed a series of concrete river reef structures, mimicking small-scale artificial reefs, to increase habitat complexity and provide in-river patches of relief from high-flow events. Benthic habitat cover measurements were paired with visual surveys of river reef structures 6 months and 2.5 years post-deployment. Generalized linear models indicated that cobbles increased structure visibility above the riverbed, displayed less erosion, and allowed for greater potential fish use, whereas sand and gravel (i.e., loose bedload materials) decreased visibility and caused structures to sink into the riverbed over time, limiting fish use. Our case study provides instructional information on the construction of artificial river reef structures and recommendations for deployment, and highlights their potential to increase benthic habitat heterogeneity, with conservation and sport fish implications.

KEYWORDS

artificial fish habitat, benthic habitat, Colorado River, reef balls

1 | INTRODUCTION

Rivers and streams are considered among the most heavily modified aquatic ecosystems worldwide (He et al., 2021; Reid et al., 2019). No fewer than 70% of the world's rivers are regulated by more than 800,000 dams (Dynesius & Nilsson, 1994; Rosenberg et al., 2000) and nearly 62,000 of these dams measure greater than 15 m in height (ICLD, 2023). These instream barriers have radically changed flow

regimes and fragmented available habitats for riverine fishes (Aarts & Nienhuis, 2003; Barbarossa et al., 2020; Couto & Olden, 2018; Perkin & Gido, 2012; Rosenberg et al., 1997). Globally, hydropeaking is common in large rivers and is among the most impactful human practices to large river habitats, with systemic negative effects on biotic and abiotic conditions (Bipa et al., 2023; Moran et al., 2018; Rosenberg et al., 1997). Hydropeaking fundamentally changes the spatial and temporal availability of habitat through

sediment reduction, channelization, debris dislodgement, and severe daily flow fluctuations, where water release rapidly changes the magnitude in flow through the turbines to coincide with regional energy demands (Cushman, 1985; Poff et al., 2007). The resultant homogenization of riverine ecosystems has impaired aquatic environments and altered aquatic insect and fish assemblage structure throughout North America (Rahel, 2000; Scott & Helfman, 2001).

Restoration methods to increase habitat heterogeneity and complexity are often linked to methods to develop more diverse aquatic communities in riverine ecosystems (Favata et al., 2018; Lyon et al., 2019; Schumann et al., 2021; Tonkin et al., 2014). Although aquatic insect assemblages are thought to respond more rapidly to such changes than fish (Miller et al., 2010; Selego et al., 2012), introduced habitat heterogeneity is often correlated with increased fish growth and abundance (Schumann et al., 2021). The recognition that diverse habitats support greater densities of fishes than less structurally complex areas in small rivers is well supported; however, the success of these efforts in concentrating or providing novel foraging opportunities for fishes in large rivers below a hydropeaking dam is less well understood (Hauer et al., 2008; Pander & Geist, 2010).

Managers and ecological practitioners have long deployed artificial structures to restore lost or enhance existing freshwater habitats (Smokorowski & Pratt, 2007). Lightweight artificial fish habitat materials composed of wood or plastic have demonstrated effects on fish populations in ponds, lakes, reservoirs, wadable streams, and small rivers; however, these structures are not able to withstand the high discharge and dynamic flows of a large river system. In lentic systems, the common materials include hay bales, tree branch bundles, entire coniferous trees, as well as ceramic, concrete, or PVC structures (Bolding et al., 2004), whereas in riverine systems, structures like bankhides, boulder clusters, locked logs, and root wads are commonly used (Iowa DNR, 2018). Projects that have adopted a river editing systems also include specifically designed weirs or flow deflectors, which provide a modified flow profile to facilitate fish passage (Alfredsen et al., 2004). Artificial reef structures have become increasingly popular as a management tool to support recreational fisheries and species conservation in coastal ecosystems and small riverine impoundments, where structural benthic habitats have been lost to sedimentation and scouring (Komyakova et al., 2019). These structures have largely been used for fish attraction and to concentrate biomass (Pander & Geist, 2010), but have more recently achieved broad ecological objectives by increasing system productivity and providing habitat for diverse aquatic taxa (Lemoine et al., 2019). Evidence suggests that artificial reef structures not only concentrate existing fish populations but can increase individual growth rates and fish abundance, and alter assemblage composition by concentrating to nearby homogenous regions (Komyakova et al., 2019; Martin & Bortone, 1997). Increasingly, the use of artificial habitat is projected to continue and mitigate the impacts of anthropogenic disturbance on freshwater ecosystems. Here, we aim to provide instructional information on the construction of artificial river reef structures, report the percent visible of structures over time, and quantify the benthic habitat cover that promotes long-term utility of river reef structures below a hydropeaking dam.

