water

MDPI

Review

Review of Methods to Repair and Maintain Lithophilic Fish Spawning Habitat

Audrey Baetz [1,*,†], Taaja R. Tucker [1], Robin L. DeBruyne [2], Alex Gatch [3,4], Tomas Höök [4,5], Jason L. Fischer [6] and Edward F. Roseman [1,*]

1 U.S. Geological Survey Great Lakes Science Center, 1451 Green Rd, Ann Arbor, MI 48105, USA; trtucker@usgs.gov
2 Department of Environmental Sciences, University of Toledo, 2801 W. Bancroft St., Toledo, OH 43606, USA; robin.debruyne@utoledo.edu
3 U.S. Fish and Wildlife Service, Lower Great Lakes Fish and Wildlife Conservation Office, 1101 Casey Road, Basom, NY 14103, USA; alexander_gatch@fws.gov
4 Department of Forestry and Natural Resources, Purdue University, Forestry Building, 195 Marsteller Street, West Lafayette, IN 47907, USA; thook@purdue.edu
5 Illinois-Indiana Sea Grant College Program, 195 Marsteller Street, West Lafayette, IN 47907, USA
6 U.S. Fish and Wildlife Service, Alpena Fish and Wildlife Conservation Office, 5437 West Jefferson Ave., Trenton, MI 48183, USA; jason_fischer@fws.gov
* Correspondence: audreybaetz@gmail.com (A.B.); eroseman@usgs.gov (E.F.R.); Tel.: +1-248-912-7545 (A.B.); +1-734-214-7237 (E.F.R.)
† Under contract with U.S.G.S.

Received: 8 July 2020; Accepted: 24 August 2020; Published: 8 September 2020



Abstract: Rocky reefs provide important spawning and refuge habitats for lithophilic spawning fishes. However, many reefs have been lost or severely degraded through anthropogenic effects like dredging, channelization, or sedimentation. Constructed reefs have been used to mitigate these effects in some systems, but these reefs are also subject to degradation which may warrant custodial maintenance. Monitoring and maintenance of natural or constructed spawning reefs are not common practices; therefore, few methodologies have been created to test the effectiveness of such tools. We conducted a literature review to assess available information on maintenance of rocky spawning habitats used by lithophilic fishes. We identified 54 rocky spawning habitat maintenance projects, most of which aimed to improve fish spawning habitats through the addition of spawning substrate (n = 33) or cleaning of substrate (n = 23). In comparison to shallow riverine studies focused on salmonids, we found little information on deep-water reefs, marine reefs, or other fish species. We discuss the possible application of potential spawning habitat cleaning methods from other disciplines (e.g., treasure hunting; archeology) that may provide effective means of reef maintenance that can be used by restoration practitioners.

Keywords: reef; custodial maintenance; fish spawning; restoration; sediment removal; anthropogenic impacts

1. Introduction

Rocky reefs are historically important fish habitats that can increase fish abundance locally [1], serve as biodiversity hotspots [2,3], and provide spawning, nursery, and refuge habitats [4–6]. Habitat requirements vary by species and life stage (e.g., egg, larvae, juvenile, or adult); thus, different fishes and life history stages benefit from rocky reefs differently. Habitat requirements for egg and larval stages are constrained due to increased sensitivity to stochastic processes, smaller energy stores, and reduced mobility compared to adults [7]. For many species, clean rocky substrates in the

form of reefs are particularly important spawning and nursery habitats and may strongly influence recruitment potential in deeper waters [8]. Gravel beds serve the same purpose for salmonids and other riverine species in shallow water environments [9,10]. Despite their importance, many reefs and other rocky spawning areas have been lost or degraded due to habitat destruction from anthropogenic stressors [11,12]. Anthropogenic destruction of fish habitats is widespread and is implicated in >70% of North American fish extinctions and includes habitat loss or degradation or reduced access to spawning areas [13].

While marine coral reefs are the focus of many restoration initiatives, both marine and freshwater rocky reefs are not as well studied as coral reefs, despite having both high biodiversity and similar levels of degradation [14]. Causes of destruction or degradation of rocky spawning habitats include physical factors such as sedimentation [15–17], channelization [18,19], and resource extraction [20–22], while biological factors include periphyton accumulation (e.g., *Cladophora* or *Didymosphenia*) [23–25] and biofouling by invasive species (e.g., mussels [26,27]). Sedimentation is a natural process in freshwater and marine systems; however, anthropogenic stressors have increased the rate at which this process can occur [15,28]. Accumulation of fine sediments such as silt and sand can lead to egg mortality via infilling of interstitial spaces that help protect fish eggs and larvae from predators and displacement [29] while allowing for adequate water flow and oxygenation [17,30,31]. Biofouling occurs when the habitat is degraded through biological processes, such as colonization by *Dreissena polymorpha* and *D. bugensis* mussels (hereafter referred to as dreissenid mussels) or periphyton. Biofouling can also reduce the interstitial spaces required for egg incubation, deplete oxygen, and create waste build-up [27]. Many lithophilic spawners prefer substrate free of epiphytic growth and debris [29,32] and select spawning habitats with water velocities that maintain such habitats [33,34]. Historic destruction of reefs for resource extraction or development, coupled with altered ecosystem processes that increase rates of physical degradation, have led to the loss of viable fish spawning habitats and reduction of other ecosystem services [15,35–37] (Figure 1).

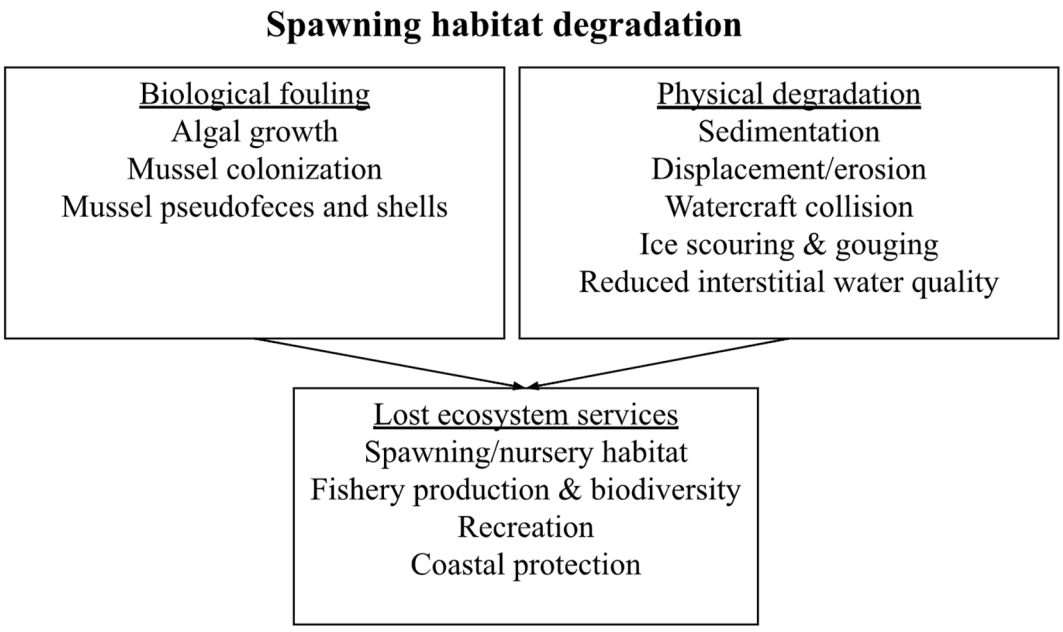


Figure 1. Conceptual diagram of the causes and effects of rocky fish spawning habitat degradation.

To mitigate impacts of degradation, construction of rocky reefs to improve spawning habitat increased during the 1980s [38] and spawning reefs have been constructed across the globe, with a majority located in North America and Europe [11,39]. Construction of reefs to attract fish has occurred in Japan for centuries, and construction of similar reefs began in the early 1800s in North America [25,40],

but the emphasis on creating spawning-specific reef habitats has been more recent. In freshwater systems such as the Laurentian Great Lakes (hereafter referred to as the Great Lakes), rocky reefs were constructed to provide spawning habitats for lithophilic spawning fishes such as lake sturgeon *Acipenser fulvescens* [24,41], lake trout *Salvelinus namaycush* [37], walleye *Sander vitreus*, and lake whitefish *Coregonus clupeaformis* [42]. Similar habitat remediation in western North American rivers has focused on the creation of gravel spawning beds for salmonids such as coho salmon *Oncorhynchus kisutch* [43], Chinook salmon *Oncorhynchus tshawytscha* [44], and rainbow trout *Oncorhynchus mykiss* [45]. Globally, salmonid gravel remediation projects have been conducted in Norway [46], Japan [10], Sweden [47], and England [48].

The creation of reefs and other rocky spawning habitats requires substantial investments of time, money, and personnel. In Japan, a large-scale government reef subsidy program invested an average of $100 million (USD) annually during the 1970s and 1980s in the installation of reefs along their coast [49]. During 1986–1995, ~$2.5 million (USD) was spent to replace lost spawning gravel and remediate habitats in tributaries of the San Joaquin River in California, USA (not shown, 38.0665861° N, 121.851069° W) [50]. Since 2004 in the St. Clair–Detroit River System (not shown, 42.4642° N, 82.7098° W), more than $7.2 million (USD) has been invested in the creation and monitoring of spawning reefs to remediate the loss of honeycombed limestone substrate removed to develop shipping channels in the early 1900s [18,51,52]. To alleviate the high cost of rock placement and design, some habitat creation projects in the Great Lakes have relied on donations of materials and/or labor while remaining funds are directed toward biological assessment and monitoring [53]. Despite the considerable investments made in habitat creation and biological monitoring, less effort has been made to evaluate physical longevity after installation [38,54]. Although limited, evaluations of reef maturation (how the reef ages through time) suggest that they are still vulnerable to the biophysical processes that degrade natural reefs. Therefore, custodial maintenance may be required to ensure constructed and natural reefs continue to provide habitat for target species [38,55].

Ideally, restoration efforts would target the root causes of degradation to prevent further loss of function and minimize need for maintenance. However, addressing the cause of degradation is not always feasible in irreparably altered systems where or when restoration conflicts with socioeconomic needs [56,57]. Therefore, identifying effective maintenance methods may be most desirable in systems where root causes of degradation cannot be addressed. Custodial maintenance of reefs may offer an alternative to expensive new construction projects. Information on evaluating the effectiveness of methods for maintaining rocky reefs is limited [38,54] and there is a gap in current knowledge of techniques developed and tested for reef cleaning and maintenance [35,58]. While information on reef maintenance is lacking, maintenance and restoration of gravel spawning beds and other shallow-water rocky habitats have been ongoing for decades. For instance, between 1976 and 1999, 73 salmonid spawning habitat rehabilitation projects on 19 separate rivers were completed in California, USA, but project performance was poorly evaluated post construction [50,59]. Furthermore, it is possible that some methods employed in these shallow rivers may be transferable to the maintenance of deeper water spawning reefs. A systematic review of fish spawning habitat maintenance and creation found that the addition of rocky material was one of the most effective mechanisms for increasing larval fish abundance and survival for substrate-spawning fishes [59]. However, the addition of more substrate to extant rocky habitats may not always be possible or necessary, and alternative maintenance methods for existing habitats warrant investigation.

A literature review aimed at identifying available techniques and knowledge gaps regarding monitoring, maintenance, and restoration of extant fish spawning reefs and other rocky spawning habitats was conducted. The aim was to focus on extant natural or constructed rocky habitats rather than the creation of entirely new structures as a number of studies previously reviewed that topic [54,60,61]. Similarly, we only cursorily address monitoring efforts, because this area is already the subject of multiple reviews. Thus, our primary focus was to synthesize the available literature on maintaining rocky habitats. By identifying maintenance methods, the goal was to provide non-construction options

for revitalizing degraded constructed and natural rocky reefs. Considering the lack of existing research on spawning reefs specifically, the scope of this search included maintenance performed on all types of rocky spawning habitat due to similarities in the types of degradation and increased availability of the studied methodology. The specific objectives were to (i) compile and review a list of empirical studies which employ maintenance and physical monitoring of existing rocky spawning habitats, (ii) discuss causes of rocky spawning habitat degradation (physical and biological), and (iii) explore potential novel rocky reef maintenance techniques, including those from fields such as marine archeology and engineering.

2. Materials and Methods

A literature search was conducted for any available peer reviewed articles or grey literature (e.g., government reports, academic theses) published at any time using the search engines Google Scholar, Web of Knowledge, and Mendeley from August 2019 to April 2020. We searched the key terms "spawning reef", "rocky reef"," "spawning habitat maintenance", "habitat maintenance", "sediment removal", "reef cleaning", "gravel cleaning", and "reef monitoring", building the list as we reviewed the literature and identified new, more specific search terms (e.g., "algae treatment"). Coral reef studies were excluded from our search. Additional relevant material was explored by analyzing the citations within the found literature forward (literature which cited that manuscript) and backward (literature cited within that manuscript). The criteria used for including texts in the review were that they (i) focused on maintaining extant spawning habitats rather than the creation of new habitats, (ii) were based on empirical field studies, (iii) focused on lithophilic spawning fishes rather than other organisms such as invertebrates and aquatic plants, and (iv) included either natural or human-made habitats. Through the literature search, a list was compiled of habitat maintenance projects (i.e., a set of remedial actions taken in a given region) and relevant information including the targeted fish species, the type(s) of spawning habitat degradation, the remediation method(s) used to mitigate the degradation type(s), the years during which the studies were conducted or habitat maintenance occurred, the study area and study system type (lacustrine or riverine), and synopses of the maintenance method (e.g., area cleaned, amount of substrate added). The information was summarized by project rather than by each scientific study/manuscript because multiple studies were occasionally conducted on the same habitat maintenance project.

3. Results

There were 54 rocky spawning habitat maintenance projects found that met the criteria for inclusion in the literature review (Table 1). These efforts were summarized into categories based on the types of degradation and the maintenance/repair method employed, along with approximate estimates of scale and cost of the project in response (Table 2; Figures 2 and 3). Note that some projects had multiple types of degradation or maintenance methods, affecting the reporting of results (e.g., the total number of projects exhibiting each degradation type is greater than the total number of studies). Loss or removal of rocky spawning substrate (typically gravel) through high river flows, scouring, or other agents was the most common habitat degradation type (n = 30 projects), followed by sedimentation or infilling of substrate (n = 27) (Figure 2). Other less common, and typically secondary, forms of degradation included channelization (n = 3), algae (n = 2), barriers to habitat (n = 2), and other biofouling (n = 1). Addition of substrate was the most common remedial action taken (n = 33) and was usually performed in response to loss of substrate (n = 27) (Figure 3). Addition of substrate included gravel/cobble augmentation, installation of timber, and/or placement of boulders. Cleaning was the second most common maintenance method (n = 23) and was used in response to sedimentation (n = 23) or algae coverage or other biofouling (each n = 1). Methods employed to clean substrates included dredges, propeller wash, pressurized water, altered river flow, or mechanical methods (e.g., raking). Other forms of remediation included the addition of structures like gabions (n = 3), creation/placement of sediment traps (n = 4), removal of structures such as weirs (n = 2), and chemical treatments (n = 1).

The majority of projects (n = 41) had no costs presented, and while (n = 13) did report costs, not all of them may have been complete.