2 | METHODS

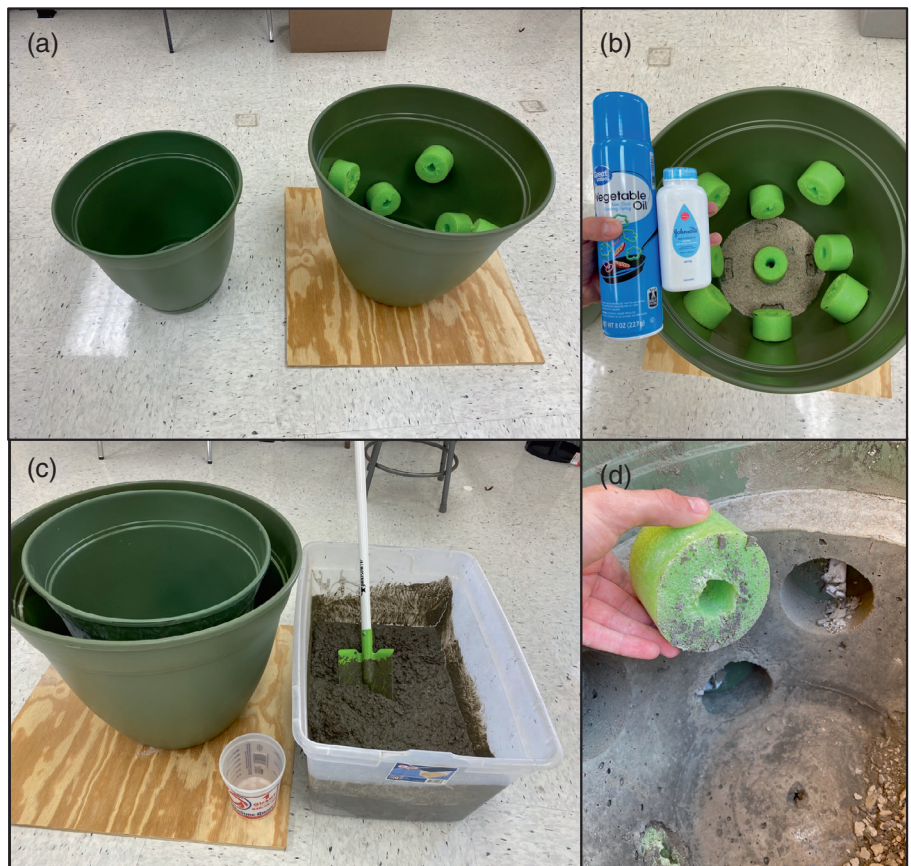
2.1 | Construction of artificial river reef structures

River reef structures were constructed using materials purchased locally and followed a modified Reef Ball™ design (Reef Ball Foundation, 2017). Nested sets of plastic planters were used to create the dome-shaped mold (Figure 1a). The large planters used for the outer part of the mold measured: 48.6 cm (top diameter), 28.3 cm (bottom diameter), and 43.2 cm (height), whereas the smaller planters used for the inner part of the mold measured: 38.7 cm (top diameter), 25.4 cm (bottom diameter), and 35.6 cm (height). Nine cavities (diameter: 8.9 cm) within the mold were made by wedging foam pieces between the spaces created by the nested planters (Figure 1b). One of the nine cavities in each mold was equipped with a crossbar, which aided in the deployment by attaching a quick-release hook. A mixture of concrete and hay was used as the fill. Hay was used as a binder to prevent cured structures from easily cracking or breaking apart (Figure 1c). To prevent the smaller planter from being displaced when filling the mold (i.e., floating in the concrete slurry), a hardware setup of 17.8 cm (7.0") hex bolt with 10.2 cm (4.0") diameter washers was used to fix the nested planters together from the bottom. Prior to pouring concrete, a 1.3-cm layer of sand was added on the bottom of the mold and the internal surfaces of the plastic mold were coated with talcum powder to facilitate removal of the planters after the concrete cured (Figure 1b,d).