The majority of rocky spawning habitat remediation projects focused on salmonids (n = 45), with few studies targeting walleye (n = 4), sturgeon Acipenseridae species (n = 3), or other fish species (n = 2), for a total of 25 fish species and one family (n = 26 total taxa). The most common individual species targeted were brown trout *Salmo trutta* (n = 14), chinook salmon (n = 13), and rainbow trout (n = 10; Figure 4). Rocky spawning habitat repair and maintenance efforts took place globally, but most occurred in North America (n = 38) and Europe (n = 13). Riverine environments (rivers, streams, creeks, etc.) were the most common habitats where projects took place (n = 52), with only two projects occurring in lacustrine environments such as lakes or reservoirs. The majority of projects took place in relatively shallow water, with 74% located in depths <1 m (n = 34 of 46 studies where depths were reported) (Figure 5). Below, the maintenance methods employed in these studies are reviewed in the context of the physical, biological, and ecological scope of each problem and other potential remedial actions. In addition, an overview is provided of the physical monitoring techniques employed to monitor spawning habitat degradation and novel techniques that could be used in maintenance and remediation.

Table 1. List of rocky spawning habitat remediation projects included in a literature review of potential remediation methods sorted by the primary type of degradation affecting the habitat and the first year in which the study or remediation took place. Scientific names of fish species are listed in Appendix A.

Type of Degradation	Remedial Action	Target Species	Study Year(s)	Location	Latitude, Longitude	Specific Remedial Method	References
Algae	Chemical treatments/Cleaning	Chinook salmon	1972–1982	Tehama-Colusa Canal on Sacramento River, California, USA	39.9660° N, 122.1350° W	Applied diquat, copper sulfate pentahydrate, and acrolein compounds to artificial spawning channels to control *Cladophora* algae, later transitioned to manual cleaning by dragging chains/scraping devices	[62,63]
Barrier to habitat/Loss of gravel	Addition of substrate	Chinook salmon, rainbow trout	2000–2003	Mokelumne River, California, USA	38.0960° N, 121.5699° W	Addition of gravel bars, berms, and riffles; 11,000 m^3 of gravel at 12 sites	[45]
Barrier to habitat/Loss of substrate	Removal of structure/Addition of substrate	Atlantic salmon, brown trout	2002–2009	Nidelva River, Norway	63.2582° N, 10.4637° E	Removed weirs and added six 52–270 m^2 gravel beds	[46]
Channelization/Loss of substrate	Addition of substrate	Masu salmon	1994–1998	Shakotan River, Japan	43.3310° N, 140.4823° E	Gabions removed, added log dams (3 sets) and gravel (5–10 cm, area unknown)	[10]
Channelization/Loss of substrate	Addition of substrate	Brown trout	1999–2013	Oulujoki River streams, Finland	64.9781° N, 25.6053° E	Addition of 77 boulder weirs, 141 log weirs, and boulders. Placed gravel beds (1.38 m^2 gravel per 100 m^2 of rehabilitated stream)	[56,64]
Channelization/Loss of substrate	Addition of substrate	Coho salmon, rainbow trout	2001–2005	Smith River reaches, Oregon, USA	43.7370° N, 124.0787° W	Added 46 boulder weirs/deflectors to six rivers	[43,57]

Table 1. *Cont.*

Type of Degradation	Remedial Action	Target Species	Study Year(s)	Location	Latitude, Longitude	Specific Remedial Method	References
Loss of substrate	Addition of substrate	Salmonids	1962–1991	Multiple rivers, California, USA	36.7783° N, 119.4179° W	Added ~800,000 m^3 of gravel to 12 different rivers/reservoirs	[65]
Loss of substrate/Sedimentation	Addition of structure/Addition of substrate/Cleaning	Chinook salmon, chum salmon	1973–1975	Four rivers and creeks, Washington, USA	47.7511° N, 120.7401° W	Cleaned gravel with a bulldozer, replaced gravel, and constructed 10 gabion dams to retain gravel	[66,67]
Loss of substrate	Addition of structure	Coho salmon, rainbow trout, cutthroat trout	1981–1983	East Fork Lobster Creek, Oregon, USA	44.3027° N, 123.7255° W	Installed gabion weirs (7 sites), boulders (1 site), and log sills (3 sites) to retain gravel	[68]
Loss of substrate	Addition of substrate	Chinook salmon, rainbow trout	1981–1984	Hurdygurdy Creek, Indiana, USA	41.6842° N, 123.9036° W	Added 156 boulder clusters/weirs and 25 boulder/rock deflectors across 1280 m of stream	[69]
Loss of substrate	Addition of structure	Coho salmon, rainbow trout, pink salmon	1982	Sachs Creek, British Columbia, Canada	53.2527° N, 132.0900° W	Installed three pairs of gabion weirs to retain gravel	[70,71]
Loss of substrate	Addition of substrate	Grayling, brown trout, rainbow trout	1990–1992	Rhine River impoundment, Germany	47.6674° N, 9.1484°E	Added 10 m^3 of gravel	[72]
Loss of substrate	Addition of substrate	Chinook salmon	1990–1994	Merced River, California, USA	37.3491° N, 120.9754°W	Addition of gravel to ~6500 m^2	[50]
Channelization/Loss of substrate	Addition of substrate	Coho salmon, rainbow trout	2001–2005	Smith River reaches, Oregon, USA	43.7370° N, 124.0787° W	Added 46 boulder weirs/deflectors to six rivers	[43,57]
Loss of substrate	Addition of substrate	Salmonids	1962–1991	Multiple rivers, California, USA	36.7783° N, 119.4179° W	Added ~800,000 m^3 of gravel to 12 different rivers/reservoirs	[65]

Table 1. *Cont.*

Type of Degradation	Remedial Action	Target Species	Study Year(s)	Location	Latitude, Longitude	Specific Remedial Method	References
Loss of substrate	Addition of substrate	Walleye	1990	Fox River, Wisconsin, USA	44.5399° N, 88.0045° W	Added 907 tons of rock (0.6–1.8 m) across 3066 m^2	[73]
Loss of substrate	Addition of substrate	Walleye	1991–1993	Current River, Ontario, Canada	48.4693°N, 89.1940° W	Added gravel and cobble in 3 areas (1575 m^2 total), randomly placed boulders in same areas	[74]
Loss of substrate/Sedimentation	Addition of substrate/Cleaning	Brown trout	1992–2003	Hartijokki Stream, Sweden	66.6930° N, 22.0641° E	Added boulders (600 m^3) and restored gravel beds by removing armored layer and raking rocks to remove sediment	[47]
Loss of substrate	Addition of substrate	Rainbow trout, coho salmon	1997–2001	Keogh River, British Columbia, Canada	50.6797° N, 127.3484° W	Added >450 boulder and log habitat structures, 905 kg inorganic nutrients as briquettes	[75]
Channelization/Loss of substrate	Addition of substrate	Coho salmon, rainbow trout	2001–2005	Smith River reaches, Oregon, USA	43.7370° N, 124.0787° W	Added 46 boulder weirs/deflectors to six rivers	[43,57]
Loss of substrate	Addition of substrate	Salmonids	1962–1991	Multiple rivers, California, USA	36.7783° N, 119.4179° W	Added ~800,000 m^3 of gravel to 12 different rivers/reservoirs	[65]
Loss of substrate	Addition of substrate	Brown trout	1999–2000	Various rivers, Denmark	56.2639° N, 9.5018° E	Assessed condition of 32 gravel projects 5–14 years post construction (area not specified)	[76]

Table 1. *Cont.*

Type of Degradation	Remedial Action	Target Species	Study Year(s)	Location	Latitude, Longitude	Specific Remedial Method	References
Loss of substrate	Addition of substrate	Chinook salmon	1999	Mokelumne River, California, USA	38.0960°N, 121.5699° W	Addition of gravel bars and boulders (2450 m^3 gravel)	[77]
Loss of substrate	Addition of substrate	Chinook salmon	2000–2002	Mokelumne River, California, USA	38.0960° N, 121.5699° W	Addition of gravel bars (976 m^3 gravel)	[44]
Loss of substrate	Addition of substrate	Chinook salmon	2001	Mokelumne River, California, USA	38.0960° N, 121.5699° W	Addition of gravel bars (650 m^3 gravel over 152 m) and 10 450–680-kg boulders	[59,78,79]
Loss of substrate	Addition of substrate	Chinook salmon	2002	Mokelumne River, California, USA	38.0960° N, 121.5699° W	Addition of gravel (1410 m^3) and 3 boulder complexes	[78,80]
Loss of substrate	Addition of substrate	Chinook salmon	2003–2005	Mokelumne River, California, USA	38.0960° N, 121.5699° W	Addition of gravel (3522 m^3) to create sloped beds; extended by 2359 m^3 in 2005	[78,81]
Channelization/Loss of substrate	Addition of substrate	Coho salmon, rainbow trout	2001–2005	Smith River reaches, Oregon, USA	43.7370° N, 124.0787° W	Added 46 boulder weirs/deflectors to six rivers	[43,57]
Loss of substrate	Addition of substrate	Salmonids	1962–1991	Multiple rivers, California, USA	36.7783° N, 119.4179° W	Added ~800,000 m^3 of gravel to 12 different rivers/reservoirs	[65]
Loss of substrate	Addition of substrate	Chinook salmon, rainbow trout	2007–2012	American River, California, USA	38.6394° N, 120.5839° W	3 gravel/cobble augmentation sites, each 6350–9707 metric tons	[82,83]
Loss of substrate	Addition of substrate	White Sturgeon	2010	Columbia River, British Columbia, Canada	50.2170° N, 115.8500° W	Addition of boulders and armored bed of pebble/cobble (600 m^3)	[84]

Table 1. *Cont.*

Type of Degradation	Remedial Action	Target Species	Study Year(s)	Location	Latitude, Longitude	Specific Remedial Method	References
Loss of substrate	Addition of substrate	Chinook salmon	2010	Merced River, California, USA	37.3491° N, 120.9754° W	Added 1.5 million tons of gravel to river	[85]
Loss of substrate/Sedimentation	Addition of substrate/Cleaning	Brown trout, grayling, brook lamprey	2010–2011	6 streams in Bavaria, Germany	4807904° N, 11.4979° E	Added 20 m^3 of gravel, raked 50 m^2 with excavator, added boulder constrictors, each to six rivers	[86]
Loss of substrate	Addition of substrate	River chub, northern hogsucker, black redhorse	2011	Cheoah River, North Carolina, USA	35.4481° N, 83.9396° W	Addition of gravel at 4 sites: 17–64 tons/site	[87]
Loss of substrate	Addition of substrate	Chinook salmon, rainbow trout	2012–2013	American River, California, USA	38.6394° N, 120.5839° W	Addition of ~50,000 metric tons of various-sized gravel	[88]
Channelization/Loss of substrate	Addition of substrate	Coho salmon, rainbow trout	2001–2005	Smith River reaches, Oregon, USA	43.7370° N, 124.0787° W	Added 46 boulder weirs/deflectors to six rivers	[43,57]
Loss of substrate	Addition of substrate	Salmonids	1962–1991	Multiple rivers, California, USA	36.7783° N, 119.4179° W	Added ~800,000 m^3 of gravel to 12 different rivers/reservoirs	[65]
Loss of substrate	Addition of substrate	Rainbow trout	2016	Lower Whatshan River, British Columbia, Canada	49.9144° N, 118.1160° W	Added gravel (amount not specified), 18 log jams, 11 boulder placements, 2 log placements along 1.3 km stretch	[89]
Sedimentation	Cleaning	Atlantic salmon	1939–1941	Moser River, Nova Scotia, Canada	44.9755° N, 62.2562° W	Cleaned gravel beds by raking, built stone barriers to flush redds (area and number of structures not quantified)	[90]

Table 1. *Cont.*

Type of Degradation	Remedial Action	Target Species	Study Year(s)	Location	Latitude, Longitude	Specific Remedial Method	References
Sedimentation	Cleaning	Salmonids	1967	Fish, Slocum, and Lover's Cove creeks, Alaska, USA	58.1253° N, 134.0461° W	Used "Riffle Sifter" machine to clean fine sediment from streams (area not quantified)	[91]
Channelization/Loss of substrate	Addition of substrate	Coho salmon, rainbow trout	2001–2005	Smith River reaches, Oregon, USA	43.7370° N, 124.0787° W	Added 46 boulder weirs/deflectors to six rivers	[43,57]
Loss of substrate	Addition of substrate	Salmonids	1962–1991	Multiple rivers, California, USA	36.7783° N, 119.4179° W	Added ~800,000 m^3 of gravel to 12 different rivers/reservoirs	[65]
Sedimentation	Cleaning	Chinook salmon	1970s–1980s	Tehama-Colusa Canal on Sacramento River, California, USA	39.9660° N, 122.1350° W	A movable ~43-m baffle was lowered into the channel and created high flows to dislodge sediment. A rotary screen gravel washer was also used to clean gravel by collecting sediment <40 mm and suctioning it to a settling basin	[62,92]
Sedimentation/Algae	Cleaning	Sockeye salmon, pink salmon	1972–1980	Fraser River spawning channels and three rivers, British Columbia, Canada	49.1485° N, 122.0878° W	Removal of algae and sediment with a toothed blade on heavy equipment, tilled or sifted gravel with bulldozer, used water jets with air injection to clean gravel in channels and rivers (up to 0.5 m deep), proposed use of dry-gravel cleaner	[93]

Table 1. *Cont.*

Type of Degradation	Remedial Action	Target Species	Study Year(s)	Location	Latitude, Longitude	Specific Remedial Method	References
Channelization/Loss of substrate	Addition of substrate	Coho salmon, rainbow trout	2001–2005	Smith River reaches, Oregon, USA	43.7370° N, 124.0787° W	Added 46 boulder weirs/deflectors to six rivers	[43,57]
Loss of substrate	Addition of substrate	Salmonids	1962–1991	Multiple rivers, California, USA	36.7783° N, 119.4179° W	Added ~800,000 m^3 of gravel to 12 different rivers/reservoirs	[65]
Sedimentation	Cleaning	Salmonids	Late 1970s–Early 1980s	Palouse River, Idaho and Kennedy Creek and Cedar River, Washington, USA	46.6215° N, 118.1993° W; 47.5006° N, 122.2162° W	Cleaned river gravel (area not quantified) with prototype machine ("Gravel Gertie") that cleaned 15–30 mm deep with water jets and extracted sediment to the streambank	[94,95]
Sedimentation	Addition of substrate/Sediment traps	Brown trout, brook trout	1984–1991	Hay, Waupee, and Chaffee creeks, Wisconsin, USA	43.94776° N, 89.3215° W	Added sediment traps (3 creeks), rock sills (2 creeks), and gravel beds (2 creeks; 23–50 m long)	[96]
Sedimentation	Cleaning	Atlantic salmon	1984	LaHave River, Nova Scotia, Canada	44.3669° N, 64.4698° W	Centrifugal pump used to hydraulically clean gravel (864 m^2)	[97]
Sedimentation	Cleaning	Coho salmon	1992	Little Qualicum River, British Columbia, Canada	49.3587° N, 124.4845° W	Drained and dredged a constructed spawning channel, then scarified by bulldozer (82 tons of sediment removed)	[98]
Channelization/Loss of substrate	Addition of substrate	Coho salmon, rainbow trout	2001–2005	Smith River reaches, Oregon, USA	43.7370° N, 124.0787° W	Added 46 boulder weirs/deflectors to six rivers	[43,57]