2.2 | Study area

River reef structures were deployed between river mile markers 7 and 12 below the Davis Dam in the lower Colorado River (Figure 2). The Davis Dam is 67 miles downstream of the Hoover Dam and adjacent to two municipalities: Laughlin, Nevada and Bullhead City, Arizona. The Davis Dam began operations in 1951, and over 70 years later, the resulting benthic river habitat is largely channelized and contains limited large woody material or other fish refugia. Depending on operational needs and flow requests, water release ranges from 2000 to 23,000 ft³/s (56.6–651.3 m³/s) in a single day (BOR, 2023). Substantial changes to the flow regime support hydroelectric, irrigation, and numerous recreational activities. In addition to the daily flow modifications, the establishment of Quagga mussels (*Dreissena bugensis*) and spread of Koi herpes virus (cyprinid herpesvirus 3 [CyHV3]) have further changed the benthic habitat (AZGFD, 2009; Hickey, 2010). Lowered turbidity and the reduction of benthic feeding fishes have promoted abundant periphyton growth, which has greatly increased primary production and invertebrate abundance, including nuisance black flies and net-spinning caddisflies. At the type locality, Rainbow Trout (*Oncorhynchus mykiss*) stocking is a critical component of the aquatic insect suppression program and provides significant public appeal. Fish are introduced seasonally as a method of biological control for hyper-dense populations of black flies (Diptera: Simuliidae) and net-spinning caddisflies (Trichoptera: Hydropsychidae) in the river

FIGURE 1 Example of the materials used to create the mold for the river reef structures. [Color figure can be viewed at wileyonlinelibrary.com]



but are subject to significant predation pressure by Striped Bass (*Morone saxatilis*) and cormorants (Phalacrocoracidae).

2.3 | River reef structure deployment and monitoring

Artificial river reefs were deployed at six sites along the bend reach of the lower Colorado River, near Bullhead City, Arizona (Figure 2), where nuisance aquatic insects have historically impacted riverfront residents. In total, 90 artificial river reef structures were placed in the river, 15 at each reef site in a chevron orientated approximate 1 meter apart in an upstream direction (Figure 2). Before deployment, we coordinated our project with the U.S. Army Corps of Engineers (South Pacific Division: Los Angeles District) and U.S. Coast Guard (Pacific Southwest: District 11) to ensure compliance with regulatory statutes under the Clean Water Act and Rivers and Harbors Act. Accordingly, river reef sites had to meet a specific water depth criterion, which provided a safe and passable waterway for boating activities. The Davis Dam releases a maximum of five operating units, or 23,000 ft³/s (651.3 m³/s), but three operating units, or 13,800 ft³/s (390.8 m³/s), represent the lowest release deemed safe for boating and a reduced risk to encounter navigational hazards. Previous accounts from fish habitat projects of safe boat clearance indicate the minimum water depth of at least 3–6 ft (1–2 m) is necessary from artificial structures (Derbyshire, 2006; Houser, 2007). In coordination with the Bureau of Reclamation (Interior Region 8: Lower Colorado

River Basin), we requested a water release of three operating units from the Davis Dam during river reef deployment and took depth measurements at five locations within a river reef deployment site, confirming depth criterion. A site was deemed safe and appropriate if it was greater than 1.5 m in depth at each of the five locations. Structures were approximately 54 kg each and were deployed by boat, which had a small crane to aid in placement (Figure 3).

Above-surface visual assessments of the river reef structures and surrounding benthic habitat were made by the first author, while the boat operator maintained a steady position near each deployment site. Using minimum denominations of 5%, the percent visibility of each river reef structure was recorded for each habitat per site. For example, if the structure was completely visible above the riverbed, a measure of 100% was record. Percent cover measurements were record 6 months and 2.5 years post-deployment. To assess benthic habitat, a 0.25 m² quadrat was secured to a telescopic hook fitted with an underwater camera. Four benthic floor photos were taken at each site, and percent cover of benthic habitat was visually assessed on a computer monitor. Percent sand (<2 mm), gravel (2–64 mm), cobble (64–256 mm), boulders (>256 mm), periphyton cover, and vascular plants were the categories used to characterize the benthic habitat. Lastly, flow was measured with a rotor mechanical flowmeter (General Oceanics Inc., Miami, Florida) from four locations per site to determine relative differences at each site. Statistical analyses were conducted in R version 4.2.3 (R Core Team, 2023). Sources of variation in river reef structure visibility over time were determined using generalized linear models (GLMs package *stats*) with a binomial



FIGURE 2 Map indicating river reef sites (yellow dots; Sites 1–6 [north to south]) below the Davis Dam (blue rectangle). [Color figure can be viewed at wileyonlinelibrary.com]

distribution (logit link). A fully parameterized model set was evaluated by the dredge function (package *MuMIn*; Bartoń, 2020). Fixed effects included the following: percent sand, gravel, cobble, boulders, periphyton cover, and vascular plants. The most parsimonious models were compared and ranked by corrected Akaike's Information Criterion (AIC_c) values. Top models with an $AIC_{wt} \geq 0.1$ were compared with likelihood ratio tests ($\alpha = 0.05$).