Table 1. *Cont.*

Type of Degradation	Remedial Action	Target Species	Study Year(s)	Location	Latitude, Longitude	Specific Remedial Method	References
Loss of substrate	Addition of substrate	Salmonids	1962–1991	Multiple rivers, California, USA	36.7783° N, 119.4179° W	Added ~800,000 m^3 of gravel to 12 different rivers/reservoirs	[65]
Sedimentation/Loss of substrate	Sediment traps	Brown trout	1992–1999	Four streams, Sweden	60.1282° N, 18.6435° E	Added 242 artificial spawning grounds (v-shaped deflector of large stones, log weir at narrowest point, gravel placed upstream) and sediment traps	[99]
Sedimentation/Algae/Biofouling	Cleaning	Lake sturgeon	1995–1998	St. Lawrence River, USA/Canada	44.5583° N, 75.6440°W	Hand tools used to clear 9 m^2 of artificial habitat, pressurized water used to clear 200 m^2	[24]
Sedimentation	Cleaning	Brown trout	1999	River Kennet, England, UK	51.4557° N, 0.9570° W	Cleaned ~2520 m^2 of substrate with 3 different methods: pump-washing, tractor rotovating, and high-pressure washing	[100]
Sedimentation	Addition of substrate/Removal of structure	Walleye	1999–2003	Pelican River and Ada Brook, Minnesota, USA	46.2956° N, 96.1523° W	Added U-shaped gravel/cobble riffles and removed beaver dams	[101]
Channelization/Loss of substrate	Addition of substrate	Coho salmon, rainbow trout	2001–2005	Smith River reaches, Oregon, USA	43.7370° N, 124.0787° W	Added 46 boulder weirs/deflectors to six rivers	[43,57]

Table 1. *Cont.*

Type of Degradation	Remedial Action	Target Species	Study Year(s)	Location	Latitude, Longitude	Specific Remedial Method	References
Loss of substrate	Addition of substrate	Salmonids	1962–1991	Multiple rivers, California, USA	36.7783° N, 119.4179° W	Added ~800,000 m^3 of gravel to 12 different rivers/reservoirs	[65]
Sedimentation	Addition of substrate	Brown trout	2003, 2009	River Stiffkey, England, UK	52.9574° N, 0.9610° E	Added 13 stone piles (gravel, cobble, and boulders) each 75–200 m^2	[48]
Sedimentation	Addition of substrate/Cleaning/Sediment traps	River blackfish, flathead gudgeon, carp gudgeon	2003–2004	Glenelg River, Australia	37.2491° S, 141.8676° E	Sediment was extracted to lower bed height of runs, created/enlarged pools, and constructed sediment traps	[102]
Sedimentation	Cleaning/Addition of substrate	Brown trout, grayling	2004–2008	Moosach River, Germany	48.3796° N, 11.7001° E	Sediment was cleaned by sifting with an excavator (3500 m^2, 12.5% of study area) and new gravel (amount not specified) was introduced	[103]
Sedimentation	Cleaning	Brown trout	2008–2009	Moosach River, Germany	48.3796° N, 11.7001° E	A walking excavator was used to sift gravel (30 m^2 cleaned)	[104]
Channelization/Loss of substrate	Addition of substrate	Coho salmon, rainbow trout	2001–2005	Smith River reaches, Oregon, USA	43.7370° N, 124.0787° W	Added 46 boulder weirs/deflectors to six rivers	[43,57]
Loss of substrate	Addition of substrate	Salmonids	1962–1991	Multiple rivers, California, USA	36.7783° N, 119.4179° W	Added ~800,000 m^3 of gravel to 12 different rivers/reservoirs	[65]

Table 1. *Cont.*

Type of Degradation	Remedial Action	Target Species	Study Year(s)	Location	Latitude, Longitude	Specific Remedial Method	References
Sedimentation	Addition of substrate/Cleaning	Brown trout, grayling	2010–2011	Six rivers in Danube, Main/Rhine, and Elbe drainages, Germany	51.1657° N, 10.4515° E	In each river, gravel was added (20 m^3), substratum was raked with an excavator (50 m^2), and boulders weirs were placed to constrict current	[105]
Sedimentation	Cleaning	Bonneville cutthroat trout	2010s	Kackley Springs of Bear River, Idaho, USA	42.5331° N, 111.7925° W	Removed 44 m^3 of sediment from 6 reaches (480 m total length) with a Sand Wand	[106]
Sedimentation	Cleaning	Brown trout	2011–2012	Two streams in Pomahaka River catchment, New Zealand	45.9065° S, 169.2251° E	Towable water blaster washed out sediment from 50-m stretches in two streams	[107]
Sedimentation	Cleaning	Bonneville cutthroat trout	2011–2014	Six creeks of Bear River, Idaho, USA	42.4277° N, 111.7380° W	Removed 14 metric tons of sediment from 6 creeks with a Sand Wand	[108]
Channelization/Loss of substrate	Addition of substrate	Coho salmon, rainbow trout	2001–2005	Smith River reaches, Oregon, USA	43.7370° N, 124.0787° W	Added 46 boulder weirs/deflectors to six rivers	[43,57]
Loss of substrate	Addition of substrate	Salmonids	1962–1991	Multiple rivers, California, USA	36.7783° N, 119.4179° W	Added ~800,000 m^3 of gravel to 12 different rivers/reservoirs	[65]
Sedimentation	Cleaning/Sediment trap	Brook trout	2012–2014	Salmon Trout River, Michigan, USA	46.8614°N, 87.7788° W	Removed sediment with a Sand Wand from a 33 m reach, placed an active sediment collector above the reach	[109]

Table 1. *Cont.*

Type of Degradation	Remedial Action	Target Species	Study Year(s)	Location	Latitude, Longitude	Specific Remedial Method	References
Sedimentation	Cleaning	Common barbel	2014–2015	River Great Ouse, England, UK	52.3178° N, 0.2107° W	Cleaned 6 riffle sites (26.9–98.0 m^2) and patches (0.25 m^2) with gravel jetting	[110]
Sedimentation	Cleaning	White sturgeon	2016	Nechako River, British Columbia, Canada	53.9689° N, 123.7139° W	7260 m^2 (75%) of degraded spawning habitat raked, sifted with mechanical excavator	[111]
Sedimentation	Cleaning	Walleye, lake whitefish	2018–2019	Saginaw Bay, Lake Huron, Michigan	43.8453° N, 83.6774° W	Cleaned 14 50-m plots on two reefs using two different experimental cleaning machines: a propulsion sled and a hydro-jet sled	[58]

Table 2. Types of rocky spawning habitat degradation, remediation measures, potential scale (small to large) of remediation measures, cost (low to high), and considerations for remediation.

Type of Degradation	Remediation Measures	Scale of Remediation *	Cost *	Considerations
Sedimentation	Dredging	Moderate	$$$	Water depth, permitting, and disposal
	Pumping	Moderate	$$	Water depth
	Scarification	Small	$	Water depth, substrate
	Increasing flows (dams)	Large	$$$$	Cost, non-target impacts
	Jetting	Small	$	Water depth, area degraded
	Collection devices/traps	Moderate	$$	Amount of sedimentation, water depth
Loss of substrate	Addition of substrate	Moderate	$$	Potential fouling, flow regimes
	Manage for natural flow (dams)	Large	$$$$	Societal impacts, non-target impacts
	Channel modification (weirs)	Moderate	$$$	Geomorphic impacts
Periphyton growth	Scarification	Small	$$	Water depth, substrate
	Jetting	Small	$$	Water depth, substrate, area degraded
	Chemical treatment	Large	$$	Non-target impacts
Biofouling by invertebrates	Hand removal (divers)	Small	$$$	Time, cost, area affected
	Chemical treatment	Large	$$	Non-target impacts
	Jetting	Small	$$	Water depth, substrate
	Biological methods	Moderate–Large	$$	Non-target impacts

* Since most studies did not report the scale or cost of remedial measures, the estimates provided are relative and categorical.

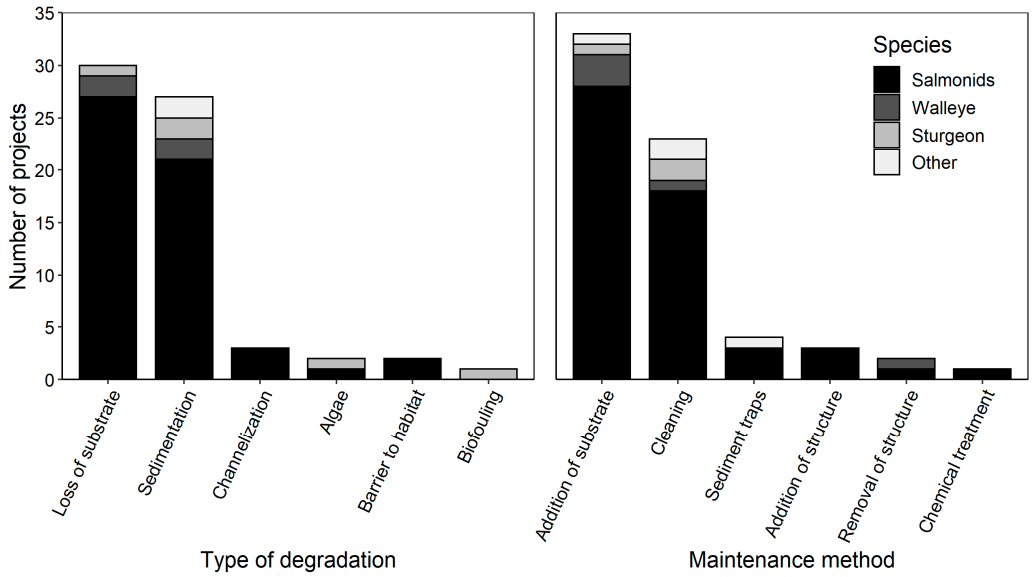


Figure 2. Number of rocky spawning habitat maintenance projects by type of degradation, maintenance method, and target taxa. Note that each project may have more than one type of degradation and/or maintenance method.

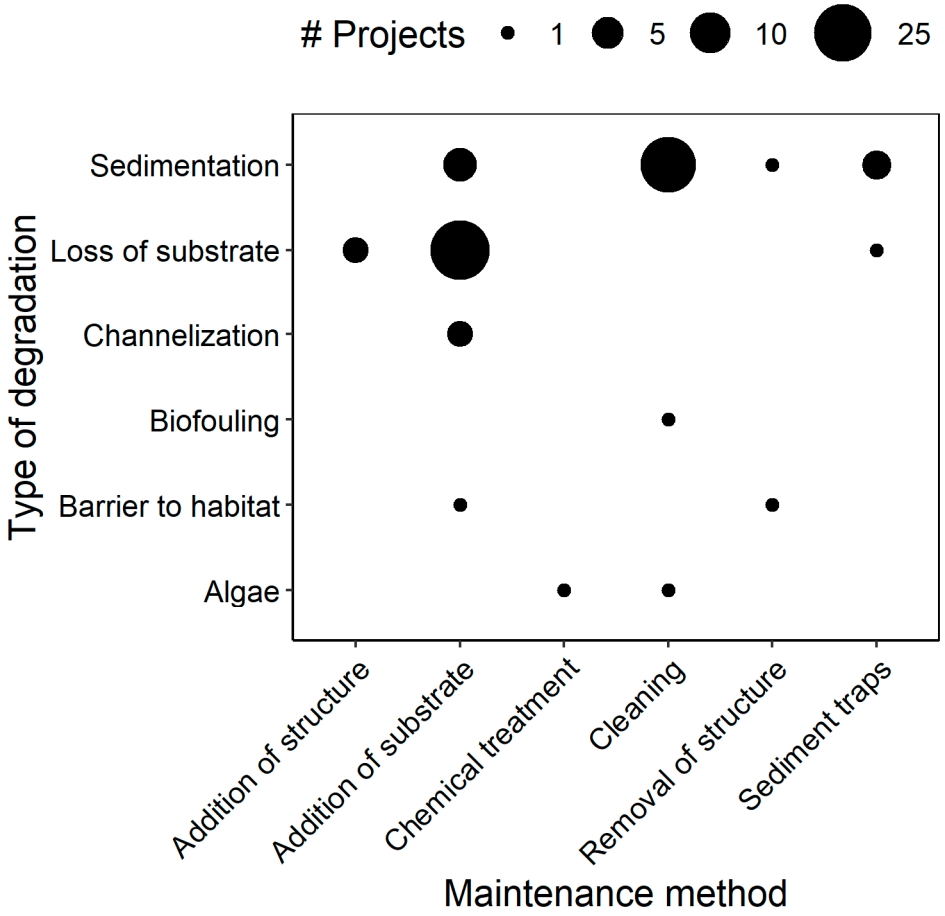


Figure 3. Numbers of rocky spawning habitat maintenance projects by type of degradation vs. the maintenance method used to treat the degradation. Note that each project may have more than one type of degradation and/or maintenance method.

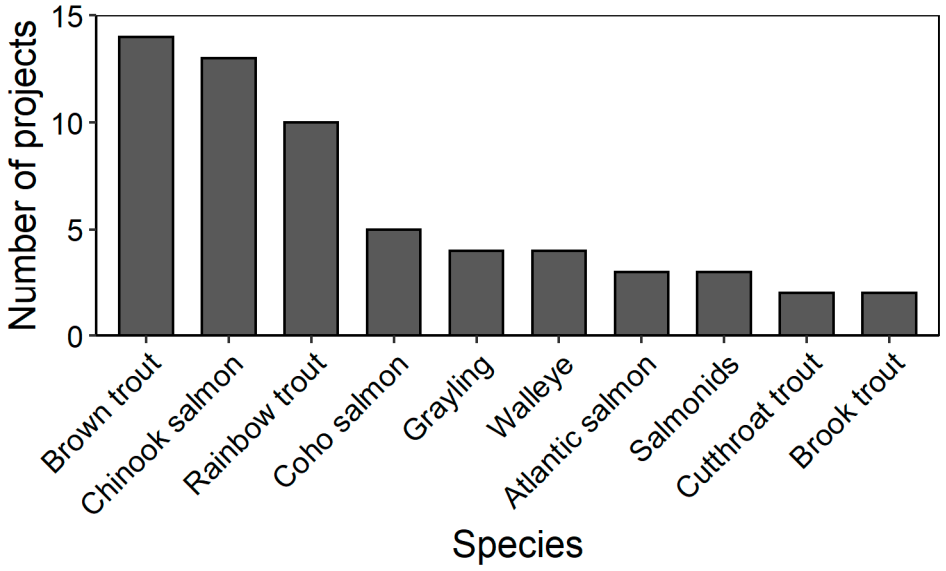


Figure 4. Most common fish taxa (n = 10 of 26 total taxa) targeted by rocky spawning habitat maintenance projects. "Salmonids" represents studies where a target species of salmonid was not identified. Note that each project may have targeted more than one focus species.

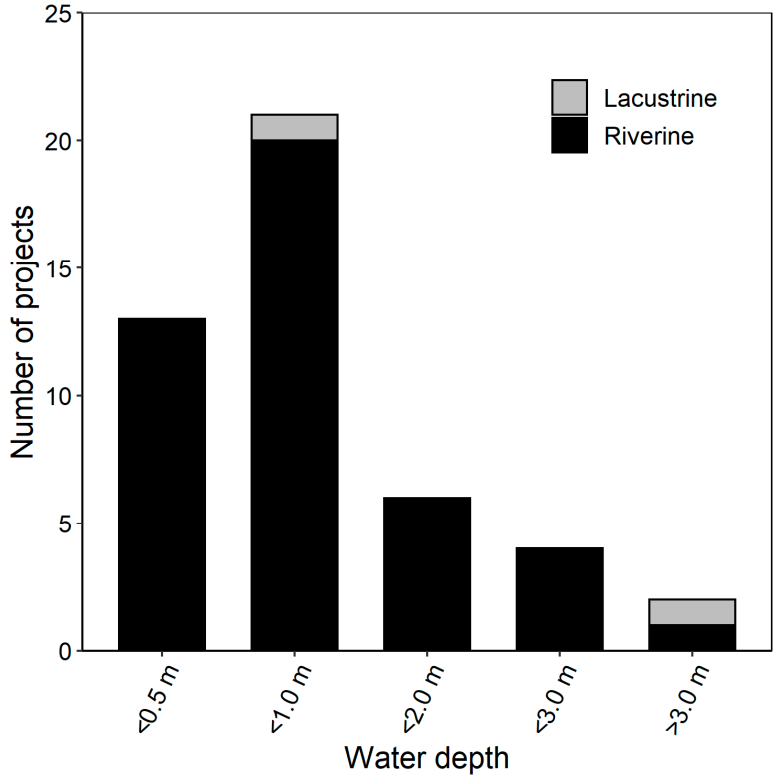


Figure 5. Water depths (m) and habitat types ("lacustrine" vs. "riverine") represented by the rocky habitat maintenance projects in our review with reported water depths (n = each water depth category represents the average or maximum water depth reported (pre- or post-maintenance)).

4. Discussion

This review highlighted several sources of degradation (e.g., loss of substrate, sedimentation, biofouling), each necessitating a different maintenance approach with options targeting the type of degradation to effectively revitalize rocky spawning habitat function. This literature review identified three primary types of degradation: loss of material, sedimentation, and biofouling by periphyton or invertebrates. Each type of degradation tended to be accompanied by a suite of tailored maintenance actions. In addition to methods reported from past studies, adapting methods from other disciplines (e.g., shellfish dredging, marine archaeology, treasure hunting and underwater recovery, marine engineering) may prove useful for maintaining reef function.

4.1. Loss of Material

Depletion of spawning gravel occurs when dams and diversion structures cut off or reduce sediment supply, preventing upstream gravel sources from replenishing downstream reaches [21]. Over time, optimal spawning substrates are transported away from spawning areas, leaving substrates that are too large for spawning fishes [112]. Due to this loss of gravel, remediation efforts often focus on the addition of spawning materials to supplement and replenish habitats. Gravel augmentation is commonly used to supplement depleted salmonid redds in western North America [44,79,85,113] but this technique has also been used to improve riverine walleye spawning habitats [74]. However, before applying gravel, there are important considerations such as substrate size, hydrology, and the frequency at which new gravel will need to be added or cleaned. While the removal of fine sediment could increase egg survivorship by improving the interstitial flow of oxygenated water [44], some studies have hypothesized that complete elimination of these small materials could damage embryos during sensitive developmental stages by inducing excessive flow velocity along with mechanical agitation [45].

4.2. Sedimentation

Sediment cover can negatively affect incubating eggs of lithophilic-spawning fishes [114–117]. Fine sediments within spawning substrates can reduce interstitial flow and dissolved oxygen, leading to decreased survival during early life stages [93,112,116,118]. Sediment compositions with over 12% fine substrates (<1 mm) are thought to reduce fry emergence by 50% in salmonids [112] and laboratory experiments found a 71% reduction in walleye egg hatch rates when covered by 2 mm of fine sediments [30]. Therefore, reducing sedimentation and fine sediments in rocky spawning habitats may be critical to successful recruitment out of the early life history stages in some locations.

Both active and passive sediment removal methods have been applied to reduce sediment accumulations on rocky spawning substrates. Active sediment removal methods, including cleaning of substrate through mechanical means, were more commonly employed in the habitat maintenance projects identified in our review (n = 23). In shallow water with shoreline access, heavy equipment such as bulldozers, walking excavators, or tractors have been used to rake or sift through substrate and dislodge sediment from impacted areas, allowing smaller particles to be washed downstream [86,93,103,105,111]. Variations of this method include use of an excavator equipped with a vibrating bucket that collects impacted gravel and sifts silt and sand away through a screened bottom [93]. A variety of gravel cleaning vehicles and devices that use high-powered water jets and/or suction mechanisms to dislodge or remove sediment have also been developed for use in shallow riverine environments. In Fraser River (British Columbia, Canada) spawning channels, a tractor-pulled, air–water jet system was used to flush fine sediment from substrate down to 50 cm below the riverbed [93]. Self-propelled vehicles such as the "Riffle Sifter" [91] and "Gravel Gertie" [94,95] drove along the river, directing vertical water jets into the streambed, removing fine sediments from down to 30 cm within the riverbed. A suction system then separated and removed the suspended fines, ejecting them onshore above the high water line. One pass could reduce the amount of fines by up to 78% [94,119]. A more modern invention for cleaning, the "Sand Wand", operates in a similar fashion as the vehicles, using water jets to dislodge fines and suction to remove suspended sediments, but instead of spraying sediment onshore, it is collected for later disposal. The unit is either float- or skid-mounted and has been used to treat several trout streams [106,108,109]. In a test of the equipment, 10 metric tons of sediment were removed from a study site at a rate of 1.2 m^3 of sediment per hour [108].

While the hydraulic cleaning methods used by the "Riffle Sifter" and "Gravel Gertie" have shown success in removing fine sediments, determining whether reductions in sediment resulted in an increase in salmonid egg to fry survival was never evaluated [119] and, in some cases, gravel cleaning did not guarantee spawning success [93]. Additionally, gravel cleaning via mechanical methods can dislodge eggs and others have detrimental side effects, including temporarily degrading water quality and distributing sediment to other areas downstream, which can disrupt insects and other aquatic invertebrates [91]. Non-target effects can be mitigated when applications are conducted outside of spawning periods and when stream flows are high enough to properly move sediment downstream [119]. Mechanical removal also requires obtaining site access for heavy machinery, which can be invasive (e.g., road construction and site clearing), and use of equipment along river corridors can reduce bank stability [120]. Therefore, the benefits of techniques to remove sediment can be weighed against the potential harm to spawning habitats to ensure that the maintenance efforts are practical and benefit the system with minimal collateral damage.

Dredging or flushing with high flows can be used to lift sediment from the target location, allowing the current to disperse the sediment downstream [121,122]. Dredging through suction methods can remove a large volume of sediment in a short amount of time. For example, hydraulic cutterhead dredges possess the ability to remove sediment at rates in excess of 1000 m^3/h. However, due to the substantial disturbance that active dredging causes in the benthic area, it can create large turbidity plumes and resuspend large volumes of sediment into the water column [123]. This increased turbidity means dredging may not be practical in fragile habitats such as spawning gravel but may be applicable

to habitats with larger substrates or where deep sediment layers persist. Passive methods of sediment removal include building sediment traps or collectors [96,99,102,109]. Sediment traps are large crevices excavated in front of rocky habitats, where the drop in depth causes the water velocity to decrease and excess sediment is allowed to settle [124–126]. While these passive methods are successful at collecting sediment from the water column, there have not been evaluations of their effects on spawning activity, egg survival, or early life history stage recruitment.

4.3. Biofouling

4.3.1. Periphyton

Periphyton is one of the most common biofouling agents, growing on the surface of rocky substrates if light penetration is adequate. Shallow freshwater reefs [127] and many nearshore areas experience some degree of algal growth (e.g., *Cladophora*) in the Great Lakes [128]. However, increased water clarity caused by the filtering action of dreissenid mussels has allowed for deeper growth in some areas, with *Cladophora* cover extending to 40 m deep on historically important lake trout spawning reefs in the Great Lakes [129]. *Cladophora* is commonly found on freshwater rocky spawning habitats, but little research has focused on other epilithic algae taxa despite their widespread nature [130]. During a study of two artificial reefs constructed in Lake Michigan, algal growth covered "nearly 100%" of the surface area of the shallower reef (9 m deep) within 1–2 years post construction, and while most of this growth was attributed to *Cladophora*, up to 131 species of periphyton were identified per year [25]. The deeper reef (11 m deep) experienced less algal growth, but algal coverage varied between 25–50% during later years [25]. Nuisance growth of algae has increased in many areas of the Great Lakes, the prevention of which is most effective at larger scales through nutrient management [131]. In systems with low nutrient levels in North America, Europe, and elsewhere, nuisance growth of the diatom *Didymosphenia geminata* can similarly blanket the benthos, causing disruption to food webs and covering valuable spawning habitats [23,132].

The presence of algae has been implicated as a factor leading to low reproductive output of lake trout [133] and lake sturgeon [134], but algae was not found to impact walleye spawning habitats in the Nipigon River, Ontario, Canada (not shown, 48.9755° N, 88.2563° W) [135] or Lake Erie [127]. However, lab experiments demonstrated that, compared to every other incubation substrate tested, the hatch rate of white sturgeon *Acipenser transmontanus* eggs on algae-covered rocks was the lowest (3–17% vs. >20–61% on most other substrates), which was attributed to fungal growth on the eggs [136]. Thick periphyton growth can form mats that cover entire spawning areas, preventing access to interstitial spaces and sometimes changing hydraulic conditions [23,132]. Sloughed mats of decomposing *Cladophora* or *Didymosphenia* diatoms can create anoxic conditions underneath the mat in as little as 3–6 h [137], which could decrease dissolved oxygen and suffocate developing embryos [132]. Periphyton growth on spawning habitats may also be detrimental to newly-hatched fry; *Didymosphenia* can entangle fish and limit food supply through the reduction of insect diversity [98].

Despite the widespread nature of periphyton growth on spawning substrates, periphyton removal as a habitat maintenance strategy has received little attention and determining the effectiveness of removal is difficult to characterize. One example is a shallow (4 m) reef constructed in the St. Lawrence River, USA that was abandoned by spawning fish three years post construction due to sedimentation, algal growth, and biofouling by dreissenid mussels [24]. To remove the fouling agents, Johnson et al. [24] used hand tools to clean a small area (9 m^2) and later used pressurized water to remove debris from a larger area (200 m^2). Despite cleaning efforts by researchers, the growth of algae and colonization by dreissenid mussels was determined to be too dense to attract spawning fishes [24]. Algae may be easier to physically remove in shallower river systems, where scarification with heavy equipment such as bulldozers is possible. In some human-made spawning channels for salmonids, the channel is dewatered in between spawning seasons and dredged and/or scoured with machinery to remove sediment and break apart debris such as algae mats [93,98]. The degree to which these

techniques removed algae, as opposed to sediment, was not specifically measured. Other physical cleaning techniques employed in sediment removal (e.g., Sand Wand mentioned above) may also be effective at removing nuisance algae. Water flow management, such as increasing flows from dams, to scour away periphyton such as *Didymosphenia* may have limited application as this taxon thrives in relatively high water velocities (>1 m/s) [138] and anecdotal evidence found no loss in coverage after several storm surges [139].

Chemical treatments can be used to reduce nuisance levels of aquatic plants and filamentous algae, although their use necessitates a cost-benefit analysis and consideration for non-target effects. A combination of diquat and copper sulfide effectively removed *Cladophora* overgrowth in an artificial salmonid spawning channel off the Sacramento River in California, USA, although associated mortality rates of fish embryos and fry were not reported [63]. However, later chemical treatments using acrolein compounds in the canal resulted in massive fish kills and were discontinued [62]. While the chronic toxicity of diquat and/or copper sulfate is not well-studied [140], acute exposure to these chemicals can harm desirable native plants [141], reduce survival of tadpoles [142], and reduce survival of rainbow trout *Oncorhynchus mykiss* in the embryo/alevin stage [140]. Nuisance *Didymosphenia* blooms are a more recent phenomenon and chemical treatment protocols are under development [138,143]. A field test of one chemical compound effectively reduced coverage of the diatom but resulted in 16–20% mortality of rainbow trout caged in the treatment area [143]. Alternative methods of algae treatment involve placing barley straw or barley straw extract (antifungal) over the affected area [144] or placing glass beads covered in titanium dioxide, which breaks down chloroplasts in a reaction with sunlight [145]; however, both will likely only have localized effects. Prevention of biofouling by stopping the introduction and spread of nuisance organisms may be necessary to protect isolated spawning habitats. Public campaigns to sterilize boats and fishing equipment may be effective for preventing the spread of invasive species, including *Didymosphenia*, to new areas [146,147]. Continued experimentation with methods to control and remove periphyton is needed, but incorporating mitigation for biofouling during reef restoration planning, design, and construction may be the best practice to minimize potential for degradation impacts.

4.3.2. Invertebrates

Infestation of rocky surfaces by invasive mussels is a common problem in North America and Europe [148] that may limit the reproductive success of lithophilic spawning fishes [27]. Dreissenid mussels, for example, were first discovered in North America in the 1980s and quickly spread throughout the Great Lakes, with live mussel densities of 100,000/m^2 typical in some nearshore areas [148]. Most rocky areas and reefs in the Great Lakes are now colonized by live mussels and dreissenid shell fragments [27,55,129,148–150] and their colonization has led to lake-wide changes in nutrient dynamics and energy flows (e.g., the "nearshore shunt") [151]. Furthermore, invasive Pacific oysters *Crassostrea gigas* in Europe have also spread quickly since the 1980s and colonized rocky habitats [152,153].

Mussel colonization of new substrates such as constructed spawning reefs can occur quickly; reefs built during 1986–1989 in Lake Erie had 75–80% coverage by 1991, just three years after zebra mussels were discovered in the area [150], and reefs in southern Lake Michigan were covered 4 years post construction [27]. Spawning habitats colonized with mussels have reduced interstitial space, which may deter or prevent fish from spawning on fouled reefs [149,154]. Large accumulations of shells from dead mussels may also decrease interstitial space, but the shells are similar in size to gravel substrates and may be used as spawning substrates by some fishes [55]. Like overgrowth of some benthic algae, mussel beds and their pseudofeces may reduce oxygen availability for developing fish embryos. Dense mussel beds can heavily influence oxygen dynamics in the surrounding substrate: trapped feces/pseudofeces can form anoxic zones, and hypoxia forms atop and within mussel beds when combined with *Cladophora* growth [137]. Often, one invasive species can facilitate the spread of more nuisance species [155,156], and dreissenid mussels have increased the biomass of *Cladophora* algae through water filtration (thus

increasing light levels) and the addition of nutrients [151]. Preliminary results from Lafrancois and Bootsma [157] show that the removal of mussels may reduce the occurrence of algae on reefs as well.

Despite the widespread invasion of mussels globally, there are limited reports about the direct effects of dreissenid mussels on spawning success. Fitzsimons et al. [158] did not observe differences in walleye spawning activity, egg deposition/survival, or interstitial water quality on Lake Erie reefs that had been fouled by mussels at extremely high densities (>300,000 m^2), but their results were not comparable to pre-invasion spawning data. In a comparison of unfouled cobble and dreissenid encrusted spawning habitats in southern Lake Michigan, lake trout egg deposition and survival were much higher on the clean substrate, with many damaged eggs found on the mussel beds [27]. Binder et al. [34] observed lake trout spawning activity on northern Lake Huron sites with clean gravel/cobble substrates but also on lower quality substrates, such as areas fouled with mussels and algae, smaller substrates, and large boulders. Reduction of substrate quality related to mussel coverage is considered an understudied aspect of lake trout management, and researchers have suggested measuring egg survival on manipulated substrates (cleaned vs. fouled) [159]. Building spawning reefs has been recommended as a strategy for lake trout recovery in the Great Lakes, with the caveat that the construction accounts for potential mussel fouling [160].