3 | RESULTS AND DISCUSSION

3.1 | Deployment recommendations and substrate limitations

River reef structures were approximately 50 kg each and designed with 10 cavities total per structure, including the largest cavity at its

base. In combination, the aim was to create a static structure, which could be deployed in groups and was minimally impacted by hydropeaking. Factors that influence river hydraulics (i.e., width, depth, shape, and flow patterns) will naturally impact the benthic habitat over time. Variation in the scouring patterns and physical changes to the benthic habitat is often created by a disruption of laminar flow, where downcutting eddy currents create spaces behind immovable bedload structures (Heede & Rinne, 1990). Consequently, the benthic substrate is spatially sorted by grain size and can result in boulders and other large structures protruding from the riverbed (Ferguson et al., 1989). Here, we determined benthic habitat cover that maintains river reef structure visibility and utility by fish over time.

River reef structures were over 90% visible 6 months post-deployment at all six sites with minimal variation. After 2.5 years, river reef structures were over 88% visible at five of the six sites, with Site 1 measuring just over 5% visibility (Table 1). Among the benthic

FIGURE 3 River reef structures before loading on to the pontoon boat for deployment. [Color figure can be viewed at wileyonlinelibrary.com]



TABLE 1 Mean (\pm SE) substrate composition ($n = 4$ per site) of the benthic habitat, water velocity ($n = 3$ per site) at the depth of the structures, and river reef structure visibility ($n = 15$ per site) at each site.

Site	Substrate composition (%)				Water velocity (cm/s)	River reef structure visibility (%)	
	Sand	Gravel	Cobble	Periphyton		6 months	2.5 years
1	86.3 \pm 2.4	6.3 \pm 1.3	5.0 \pm 1.3	3.8 \pm 1.3	35.6 \pm 7.4	90.7 \pm 2.0	5.3 \pm 1.3
2	6.3 \pm 2.4	1.3 \pm 1.3	78.8 \pm 6.6	13.8 \pm 5.5	144.9 \pm 5.7	96.7 \pm 0.8	95.0 \pm 1.4
3	13.8 \pm 3.8	1.3 \pm 1.3	65.0 \pm 5.0	20.0 \pm 4.6	109.3 \pm 3.1	98.3 \pm 0.6	88.7 \pm 2.5
4	5.0 \pm 2.0	0.0 \pm 0.0	81.3 \pm 2.4	13.8 \pm 1.3	34.7 \pm 6.0	98.5 \pm 0.6	96.5 \pm 1.0
5	6.3 \pm 1.3	1.3 \pm 1.3	86.3 \pm 3.8	6.3 \pm 1.3	177.0 \pm 4.5	98.4 \pm 0.6	96.0 \pm 1.4
6	5.0 \pm 0.0	0.0 \pm 0.0	87.5 \pm 2.5	3.8 \pm 1.3	154.3 \pm 5.3	98.4 \pm 0.8	94.7 \pm 1.7

Note: Percent cover of boulders (<1%) and vascular plants (0%) are not included.

habitat cover variables measured, cobbles were the best indicator of sustained visibility of river reef structures, whereas sand and gravel (i.e., loose bedload materials) decreased visibility over time. This was apparent at Site 1, which had the greatest mean (\pm SE) sand and gravel cover at 86.3% \pm 2.4% and 6.3% \pm 1.3%, respectively. River reef structures at Sites 4, 5, and 6 were the most visible after 2.5 years and had a percent cobble cover greater than 80% (Table 1). Among the benthic habitat cover categories, GLMs indicated that percent sand cover generated the greatest variation in river reef structure visibility (Table 2). Benthic habitat cover significantly contributes to substrate stability, impacting the biophysical state of the riverbed (Scheder et al., 2015). Our data show that deploying structures on cobbles can prolong the lifespan of artificial river reefs. Before deployment, visual assessments of the benthic habitat should confirm

TABLE 2 Top generalized linear model selection results assessing the relative variation in benthic habitat cover that resulted in river reef structure visibility, that is, increased visibility (+), decreased visibility (-).