In this review of rocky spawning habitat maintenance methods, studies detailing the removal of mussels from spawning habitats were not found, but this is likely because efficient large-scale treatments have only recently been tested or implemented. Treating larger infestations of mussels is complicated due to greater possible effects on non-target organisms. Water drawdowns of impounded lakes are effective at decreasing nearshore concentrations of mussels [161] but can also harm nearshore fauna such as native unionids or herpetofauna [162] unless they are transplanted. Chemical treatments may be one of the most effective ways to remove larger dreissenid infestations from small lakes or targeted areas of large lakes. A number of molluscicides are effective against dreissenid mussels, including niclosamide, potassium chloride (usually in potash), and copper compounds (e.g., cupric ions in EarthTec QZ), but all have been shown to have non-target effects on native unionid mussels except for Zequanox, which specifically targets dreissenids, using dead soil bacteria *Pseudomonas fluorescens* to degrade their digestive lining [163].

The widespread nature of mussel invasions makes management of the problem difficult, especially in large lake ecosystems. However, mussel prevention and removal techniques are being field-tested, and some targeted removal strategies may be employed to maintain rocky spawning habitats. Aquaculture facilities can also prevent the spread of veligers (i.e., larval dreissenid mussels) by treating water containing fish eggs [164,165] and juvenile fish [166] during transport to other water bodies. In newly colonized areas, manual removal of small mussel beds by divers is labor intensive but may be possible to prevent further spread, such as in Lake George, New York, USA (not shown, 43.4262° N, 73.7123° W) [167]. Volunteer divers and biologists are currently testing this technique on spawning shoals in northern Lake Michigan to measure the effects of mussel removal on water quality and algae growth, removing ~1 million mussels during 2016 [157]. Small patches of mussels can also be removed using water jetting at 3000 psi (e.g., Figure 6A), although this may be limited to applications such as hull and dock cleaning unless detached mussels can be collected and removed from the area [168,169]. Additionally, adaptation of a tillage disc cultivator offers the opportunity to crush and dislodge the mussels without destroying the reef (e.g., Figure 6B). Depriving mussels of oxygen by covering mussel beds with tarps or by pumping carbon dioxide over mussel beds can also target smaller mussel accumulations, although these have yet to be employed in many field applications [170,171].

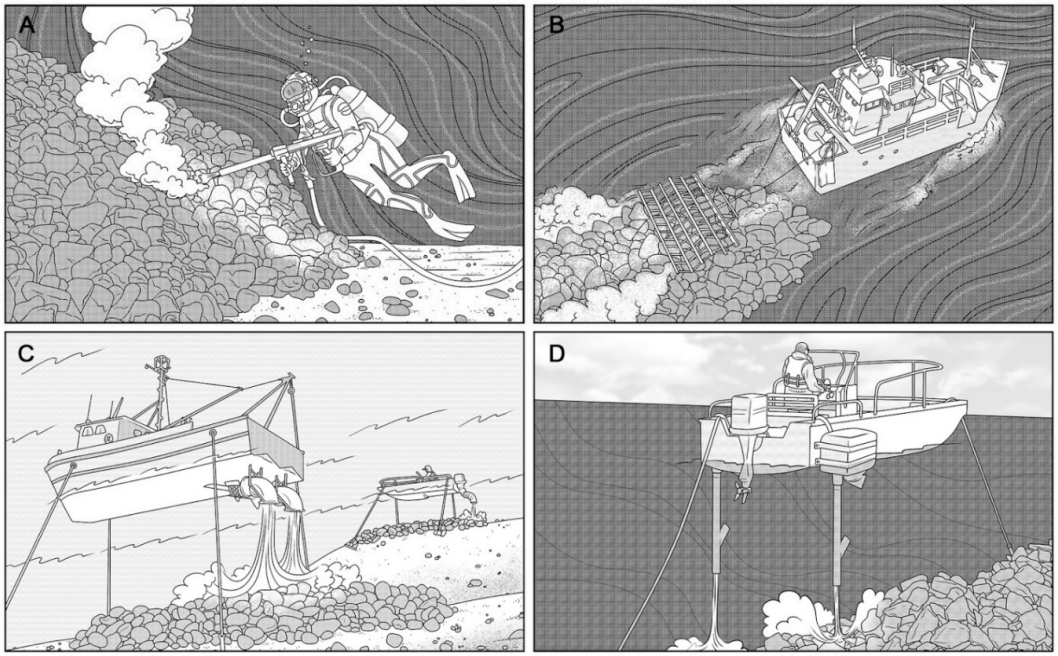


Figure 6. Potential reef cleaning mechanisms, including (**A**) pressure washing by divers using tools for cleaning large vessels, (**B**) removal of mussels or periphyton using a large vessel and a pasture or disc harrow, (**C**) excavation of sediment with a prop wash diverting mailbox system for large vessels (depths up to 15 m) and small vessels (water depths <5 m), (**D**) sediment removal via pumps or engines such as those used by personal watercraft.

4.4. Novel Remediation Techniques

Our results suggest a need to explore multiple disciplines for remediation methods, especially for deep-water and/or lacustrine environments, which were underrepresented in our review. For example, marine archeologists commonly use hydro suction technology such as airlifts or suction dredges to remove sediment by a vacuum-like process, allowing the substrate below to remain intact [172–174]. While effective on a small scale, this methodology has a small footprint and is labor intensive. Thus, hydro suction methods may require additional modification to be an efficient method for maintaining large spawning reefs. Propeller wash from marine vessels is another method to flush fine sediments that is less precise but has a larger target area than hydro suction methods [175–177]. Using a "mailbox" device, turbulent water is directed downward by the propulsion of the vessel's propeller and suspends fine sediments from the benthic substrate; however, this requires a vessel large enough to produce adequate propulsion to sufficiently reach the target depth (Figure 6C). Additional novel methodologies that could potentially be adapted for sediment removal include long-tail motors, bow thrusters, and even personal watercrafts (PWC) with modified propulsion units (Figure 6D). Since these methods are portable and deployable from a range of vessels, they could provide effective methods for maintaining rocky habitats in both lentic and lotic systems.

Fine sediment removal methods were recently tested in lentic environments using two benthic sled devices that utilized either pressurized water or propulsion-driven water to clear sediments and other fouling from the interstitial spaces of two rocky spawning reefs in Saginaw Bay, Lake Huron, USA [58]. These devices were small in scale (1.35 m × 1.0 m; <90 kg) and were able to be towed by a smaller research vessel (6.4 m long). Results showed that both cleaning devices were able to successfully increase the relative hardness of the bottom substrate in some sampling areas, suggesting that the cleaning devices have the potential to remove sediments from rocky spawning reefs [58]. Furthermore, removal of sediments and increases in relative hardness over cleaned areas of the reef resulted in increased egg deposition by walleye and lake whitefish in these areas. Though these results are just one example of novel reef cleaning methodology being tested, the development of cleaning

devices and subsequent results of cleaning (e.g., increased relative hardness of cleaned areas and increased egg deposition) provide support and future guidance for the implementation of this method.

Prevention of sediment accumulation through mechanical means may be possible in some lotic environments. While techniques such as adding riparian vegetation have been used extensively to control runoff and sediment loads [178,179], recently developed "active sediment collectors" have been installed in several Michigan, USA salmon streams and have had some efficacy in preventing the deposition of bedload sediments [109,180], although additional field testing and quantification of sediment collection would be beneficial to assess their efficacy in spawning habitat maintenance. The sediment collector is a ramped box placed perpendicular to the flow across the river bottom, which allows for the settling and collection of sediments that are periodically suctioned onshore for disposal. Laboratory testing of a small (0.6 × 1.1 m) active sediment collector found bedload reductions of 93–99% for grain sizes >0.5 mm and reductions of 54–75% for smaller-grain materials under a variety of flow conditions [181]. Field testing of a larger (9.14 m wide) collector in Fountain Creek, Colorado, USA (not shown, 40.5163° N, 87.8094° W) was undertaken to determine whether the system could reduce the need for dredging operations in the system, and the collector obtained maximum sediment collections of 76.5 m^3/h under high flow regimes, removing an estimated ~670,000 m^3 of sediment per year with minimal maintenance [182]. More conceptual methods of sedimentation prevention include the development of a plan for a "self-cleaning substrate" or a system of tubing placed under spawning substrate that uses the hydraulic head of the river to push water under and through the substrate, potentially dislodging accumulated particles [183]. Although never field tested (D. Geiling, Fisheries and Oceans Canada, personal communication), this technology could be considered for testing in the creation of new habitat projects or could be retooled for use in lentic habitats by using pump action instead of river head to create flow through the system. Development of novel sediment removal devices for fisheries should include input from biologists and rigorous field testing, as scale models may yield different results. This was the case with the movable baffle developed for the Tehama-Colusa Canal, CA, USA, which was designed to lower into the water to create high flows and clean sediments [92] but was largely ineffective at scale, creating unsuitable patches in the spawning habitat, blocking fish access, and frequently breaking down [62].

Large-scale chemical treatments to remove and destroy invasive invertebrate species have been tested with success; however, until more treatments are conducted to analyze their effects on native species, other methods may be necessary for large-scale removal. One such example that we propose is a modified pasture harrow (Figure 6B), used to break apart and distribute oysters on reefs, that can be dragged across the site by boat to dislodge and crush nuisance mussels or break apart mats of epiphytic algae or diatoms without displacing reef structure. Both boat-towed disc and tooth harrows have been tested for use in oyster cultivation [184], and specialized toothed raking apparatus or "mud cleaning machines" have been developed to scatter accumulated sediment and clustered shells [185]. Conventional dredging methods and hydraulic excavators have also been used to exhume oyster reefs buried by sediment [186,187]. Published literature about the use of harrows and other oyster reef cleaning mechanisms is scant but contact with local managers about adapting techniques used may prove useful to maintaining lithophilic fish spawning habitat as well.

4.5. Physical Monitoring Techniques

Physical monitoring of spawning habitats is often necessary to determine whether maintenance is warranted, and, if the habitat has been constructed or remediated, monitoring is needed in order to determine whether the project is meeting management objectives. Identifying possible problems in a system before construction begins allows managers to plan and manage for degradation before it makes the site unusable. Biological monitoring of remediated habitats is common, but for spawning reefs constructed in the Great Lakes only 24% of projects reviewed included some form of physical monitoring post construction [54]. Through these monitoring efforts, researchers observed changes in reef placement [188], physical damage from logs and ice jams [189],

or sedimentation/biofouling [27,55,189–191]. Furthermore, similar degradations have been observed in marine systems [192,193], highlighting the need for incorporating metrics of salmonid habitat improvement projects reporting any type of project structure into monitoring.

The type of physical monitoring needed depends on the management goals and the type of environment; different protocols will be needed for physical monitoring in shallow vs. deep-water areas or lentic vs. lotic environments. Designing a physical habitat monitoring program should consider which physical variables are important to the study species and which physical processes in the study system may act on the habitat to degrade its effectiveness over time. Key elements to consider monitoring are the physical structure of the habitat, hydrology, and water quality. Furthermore, research on potential elements to include in physical monitoring programs for deep-water reefs include focusing on measuring the following metrics: water depth, tide, current magnitude and direction, wave height, reef position, and condition. Monitoring is suggested to be conducted 6 months after initial deployment and following up every 12 months from then on [194].

Methods for monitoring the spawning habitat's physical structure (e.g., substrate, placement, structural integrity) will depend on the project's goals, budget, and expertise in collection and post-processing of data. Loss or infilling of substrate is one of the most important elements to monitor, and traditional methods for measuring substrate size (e.g., Ponar or Eckman grabs) may not be effective in rocky, deep-water environments or may represent too small of an area relative to the size of the habitat. In situ measurements of substrate size are complicated in deep-water environments, and divers may be needed to map habitat structure, count organisms, or assess conditions, either by placing quadrats [27] or by following transects [195]. In shallow or deep water, stable reference points (such as rods) can be placed to determine whether rock pile height has changed [196]. Sediment collection devices can be used to measure deposition rates over time [127]. In lieu of in situ measurements of habitat structure, underwater video (UTV) cameras towed from a boat, hauled along dive transects, or carried by remotely operated vehicles are commonly used reef monitoring tools [55,190,197–199]. Obtaining quantifiable data from UTV can range from relatively simple techniques (e.g., calculating substrate size and area fouled from still frames) [55] to using computer vision/deep-learning algorithms to delineate substrates and map habitats [198], vegetation [200], or invertebrates [201]. Side-scan sonar and multibeam bathymetry are other advanced technologies that allow researchers to map substrates and benthic structures that are commonly used to assess fishes' habitats [55,202,203]. These advanced technologies are an effective suite of tools for assessing reef condition. Standardizing methods and protocols for monitoring rocky reefs will further improve their application and future efforts to compare reef maintenance methods across systems.

Biological monitoring of remediated habitats is common, but for spawning reefs constructed in the Great Lakes, only 24% of projects reviewed included some form of physical monitoring post construction [54]. Another example shows that only 6.7% of salmonid habitat improvement projects report any type of monitoring [204], as discussed in the previous review. In addition, a review assessing whether or not these spawning habitat projects are effective found that only 4% of all projects evaluated were considered successful. A majority of these studies did not qualify for success because of the 3-year post-monitoring requirement to be considered effective [61]. This lack of monitoring creates a situation in which success and effectiveness cannot be evaluated.

5. Conclusions

This review of rocky spawning habitat maintenance shows that maintenance of rocky spawning habitats and reefs is not a common practice, with few standardized techniques developed, including a lack of information regarding cost information and evaluating success. Increased monitoring and reporting of costs and effectiveness will improve the ability of practitioners to make informed decisions on proceeding with maintenance projects. This effort identified that most habitat maintenance projects focus primarily on riverine habitats and salmonids, highlighting the need for more research conducted on deep-water species like lake trout, cisco *Coregonus artedi*, and sturgeon species. We also found a

dearth of publications detailing rocky reef maintenance in marine habitats, despite the high rates of sedimentation observed on marine reefs such as those off the coast of Italy and Turkey [205], but this may be due to our bias in selection of English language publications and search terms. Although maintenance through substrate addition has the potential to be successful for habitats suffering from loss of substrate, each habitat is unique and, while gravel augmentation is the most common remediation technique, it might not be uniformly applicable for all target species or life stages. For habitats that experience an influx of too much material, i.e., sedimentation, adding gravel is not a viable solution; therefore, when considering potential methods of maintenance, the solution should incorporate the source and mechanism of degradation. Adapting and experimenting with methods from other disciplines (e.g., shellfish dredging, marine archeology, treasure hunting and underwater recovery, marine navigation, and dredging) may prove useful for repair and add value to these reef restoration programs. Furthermore, cleaning systems and anticipated maintenance needs can be incorporated into artificial reef construction designs and budgeting to facilitate routine maintenance and increase the long-term success and function of spawning reefs. Finally, our review shows that post-management monitoring and shared results through scientific outlets could be beneficial to all those involved in rocky reef restoration and maintenance, including managers, researchers, and practitioners.

Author Contributions: Conceptualization, E.F.R., R.L.D., J.L.F., and A.B.; Investigation, A.B. and T.R.T.; Writing—Original Draft Preparation, A.B. and T.R.T.; Writing—Review and Editing, E.F.R., R.L.D., J.L.F., T.R.T., T.H., A.G., and A.B.; Visualization, T.R.T.; Supervision, E.F.R.; Project Administration, E.F.R.; Funding Acquisition, E.F.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Great Lakes Restoration Initiative.

Acknowledgments: We thank E. Binkowski, D. Jones, E. Olds, M. Tomczak, and F. VanDrunen for assistance with data compilation. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government. The findings and conclusions in this article are those of the authors and do not necessarily represent the views of the U.S. Fish and Wildlife Service.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Common and scientific names of fish taxa referenced in Table 1 of the main text.

Family	Common Name	Scientific Name
Acipenseridae	Lake sturgeon	*Acipenser fulvescens*
Acipenseridae	White sturgeon	*Acipenser transmontanus*
Catostomidae	Black redhorse	*Moxostoma duquesni*
Catostomidae	Northern hogsucker	*Hypentelium nigricans*
Cyprinidae	Common barbel	*Barbus barbus*
Cyprinidae	River chub	*Nocomis micropogon*
Eleotridae	Carp gudgeon	*Hypseleotris* spp.
Eleotridae	Flathead gudgeon	*Philypnodon grandiceps*
Percichthyidae	River blackfish	*Gadopsis marmoratus*
Percidae	Walleye	*Sander vitreus*
Petromyzontidae	Brook lamprey	*Lampetra planeri*
Salmonidae	Atlantic salmon	*Salmo salar*
Salmonidae	Bonneville cutthroat trout	*Oncorhynchus clarkii utah*
Salmonidae	Brook trout	*Salvelinus fontinalis*
Salmonidae	Brown trout	*Salmo trutta*
Salmonidae	Chinook salmon	*Oncorhynchus tshawytscha*
Salmonidae	Chum salmon	*Oncorhynchus keta*
Salmonidae	Cisco	*Coregonus artedi*
Salmonidae	Coho salmon	*Oncorhynchus kisutch*
Salmonidae	Cutthroat trout	*Oncorhynchus clarkii*
Salmonidae	Grayling	*Thymallus thymallus*
Salmonidae	Lake trout	*Salvelinus namaycush*
Salmonidae	Lake whitefish	*Coregonus clupeaformis*
Salmonidae	Masu salmon	*Oncorhynchus masou*
Salmonidae	Pink salmon	*Oncorhynchus gorbuscha*
Salmonidae	Rainbow trout	*Oncorhynchus mykiss*
Salmonidae	Sockeye salmon	*Oncorhynchus nerka*

References

1. Brickhill, M.J.; Lee, S.Y.; Connolly, R.M. Fishes associated with artificial reefs: Attributing changes to attraction or production using novel approaches. *J. Fish Biol.* **2005**, *67*, 53–71. [CrossRef]
2. Gunderson, D.R.; Parma, A.M.; Hilborn, R.; Cope, J.M.; Fluharty, D.L.; Miller, M.L.; Vetter, R.D.; Heppell, S.S.; Greene, G.H. The challenge of managing nearshore rocky reef resources. *Fisheries* **2008**, *33*, 172–179. [CrossRef]
3. Kennedy, D. Year of the Reef. *Science* **2007**, *318*, 1695–1696. [CrossRef] [PubMed]
4. Bouckaert, E.K.; Auer, N.A.; Roseman, E.F.; Boase, J. Verifying success of artificial spawning reefs in the St. Clair-Detroit River System for lake sturgeon (*Acipenser fulvescens* Rafinesque, 1817). *J. Appl. Ichthyol.* **2014**, *30*, 1393–1401. [CrossRef]
5. Riley, S.C.; Marsden, J.E.; Ridgway, M.S.; Konrad, C.P.; Farha, S.A.; Binder, T.R.; Middel, T.A.; Esselman, P.C.; Krueger, C.C. A conceptual framework for the identification and characterization of lacustrine spawning habitats for native lake charr *Salvelinus namaycush*. *Environ. Biol. Fishes* **2019**, *102*, 1533–1557. [CrossRef]
6. Roseman, E.F.; Kennedy, G.W.; Boase, J.; Manny, B.A.; Todd, T.N.; Stott, W. Evidence of lake whitefish spawning in Detroit River: Implications for habitat and population recovery. *J. Gt. Lakes Res.* **2007**, *33*, 397–406. [CrossRef]
7. Shuter, B.J. Population-level indicators of stress. *Am. Fish. Soc. Symp.* **1990**, *8*, 145–166.
8. Hayes, D. Issues affecting fish habitat in the Great Lakes Basin. In *Great Lakes Fisheries Policy and Management: A Binational Perspective*; Taylor, W.W., Ferreri, C.P., Eds.; Michigan State University Press: East Lansing, MI, USA, 1999; pp. 207–237.
9. Hendry, K.; Cragg-Hine, D.; O'Grady, M.; Sambrook, H.; Stephen, A. Management of habitat for rehabilitation and enhancement of salmonid stocks. *Fish. Res.* **2003**, *62*, 171–192. [CrossRef]

10. Nagata, M.; Omori, H.; Yanai, S. Restoration of spawning and rearing habitats for masu salmon, *Oncorhynchus masou* in a channelized stream. *Fish. Sci.* **2002**, *68*, 1707–1710. [CrossRef]
11. Baine, M. Artificial reefs: A review of their design, application, management and performance. *Ocean Coast. Manag.* **2001**, *44*, 241–259. [CrossRef]
12. Bohnsack, J.A.; Sutherland, D.L. Artificial reef research: A review with recommendations for future priorities. *Bull. Mar. Sci.* **1985**, *37*, 11–39.
13. Miller, R.R.; Williams, J.D.; Williams, J.E. Extinctions of North American fishes during the past century. *Fisheries* **1989**, *14*, 22–38. [CrossRef]
14. Gladstone, W. Requirements for marine protected areas to conserve the biodiversity of rocky reef fishes. *Aquat. Conserv. Mar. Freshw. Ecosyst.* **2006**, *17*, 71–87. [CrossRef]
15. Airoldi, L. The effects of sedimentation on rocky coast assemblages. *Oceanogr. Mar. Biol. Annu. Rev.* **2003**, *41*, 161–236.
16. Connell, S.D. Assembly and maintenance of subtidal habitat heterogeneity: Synergistic effects of light penetration and sedimentation. *Mar. Ecol. Prog. Ser.* **2005**, *289*, 53–61. [CrossRef]
17. Kemp, P.; Sear, D.; Collins, A.; Naden, P.; Jones, I. The impacts of fine sediment on riverine fish. *Hydrol. Process.* **2011**, *25*, 1800–1821. [CrossRef]
18. Bennion, D.H.; Manny, B.A. *Construction of Shipping Channels in the Detroit River: History and Environmental Consequences*; US Geological Survey: Ann Arbor, MI, USA, 2011.
19. Rutherford, E.S.; Marshall, E.; Clapp, D.; Horns, W.; Gorenflo, T.; Trudeau, T. *Lake Michigan Environmental Objectives*; Great Lakes Fishery Commission: Ann Arbor, MI, USA, 2004; p. 81.
20. Brown, A.V.; Lyttle, M.M.; Brown, K.B. Impacts of gravel mining on gravel bed streams. *Trans. Am. Fish. Soc.* **1998**, *127*, 979–994. [CrossRef]
21. Kondolf, G.M. Hungry water: Effects of dams and gravel mining on river channels. *Environ. Manag.* **1997**, *21*, 533–551. [CrossRef]
22. Støttrup, J.G.; Dahl, K.; Niemann, S.; Stenberg, C.; Reker, J.; Stamphøj, E.M.; Göke, C.; Svendsen, J.C. Restoration of a boulder reef in temperate waters: Strategy, methodology and lessons learnt. *Ecol. Eng.* **2017**, *102*, 468–482. [CrossRef]
23. Bickel, T.O.; Closs, G.P. Impact of *Didymosphenia geminata* on hyporheic conditions in trout redds: Reason for concern? *Mar. Freshw. Res.* **2008**, *59*, 1028–1033. [CrossRef]
24. Johnson, J.H.; LaPan, S.R.; Klindt, R.M.; Schiavone, A. Lake sturgeon spawning on artificial habitat in the St Lawrence River. *J. Appl. Ichthyol.* **2006**, *22*, 465–470. [CrossRef]
25. Rutecki, T.L.; Dorr, J.A.; Jude, D.J. Preliminary analysis of colonization and succession of selected algae, invertebrates, and fish on two artificial reefs in inshore southeastern Lake Michigan. In *Artificial Reefs: Marine and Freshwater Applications*; D'Itri, F.M., Ed.; Lewis Publishers, Inc.: Chelsea, MI, USA, 1985; pp. 459–489.
26. Leach, J.H. Biota of Lake St. Clair: Habitat evaluation and environmental assessment. *Hydrobiologia* **1991**, *219*, 187–202. [CrossRef]
27. Marsden, J.E.; Chotkowski, M.A. Lake trout spawning on artificial reefs and the effect of zebra mussels: Fatal attraction? *J. Gt. Lakes Res.* **2001**, *27*, 33–43. [CrossRef]
28. Evans, E.P.; Simm, J.D.; Thorne, C.R.; Arnell, N.W.; Ashley, R.M.; Hess, T.; Lane, S.; Morris, J.; Nicholls, R.; Penning-Rowsell, E.; et al. *An Update of the Foresight Future Flooding 2004 Qualitative Risk Analysis*; Cabinet Office: London, UK, 2008.
29. Marsden, J.E.; Perkins, D.L.; Krueger, C.C. Recognition of spawning areas by lake trout: Deposition and survival of eggs on small, man-made rock piles. *J. Gt. Lakes Res.* **1995**, *21*, 330–336. [CrossRef]
30. Gatch, A.J.; Koenigbauer, S.T.; Roseman, E.F.; Höök, T.O. The effect of sediment cover and female characteristics on the hatching success of walleye. *N. Am. J. Fish. Manag.* **2020**, *40*, 293–302. [CrossRef]
31. Sly, P.G. Interstitial water quality of lake trout spawning habitat. *J. Gt. Lakes Res.* **1988**, *14*, 301–315. [CrossRef]
32. Claramunt, R.M.; Jonas, J.L.; Fitzsimons, J.D.; Marsden, J.E. Influences of spawning habitat characteristics and interstitial predators on lake trout egg deposition and mortality. *Trans. Am. Fish. Soc.* **2005**, *134*, 1048–1057. [CrossRef]
33. Bennion, D.H.; Manny, B.A. A model to locate potential areas for lake sturgeon spawning habitat construction in the St. Clair-Detroit River System. *J. Gt. Lakes Res.* **2014**, *40*, 43–51. [CrossRef]

34. Binder, T.R.; Farha, S.A.; Thompson, H.T.; Holbrook, C.M.; Bergstedt, R.A.; Riley, S.C.; Bronte, C.R.; He, J.; Krueger, C.C. Fine-scale acoustic telemetry reveals unexpected lake trout, *Salvelinus namaycush*, spawning habitats in northern Lake Huron, North America. *Ecol. Freshw. Fish* **2018**, *27*, 594–605. [CrossRef]
35. Gannon, J. *International Position Statement and Evaluation Guidelines for Artificial Reef Development in the Great Lakes*; Great Lakes Fishery Commission: Ann Arbor, MI, USA, 1990.
36. Manny, B.A.; Roseman, E.F.; Kennedy, G.; Boase, J.C.; Craig, J.M.; Bennion, D.H.; Read, J.; Vaccaro, L.; Chiotti, J.; Drouin, R.; et al. A scientific basis for restoring fish spawning habitat in the St. Clair and Detroit Rivers of the Laurentian Great Lakes. *Restor. Ecol.* **2015**, *23*, 149–156. [CrossRef]
37. Marsden, J.E.; Binder, T.R.; Johnson, J.; He, J.; Dingledine, N.; Adams, J.; Johnson, N.S.; Buchinger, T.J.; Krueger, C.C. Five-year evaluation of habitat remediation in Thunder Bay, Lake Huron: Comparison of constructed reef characteristics that attract spawning lake trout. *Fish. Res.* **2016**, *183*, 275–286. [CrossRef]
38. Roseman, E.F.; McLean, M.; Pritt, J.J.; Fischer, J.; Kennedy, G. Artificial reefs and reef restoration in the Laurentian Great Lakes. In *Biodiversity, Conservation, and Environmental Management in the Great Lakes Basin*; Freedman, E., Neuzil, M., Eds.; Routledge: New York, NY, USA, 2017; pp. 33–46.
39. Jensen, A. Artificial reefs of Europe: Perspective and future. *ICES J. Mar. Sci.* **2002**, *59*, S3–S13. [CrossRef]
40. Stone, R.B. History of artificial reef use in the United States. In *Artificial Reefs: Marine and Freshwater Applications*; D'itri, F., Ed.; Lewis Publishers, Inc.: Chelsea, MI, USA, 1985; pp. 3–11.
41. Roseman, E.F.; Manny, B.; Boase, J.; Child, M.; Kennedy, G.; Craig, J.; Soper, K.; Drouin, R. Lake sturgeon response to a spawning reef constructed in the Detroit River. *J. Appl. Ichthyol.* **2011**, *27*, 66–76. [CrossRef]
42. Prichard, C.G.; Craig, J.M.; Roseman, E.F.; Fischer, J.L.; Manny, B.A.; Kennedy, G.W. *Egg Deposition by Lithophilic-Spawning Fishes in the DETROIT and Saint Clair Rivers, 2005–2014*; US Geological Survey: Ann Arbor, MI, USA, 2017; p. 20.
43. Roni, P.; Slyke, D.V.; Miller, B.A.; Ebersole, J.L.; Pess, G. Adult coho salmon and steelhead use of boulder weirs in southwest Oregon streams. *N. Am. J. Fish. Manag.* **2008**, *28*, 970–978. [CrossRef]
44. Merz, J.E.; Setka, J.D. Evaluation of a spawning habitat enhancement site for chinook salmon in a regulated California river. *N. Am. J. Fish. Manag.* **2004**, *24*, 397–407. [CrossRef]
45. Merz, J.E.; Setka, J.D.; Pasternack, G.B.; Wheaton, J.M. Predicting benefits of spawning-habitat rehabilitation to salmonid (*Oncorhynchus* spp.) fry production in a regulated California river. *Can. J. Fish. Aquat. Sci.* **2004**, *61*, 1433–1446. [CrossRef]
46. Fjeldstad, H.-P.; Barlaup, B.T.; Stickler, M.; Gabrielsen, S.-E.; Alfredsen, K. Removal of weirs and the influence on physical habitat for salmonids in a Norwegian river. *River Res. Appl.* **2012**, *28*, 753–763. [CrossRef]
47. Palm, D.; Bränäs, E.; Lepori, F.; Nilsson, K.; Stridsman, S. The influence of spawning habitat restoration on juvenile brown trout (*Salmo trutta*) density. *Can. J. Fish. Aquat. Sci.* **2007**, *64*, 509–515. [CrossRef]
48. Mitchell, L.T.N. An Assessment of Rehabilitation Gravels for *Salmo trutta* Spawning: A Case Study from a Small Chalk Stream, the River Stiffkey, Norfolk UK. Ph.D. Thesis, University College London, London, UK, 2016.
49. Nakamura, M. Evolution of artificial fishing reef concepts in Japan. *Bull. Mar. Sci.* **1985**, *37*, 271–278.
50. Kondolf, G.M.; Vick, J.C.; Ramirez, T.M. Salmon spawning habitat rehabilitation on the Merced River, California: An evaluation of project planning and performance. *Trans. Am. Fish. Soc.* **1996**, *125*, 899–912. [CrossRef]
51. Larson, J.W. *Essayons: A History of the Detroit District, US Army Corps of Engineers*; US Army Corps of Engineers, Detroit District: Detroit, MI, USA, 1995.
52. Vaccaro, L.; Bennion, D.; Boase, J.; Bohling, M.; Chiotti, J.; Craig, J.; Drouin, R.; Fischer, J.; Kennedy, G.; Manny, B.; et al. *Science in Action: Lessons Learned from Fish Spawning Habitat Restoration in the St. Clair and Detroit Rivers*; University of Michigan: Ann Arbor, MI, USA, 2016.
53. Kelso, J.R.M.; Hartig, J.H. *Methods of Modifying Habitat to Benefit the Great Lakes Ecosystem. CISTI (Canada Institute for Scientific and Technical Information) Occasional Paper No. 1*; National Research Council of Canada: Ottawa, ON, Canada, 1995.
54. McLean, M.; Roseman, E.F.; Pritt, J.J.; Kennedy, G.; Manny, B.A. Artificial reefs and reef restoration in the Laurentian Great Lakes. *J. Gt. Lakes Res.* **2015**, *1*, 1–8. [CrossRef]
55. Fischer, J.L.; Roseman, E.F.; Mayer, C.; Wills, T. If you build it and they come, will they stay? Maturation of constructed fish spawning reefs in the St. Clair-Detroit River System. *Ecol. Eng.* **2020**, *150*, 105837. [CrossRef]