Fixed effect	Model parameters ^a			
	AIC _c	Δ AIC _c	AIC _{wt}	-2LL
Sand (-)	15.3	0.0	0.23	-5.57
Cobble (+)	16.2	0.9	0.15	-6.01
Gravel (-)	16.4	1.1	0.13	-6.11
Intercept-only (null)	84.2	68.9	0.00	-41.01

Note: Models with an AIC_{wt} \geq 0.1 and the null (intercept-only) are listed. ^aModel parameters are listed by column: corrected Akaike's Information Criterion (AIC_c), change in AIC_c (Δ AIC_c), model weights (AIC_{wt}), and -2LL (-2 \times log likelihood).

greater than 80% cobbles with minimal loose bedload materials, including sand, gravel, and silt. For highly turbid rivers with limited riverbed visibility, the benthic habitat could be evaluated with a large dredge or benthic sled to estimate percent cover.

3.2 | Future habitat management considerations and growth of hydropower

Globally, over 1000 freshwater species on the International Union for Conservation of Nature (IUCN) Red List of Threatened Species are vulnerable from river fragmentation and the associated removal of age-related habitat types or migrations (IUCN, 2019). He et al. (2021) determined that 41.9% of non-migratory freshwater megafauna taxa were likely to be threatened by dams, and of the 207 taxa used in their analysis, 130 fish species were considered. A global assessment of lotic fish species impacted by hydroelectric dams identified river basins in the tropics to be most at risk to future projects (Barbarossa et al., 2020). Habitat enhancement like artificial river reef structures may provide a tangible management strategy to increase productivity and diversity on scoured riverbed conditions below small and large dams subject to extreme, variable flow regimes. Artificial river reef projects may further advance habitat suitability by taking a trait-based approach to structure placement relative to fish passages, where fish movement ecology and life histories are considered (see Barbarossa et al., 2020; Rahel & McLaughlin, 2018). Fisheries managers and ecological practitioners may be required to expand their toolbox to include artificial river reef structures, keeping pace with the projected growth and continued construction of hydroelectric dams.

Expansion of hydropower as a renewable energy resource is predicted to further fragment and threaten free-flowing river systems (He et al., 2021). Renewable resources provide 29% of the world's electricity needs, 58% of that figure by hydropower (C2E2, 2023). Decarbonization goals suggest that hydropower will need to increase by nearly 35% by 2050 (IRENA, 2020), placing additional stress on the biological integrity and ecosystem function of lotic systems. Seliger and Zeiringer (2018) review a collection of large-scale concepts suited for hydropower planning that stress the reduction in overall impact and offer diverse decision-making tools. Troia et al. (2021) offer modeling tools that consider the overlap between conservation areas and potential hydropower projects, with the goal of maximizing renewable energy resources and minimizing negative impacts to freshwater biodiversity. Moreover, basin-scale risk assessments provide a regional approach to evaluating future large dam projects and consider river network connectivity, aiming to optimize the threats to specific species (Zarfl et al., 2019). Beyond large dams, Couto and Olden (2018) estimate there are over 82,000 small hydropower plants, which in their global synthesis amounted to 11 small hydropower plants for every large hydropower plant. A future estimate of nearly 182,000 additional small hydropower plants across 150 countries is possible, if all potential capacity was exploited (Couto & Olden, 2018), and only 50% of the technical feasible potential of hydropower has been implemented in developed countries

(Berga, 2016). Given the spatial coverage of forecasted small hydropower dam projects, future work should assess the role of river reef structures in offsetting or preventing potential ecological degradation, whereas the ecological restoration with river reef structures of existing large hydropower plants can be evaluated on a case-by-case basis, depending on the local-scale goals of the fishery (i.e., conservation vs. economic).

Regardless of the aquatic environment, artificial reef structures are deployed for biological and socioeconomic gain, which may include projects with conservation or sport fish implications. Targeted boat electrofishing efforts, entanglement gears, tagging and telemetry, and visual assessments are among the potential methods to quantify fish usage of the river reef structures. Paired with fish monitoring, we recommend explicitly testing design, number, and size of river reef structures for future deployment efforts, refining the scale and effort required to significantly impact fish attraction and production. Meaningful improvement to degraded environments (i.e., habitat structure supplementation or replacement) have benefited from targeted deployment of artificial habitat structures, advancing species-specific populations or communities (Watchorn et al., 2022), and with the widespread projected growth of hydropower, river reef structures may play a role in evidence-based habitat enhancement.

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CONFLICT OF INTEREST STATEMENT

There are no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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