56. Vehanen, T.; Huusko, A.; Mäki-Petäys, A.; Louhi, P.; Mykrä, H.; Muotka, T. Effects of habitat rehabilitation on brown trout (*Salmo trutta*) in boreal forest streams. *Freshw. Biol.* **2010**, *55*, 2200–2214. [CrossRef]
57. Roni, P.; Bennett, T.; Morley, S.; Pess, G.R.; Hanson, K.; Slyke, D.V.; Olmstead, P. Rehabilitation of bedrock stream channels: The effects of boulder weir placement on aquatic habitat and biota. *River Res. Appl.* **2006**, *22*, 967–980. [CrossRef]
58. Gatch, A.J.; Koenigbauer, S.T.; Roseman, E.F.; Höök, T.O. Assessment of two techniques for maintenance of rocky reef spawning habitat. *J. Gt. Lakes Res.* **2020**. [CrossRef]
59. Wheaton, J.M. Spawning Habitat Rehabilitation. Master's Thesis, University of California at Davis, Davis, CA, USA, 2003.
60. Taylor, J.J.; Rytwinski, T.; Bennett, J.R.; Smokorowski, K.E.; Lapointe, N.W.R.; Janusz, R.; Clarke, K.; Tonn, B.; Walsh, J.C.; Cooke, S.J. The effectiveness of spawning habitat creation or enhancement for substrate-spawning temperate fish: A systematic review. *Environ. Evid.* **2019**, *8*, 19. [CrossRef]
61. Rytwinski, T.; Elmer, L.K.; Taylor, J.J.; Donaldson, L.A.; Bennett, J.R.; Smokorowski, K.E.; Winegardner, A.K.; Cooke, S.J. *How Effective Are Spawning-Habitat Creation or Enhancement Measures for Substrate-Spawning Fish?: A Synthesis*; Department of Fisheries and Oceans Canada: Ottawa, ON, Canada, 2019; p. 183.
62. Bureau of Reclamation. *Central Valley Fish and Wildlife Management Study: Fishery Problems at Red Bluff Diversion Dam and Tehama-Colusa, Canal Fish Facilities*; Bureau of Reclamation Mid-Pacific Region: Sacramento, CA, USA, 1985.
63. Yeo, R.R.; Dechoretz, N. Diquat and copper-ion residues in salmon-spawning channel. *Weed Sci.* **1976**, *24*, 405–409. [CrossRef]
64. Louhi, P.; Vehanen, T.; Huusko, A.; Petays, A.; Muotka, T. Long-term monitoring reveals the success of salmonid habitat restoration. *Can. J. Fish. Aquat. Sci.* **2013**, *73*, 1733–1741. [CrossRef]
65. Kondolf, G.M.; Matthews, W.V. *Management of Coarse Sediment in Regulated Rivers of California*; University of California Water Resources Center: Berkeley, CA, USA, 1991; p. 102.
66. Gerke, R.J. *Salmon Spawning Habitat Improvement Study*; Washington Department of Fisheries: Olympia, WA, USA, 1974; p. 93.
67. Wilson, D. *Salmonid Spawning Habitat Improvement Study*; Washington State Department of Fisheries: Olympia, WA,USA, 1976; p. 20.
68. House, R.A.; Boehne, P.L. Evaluation of instream enhancement structures for salmonid spawning and rearing in a coastal Oregon stream. *N. Am. J. Fish. Manag.* **1985**, *5*, 283–295. [CrossRef]
69. Moreau, J.K. Anadromous salmonid habitat enhancement by boulder placement in Hurdygurdy Creek, California. In Proceedings of the Pacific Northwest Stream Habitat Management Workshop, Arcata, CA, USA, 10–12 October 1984; Hassler, T.J., Ed.; American Fisheries Society, Humboldt Chapter: Arcata, CA, USA, 1984.
70. Klassen, H.D.; Northcote, T.G. Use of gabion weirs to improve spawning habitat for pink salmon in a small logged watershed. *N. Am. J. Fish. Manag.* **1988**, *8*, 36–44. [CrossRef]
71. Klassen, H.; Northcote, T. Stream bed configuration and stability following gabion weir placement to enhance salmonid production in a logged watershed subject to debris torrents. *Can. J. For. Res.* **1986**, *16*, 197–203. [CrossRef]
72. Zeh, M.; Dönni, W. Restoration of spawning grounds for trout and grayling in the river High-Rhine. *Aquat. Sci.* **1994**, *56*, 59–69. [CrossRef]
73. Lychwick, T.L. Fox River Walleye Habitat Improvement. In *Methods of Modifying Habitat to Benefit the Great Lakes Ecosystem. CISTI (Canada Institute for Scientific and Technical Information) Occasional Paper No. 1*; Kelso, J.R.M., Hartig, J.H., Eds.; National Research Council of Canada: Ottawa, ON, Canada, 1995; pp. 272–281.
74. Geiling, W.D.; Kelso, J.R.M.; Iwachewski, E. Benefits from incremental additions to walleye spawning habitat in the Current River, with reference to habitat modification as a walleye management tool in Ontario. *Can. J. Fish. Aquat. Sci.* **1996**, *53*, 79–87. [CrossRef]
75. Ward, B.R.; McCubbing, D.J.F.; Slaney, P.A. Stream restoration for anadromous salmonids by the addition of habitat and nutrients. In *Salmon at the Edge*; Mills, D., Ed.; Blackwell Science Ltd.: Oxford, UK, 2003; pp. 235–254.
76. Pedersen, M.L.; Kristensen, E.A.; Kronvang, B.; Thodsen, H. Ecological effects of re-introduction of salmonid spawning gravel in lowland Danish streams. *River Res. Appl.* **2009**, *25*, 626–638. [CrossRef]

77. Pasternack, G.B.; Wang, C.L.; Merz, J.E. Application of a 2D hydrodynamic model to design of reach-scale spawning gravel replenishment on the Mokelumne River, California. *River Res. Appl.* **2004**, *20*, 205–225. [CrossRef]
78. Sawyer, A.M.; Pasternack, G.B.; Merz, J.E.; Escobar, M.; Senter, A.E. Construction constraints for geomorphic-unit rehabilitation on regulated gravel-bed rivers. *River Res. Appl.* **2009**, *25*, 416–437. [CrossRef]
79. Wheaton, J.M.; Pasternack, G.B.; Merz, J.E. Spawning habitat rehabilitation-II. Using hypothesis development and testing in design, Mokelumne river, California, USA. *Int. J. River Basin Manag.* **2004**, *2*, 21–37. [CrossRef]
80. Pasternack, G.B. Spawning habitat rehabilitation: Advances in analysis tools. In *Salmonid Spawning Habitat in Rivers: Physical Controls, Biological Responses, and Approaches to Remediation. Symposium 65*; Sear, D.A., DeVries, P., Greig, S., Eds.; American Fisheries Society: Bethesda, MD, USA, 2008; Volume 65, pp. 321–348.
81. Elkins, E.V.; Pasternack, G.B.; Merz, J.E. Use of slope creation for rehabilitating incised, regulated, gravel bed rivers. *Water Resour. Res.* **2007**, *43*, W05432. [CrossRef]
82. Sellheim, K.L.; Watry, C.B.; Rook, B.; Zeug, S.C.; Hannon, J.; Zimmerman, J.; Dove, K.; Merz, J.E. Juvenile salmonid utilization of floodplain rearing habitat after gravel augmentation in a regulated river. *River Res. Appl.* **2016**, *32*, 610–621. [CrossRef]
83. Zeug, S.C.; Sellheim, K.; Watry, C.; Rook, B.; Hannon, J.; Zimmerman, J.; Cox, D.; Merz, J. Gravel augmentation increases spawning utilization by anadromous salmonids: A case study from California, USA. *River Res. Appl.* **2014**, *30*, 707–718. [CrossRef]
84. Crossman, J.A.; Hildebrand, L.R. Evaluation of spawning substrate enhancement for white sturgeon in a regulated river: Effects on larval retention and dispersal. *River Res. Appl.* **2014**, *30*, 1–10. [CrossRef]
85. Utz, R.M.; Mesick, C.F.; Cardinale, B.J.; Dunne, T. How does coarse gravel augmentation affect early-stage Chinook salmon *Oncorhynchus tshawytscha* embryonic survivorship? *J. Fish Biol.* **2013**, *82*, 1484–1496. [CrossRef] [PubMed]
86. Pander, J.; Mueller, M.; Geist, J. A comparison of four stream substratum restoration techniques concerning interstitial conditions and downstream effects. *River Res. Appl.* **2015**, *31*, 239–255. [CrossRef]
87. McManamay, R.A.; Orth, D.J.; Dolloff, C.A.; Cantrell, M.A. Gravel additions as a habitat restoration technique for tailwaters. *N. Am. J. Fish. Manag.* **2011**, *30*, 1238–1257. [CrossRef]
88. Merz, J.; Caldwell, L.; Beakes, M.; Hammersmark, C.; Sellheim, K. Balancing competing life-stage requirements in salmon habitat rehabilitation: Between a rock and a hard place. *Restor. Ecol.* **2018**, *27*, 661–671. [CrossRef]
89. Naito, G. *Lower Whatshan River Fish Habitat Enhancement Physical and Biological Effectiveness Monitoring 2015 (Year 10)*; Naito Environmental: Vernon, BC, Canada, 2016.
90. White, H.C. Atlantic salmon redds and artificial spawning beds. *J. Fish. Res. Board Can.* **1942**, *6*, 37–45. [CrossRef]
91. Meehan, W.R. Effects of gravel cleaning on bottom organisms in three southeast Alaska streams. *Prog. Fish Cult.* **1971**, *33*, 107–111. [CrossRef]
92. Zeigler, E.R. *An Artificially Produced Velocity Barrier for Controlling Fish Movement: Tehama-Colusa Canal*; Bureau of Reclamation Hydraulics Branch: Denver, CO, USA, 1967; p. 33.
93. Andrew, F.J. Gravel cleaning to increase salmon production in rivers and spawning channels. In Proceedings of the Salmon Spawning Gravel: A Renewable Resource in the Pacific Northwest, Seattle, WA, USA, 6–7 October 1980; State of Washington Water Resource Center Washington State University: Pullman, WA, USA, 1981; pp. 15–31.
94. Mih, W.C.; Bailey, G.C. The development of a machine for the restoration of stream gravel for spawning and rearing of salmon. *Fisheries* **1981**, *6*, 16–20.
95. Mih, W.C.; Bailey, G.C. A machine for mitigation of salmonid spawning habitat from silting. In Proceedings of the Mitigation Symposium, Fort Collins, CO, USA, 16–20 July 1979; Rocky Mountain Forest and Range Experiment Station; US Forest Service, and Colorado State University: Fort Collins, CO, USA, 1979; pp. 645–648.
96. Avery, E.L. Evaluations of sediment traps and artificial gravel riffles constructed to improve reproduction of trout in three Wisconsin streams. *N. Am. J. Fish. Manag.* **1996**, *16*, 282–293. [CrossRef]
97. Semple, J.R. *A Simple and Effective Method of Cleaning the Gravel of Atlantic Salmon Spawning Habitat*; Canada Department of Fisheries and Oceans: Halifax, NS, Canada, 1987; p. 13.
98. Mundie, J.H.; Crabtree, D.G. Effects on sediments and biota of cleaning a salmonid spawning channel. *Fish. Manag. Ecol.* **1997**, *4*, 111–126. [CrossRef]

99. Rubin, J.F.; Glimsater, C.G.; Jarvi, T. Characteristics and rehabilitation of the spawning habitats of the sea trout, *Salmo trutta*. *Fish. Ecol. Manag.* **2004**, *11*, 15–22. [CrossRef]
100. Shackle, V.J.; Hughes, S.; Lewis, V.T. The influence of three methods of gravel cleaning on brown trout, *Salmo trutta*, egg survival. *Hydrol. Process.* **1999**, *13*, 477–486. [CrossRef]
101. Dustin, D.L.; Jacobson, P.C. *Evaluation of Walleye Spawning Habitat Improvement Projects in Streams*; Minnesota Department of Natural Resources: St. Paul, MN, USA, 2003.
102. Howson, T.J.; Robson, B.J.; Mitchell, B.D. Patch-specific spawning is linked to restoration of a sediment-disturbed lowland river, south-eastern Australia. *Ecol. Eng.* **2010**, *36*, 920–929. [CrossRef]
103. Pulg, U.; Barlaup, B.T.; Sternecker, K.; Trepl, L.; Unfer, G. Restoration of spawning habitats of Brown Trout (*Salmo trutta*) in a regulated chalk stream. *River Res. Appl.* **2011**, *29*, 172–182. [CrossRef]
104. Sternecker, K.; Wild, R.; Geist, J. Effects of substratum restoration on salmonid habitat quality in a subalpine stream. *Environ. Biol. Fishes* **2013**, *96*, 1341–1351. [CrossRef]
105. Mueller, M.; Pander, J.; Geist, J. The ecological value of stream restoration measures: An evaluation on ecosystem and target species scales. *Ecol. Eng.* **2014**, *62*, 129–139. [CrossRef]
106. Sepulveda, A.J.; Sechrist, J.; Marczak, L.B. Testing ecological tradeoffs of a new tool for removing fine sediment in a spring-fed stream. *Ecol. Restor.* **2014**, *32*, 68–77. [CrossRef]
107. Ramezani, J.; Rennebeck, L.; Closs, G.P.; Matthaei, C.D. Effects of fine sediment addition and removal on stream invertebrates and fish: A reach-scale experiment. *Freshw. Biol.* **2014**, *59*, 2584–2604. [CrossRef]
108. Sepulveda, A.J.; Layhee, M.; Sutphin, Z.A.; Sechrist, J.D. Evaluation of a fine sediment removal tool in a spring fed and snowmelt driven streams. *Ecol. Restor.* **2015**, *33*, 303–315. [CrossRef]
109. Matthys, T. Estimating Fish Habitat Selection and Monitoring Stream Habitat Quality Requires More Than Simply Counting Fish. Ph.D. Dissertation, Michigan Technological University, Houghton, MI, USA, 2017.
110. Basic, T.; Britton, J.R.; Rice, S.P.; Pledger, A.G. Impacts of gravel jetting on the composition of fish spawning substrates; Implications for river restoration and fisheries management. *Ecol. Eng.* **2017**, *107*, 71–81. [CrossRef]
111. NHC (Northwest Hydraulic). *2016 Spawning Substrate Restoration on the Nechako River at Vanderhoof, BC*; Prepared for Ministry of Forest, Lands and Natural Resource Operation: Prince George, BC, Canada, 2016; p. 35.
112. Kondolf, G.M. Assessing salmonid spawning gravel quality. *Trans. Am. Fish. Soc.* **2000**, *129*, 262–281. [CrossRef]
113. Wheaton, J.M.; Pasternack, G.B.; Merz, J. Spawning habitat rehabilitation—I. conceptual approach and methods. *Int. J. River Basin Manag.* **2004**, *2*, 3–20. [CrossRef]
114. Argent, D.G.; Flebbe, P.A. Fine sediment effects on brook trout eggs in laboratory streams. *Fish. Res.* **1999**, *39*, 253–262. [CrossRef]
115. Fudge, R.J.P.; Bodaly, R.A. Postimpoundment winter sedimentation and survival of lake whitefish (*Coregonus clupeaformis*) eggs in Southern Indian Lake, Manitoba. *Can. J. Fish. Aquat. Sci.* **1984**, *41*, 701–705. [CrossRef]
116. Kock, T.J.; Congleton, J.L.; Anders, P.J. Effects of sediment cover on survival and development of white sturgeon embryos. *N. Am. J. Fish. Manag.* **2006**, *26*, 134–141. [CrossRef]
117. Turnpenny, A.W.H.; Williams, R. Effects of sedimentation on the gravels of an industrial river system. *J. Fish Biol.* **1980**, *17*, 681–693. [CrossRef]
118. Einum, S.; Hendry, A.P.; Fleming, I.A. Egg-size evolution in aquatic environments: Does oxygen availability constrain size? *Proc. R. Soc. Lond. B Biol. Sci.* **2002**, *269*, 2325–2330. [CrossRef] [PubMed]
119. Saldi-Caromile, K.; Bates, K.; Skidmore, P.; Barenti, J.; Pineo, D.L. *Stream Habitat Restoration Guidelines: Final Draft*; Co-published by the Washington Departments of Fish and Wildlife and Ecology and the U.S. Fish and Wildlife Service: Olympia, WA, USA, 2004.
120. Trombulak, S.C.; Frissell, C.A. Review of ecological effects of roads on terrestrial and aquatic communities. *Conserv. Biol.* **2000**, *14*, 18–30. [CrossRef]
121. Richardson, T.W. *Agitation Dredging: Lessons and Guidelines from Past Projects*; US Army Corps of Engineers: Vicksburg, MS, USA, 1984; p. 145.
122. Sullivan, N. The use of agitation dredging, water injection dredging and sidecasting: Results of a survey of ports in England and Wales. *Terra Aqua* **2000**, *78*, 11–20.
123. Peterson, S.A. Lake restoration by sediment removal. *J. Am. Water Resour. Assoc.* **1982**, *18*, 423–436. [CrossRef]

124. Baker, E.; Milburn, T.; Hugh, B.; Tennant, D.A. Field assessment of sediment trap efficiency under varying flow conditions. *J. Mar. Res.* **1988**, *46*, 573–592. [CrossRef]
125. Gardner, W.D. Field assessment of sediment traps. *J. Mar. Res.* **1980**, *38*, 41–52.
126. Parchure, T.M.; Teeter, A.M. *Lessons Learned from Existing Projects on Shoaling in Harbors and Navigation Channels*; US Army Corps of Engineers: Vicksburg, MS, USA, 2003.
127. Herdendorf, C.E. Physical and limnological characteristics of natural spawning reefs in western Lake Erie. In *Artificial Reefs Marine and Freshwater Applications*; D'itri, F., Ed.; Lewis Publishers, Inc.: Chelsea, MI, USA, 1985; pp. 149–183.
128. Brooks, C.; Grimm, A.; Shuchman, R.; Sayers, M.; Jessee, N. A satellite-based multi-temporal assessment of the extent of nuisance *Cladophora* and related submerged aquatic vegetation for the Laurentian Great Lakes. *Remote Sens. Environ.* **2015**, *157*, 58–71. [CrossRef]
129. Redman, R.; Mackey, S.; Dub, J.; Czesny, S. Lake trout spawning habitat suitability at two offshore reefs in Illinois waters of Lake Michigan. *J. Gt. Lakes Res.* **2017**, *43*, 335–344. [CrossRef]
130. Janssen, J.; Berg, M.B.; Lozano, S.J. Submerged terra incognita: Lake Michigan's abundant but unknown rocky zones. *State Lake Mich. Ecol. Health Manag. Ecovision World Monogr. Ser.* **2005**, 113–139.
131. Auer, M.T.; Tomlinson, L.M.; Higgins, S.N.; Malkin, S.Y.; Howell, E.T.; Bootsma, H.A. Great Lakes *Cladophora* in the 21st century: Same algae—Different ecosystem. *J. Gt. Lakes Res.* **2010**, *36*, 248–255. [CrossRef]
132. Blanco, S.; Ector, L. Distribution, ecology and nuisance effects of the freshwater invasive diatom *Didymosphenia geminata* (Lyngbye) M. Schmidt: A literature review. *Nova Hedwig.* **2009**, *88*, 347–422. [CrossRef]
133. Dorr, J.A., III; O'Connor, D.V.; Foster, N.R.; Jude, D.J. Substrate conditions and abundance of lake trout eggs in a traditional spawning area in southeastern Lake Michigan. *N. Am. J. Fish. Manag.* **1981**, *1*, 165–172. [CrossRef]
134. Tucker, S. Lake Sturgeon Spawning Behavior, Larval Production and Juvenile Habitat Use Within The Lower Fox River, Wisconsin. Master's Thesis, University of Wisconsin-Green Bay, Green Bay, WI, USA, 2020.
135. Da Silva, S.; Taillon, K.; McChristie, M.; Chase, M.; Berglund, E. *Nipigon Bay Remedial Action Plan Report Recommending Delisting and Path Forward*; North Shore of Lake Superior Remedial Action Plans: Toronto, ON, Canada, 2015; p. 80.
136. Parsley, M.J.; Kofoot, E. *Effects of Incubation Substrates on Hatch Timing and Success of White Sturgeon (Acipenser transmontanus) Embryos*; US Department of the Interior, US Geological Survey: Reston, VA, USA, 2013; p. 16.
137. Tyner, E.H. Nearshore Benthic Oxygen Dynamics in Lake Michigan. Master's Thesis, University of Wisconsin-Milwaukee, Milwaukee, WI, USA, 2013.
138. Jellyman, P.G.; Clearwater, S.J.; Clayton, J.S.; Kilroy, C.; Hickey, C.W.; Blair, N.; Biggs, B.J.F. Rapid screening of multiple compounds for control of the invasive diatom *Didymosphenia geminata*. *J. Aquat. Plant Manag.* **2010**, *48*, 63.
139. Klauda, R.J.; Hanna, K.V. *Didymosphenia Geminata Infestation in Maryland: Reactions and Responses by the Maryland Department of Natural Resources*; Maryland Department of Natural Resources Resource Assessment Service Monitoring and Non-tidal Assessment Division: Annapolis, MD, USA, 2016; p. 36.
140. McCuaig, L.M.; Martyniuk, C.J.; Marlatt, V.L. Morphometric and proteomic responses of early-life stage rainbow trout (*Oncorhynchus mykiss*) to the aquatic herbicide diquat dibromide. *Aquat. Toxicol.* **2020**, *222*, 105446. [CrossRef]
141. Sesin, V.; Dalton, R.L.; Boutin, C.; Robinson, S.A.; Bartlett, A.J.; Pick, F.R. Macrophytes are highly sensitive to the herbicide diquat dibromide in test systems of varying complexity. *Ecotoxicol. Environ. Saf.* **2018**, *165*, 325–333. [CrossRef] [PubMed]
142. Thomas, C.B. Survival and Growth Responses of *Lithobates Pipiens* Tadpoles to an Herbicide and an Algaecide used to Control Aquatic Invasive Plants. Ph.D. Thesis, Bowling Green State University, Bowling Green, OH, USA, 2015.
143. Clearwater, S.J.; Jellyman, P.G.; Biggs, B.J.F.; Hickey, C.W.; Blair, N.; Clayton, J.S. Pulse-dose application of chelated copper to a river for *Didymosphenia geminata* control: Effects on macroinvertebrates and fish. *Environ. Toxicol. Chem.* **2011**, *30*, 181–195. [CrossRef] [PubMed]
144. Boylan, J.D.; Morris, J.E. Limited effects of barley straw on algae and zooplankton in a midwestern pond. *Lake Reserv. Manag.* **2003**, *19*, 265–271. [CrossRef]

145. Peller, J.R.; Whitman, R.L.; Griffith, S.; Harris, P.; Peller, C.; Scalzitti, J. TiO_2 as a photocatalyst for control of the aquatic invasive alga, *Cladophora*, under natural and artificial light. *J. Photochem. Photobiol. Chem.* **2007**, *186*, 212–217. [CrossRef]
146. Elwell, L.C.; Gillis, C.-A.; Kunza, L.A.; Modley, M.D. Management challenges of *Didymosphenia geminata*. *Diatom Res.* **2014**, *29*, 303–305. [CrossRef]
147. Root, S.; O'Reilly, C.M. Didymo control: Increasing the effectiveness of decontamination strategies and reducing spread. *Fisheries* **2012**, *37*, 440–448. [CrossRef]
148. Nalepa, T.F. An overview of the spread, distribution, and ecological impacts of the quagga mussel, Dreissena rostriformis bugensis, with possible implications to the Colorado River system. In Proceedings of the Colorado River Basin Science and Resource Management Symposium. Coming Together, Coordination of Science and Restoration Activities for the Colorado River Ecosystem, Scottsdale, AZ, USA, 18–20 November 2008; U.S. Geological Survey: Reston, VA, USA, 2010; p. 372.
149. Furgal, S.; Lantry, B.F.; Weidel, B.C.; Farrell, J.M.; Gorsky, D.; Biesinger, Z. *Lake Trout Spawning and Habitat Assessment at Stony Island Reef*; New York State Department of Environmental Conservation (NYSDEC): Albany, NY, USA, 2018.
150. Kelch, D.O.; Snyder, F.L.; Reutter, J.M. Artificial reefs in Lake Erie: Biological impacts of habitat alteration. In *Fish Habitat: Essential Fish Habitat and Rehabilitation*; Benaka, L.R., Ed.; American Fisheries Society: Bethesda, MD, USA, 1999; Volume 22, pp. 335–347.
151. Hecky, R.E.; Smith, R.E.H.; Barton, D.R.; Guildford, S.J.; Taylor, W.D.; Charlton, M.N.; Howell, T. The nearshore phosphorus shunt: A consequence of ecosystem engineering by dreissenids in the Laurentian Great Lakes. *Can. J. Fish. Aquat. Sci.* **2004**, *61*, 1285–1293. [CrossRef]
152. Eschweiler, N.; Christensen, H.T. Trade-off between increased survival and reduced growth for blue mussels living on Pacific oyster reefs. *J. Exp. Mar. Biol. Ecol.* **2011**, *403*, 90–95. [CrossRef]
153. Norling, P.; Lindegarth, M.; Lindegarth, S.; Strand, Å. Effects of live and post-mortem shell structures of invasive Pacific oysters and native blue mussels on macrofauna and fish. *Mar. Ecol. Prog. Ser.* **2015**, *518*, 123–138. [CrossRef]
154. Eshenroder, R.L.; Peck, J.W.; Olver, C.H. *Research Priorities for Lake Trout Rehabilitation in the Great Lakes: A 15-Year Retrospective*; Great Lakes Fishery Commission: Ann Arbor, MI, USA, 1999; Volume 64, pp. 1–40.
155. Glon, M.G.; Larson, E.R.; Reisinger, L.S.; Pangle, K.L. Invasive dreissenid mussels benefit invasive crayfish but not native crayfish in the Laurentian Great Lakes. *J. Gt. Lakes Res.* **2017**, *43*, 289–297. [CrossRef]
156. Levin, P.S.; Coyer, J.A.; Petrik, R.; Good, T.P. Community wide effects of nonindigenous species on temperate rocky reefs. *Ecology* **2002**, *83*, 3182–3193. [CrossRef]
157. LaFrancois, B.; Bootsma, H. *Manual Removal of Invasive Mussels: A Case Study from Sleeping Bear Dunes, Lake Michigan*; National Park Service: Porter, IN, USA, 2018.
158. Fitzsimons, J.D.; Leach, J.H.; Nepszy, S.J.; Cairns, V.W. Impacts of zebra mussel on walleye (*Stizostedion vitreum*) reproduction in western Lake Erie. *Can. J. Fish. Aquat. Sci.* **1995**, *52*, 578–586. [CrossRef]
159. Muir, A.M.; Blackie, C.T.; Marsden, J.E.; Krueger, C.C. Lake charr *Salvelinus namaycush* spawning behaviour: New field observations and a review of current knowledge. *Rev. Fish Biol. Fish.* **2012**, *22*, 575–593. [CrossRef]
160. Muir, A.M.; Krueger, C.C.; Hansen, M.J. Re-establishing lake trout in the Laurentian Great Lakes: Past, present, and future. In *Great Lakes Fishery Policy and Management: A Binational Perspective*, 2nd ed.; Michigan State University Press: East Lansing, MI, USA, 2012; pp. 533–588.
161. Hargrave, J.; Jensen, D. *Assessment of the Water Quality Conditions at ed Zorinsky Reservoir and the Zebra Mussel (Dreissena Polymorpha) Population Emerged after the Drawdown of the Reservoir and Management Implications for the District's Papillion and Salt Creek Reservoirs*; U.S. Army Corps of Engineers: Omaha, NE, USA, 2012.
162. Grazio, J.L.; Montz, G. Winter lake drawdown as a strategy for zebra mussel (*Dreissena polymorpha*) control: Results of pilot studies in Minnesota and Pennsylvania. In Proceedings of the 11th International Conference on Aquatic Invasive Species, Alexandria, VA, USA, 25 February–1 March 2002; pp. 207–217.
163. Whitledge, G.W.; Weber, M.M.; DeMartini, J.; Oldenburg, J.; Roberts, D.; Link, C.; Rackl, S.M.; Rude, N.; Yung, A.; Bock, L.R.; et al. An evaluation Zequanox efficacy and application strategies for targeted control of zebra mussels in shallow-water habitats in lakes. *Manag. Biol. Invasions* **2015**, *6*, 71–82. [CrossRef]
164. Crank, K.M.; Barnes, M.E. Zebra mussel veliger chemical control treatments do not impact rainbow trout eyed egg survival. *Int. J. Innov. Stud. Aquat. Biol. Fish.* **2017**, *3*, 15–17.

165. Hillard, S.; Huysman, N.; Barnes, M.E. Impacts of zebra mussel veliger control treatments on the survival of water-hardened landlocked fall chinook salmon eggs. *Nat. Resour.* **2019**, *10*, 115–120. [CrossRef]
166. Edwards, W.J.; Babcock-Jackson, L.; Culver, D.A. Field testing of protocols to prevent the spread of zebra mussels *Dreissena polymorpha* during fish hatchery and aquaculture activities. *N. Am. J. Aquac.* **2002**, *64*, 220–223. [CrossRef]
167. Wimbush, J.; Frischer, M.E.; Zarzynski, J.W.; Nierzwicki-Bauer, S.A. Eradication of colonizing populations of zebra mussels (*Dreissena polymorpha*) by early detection and SCUBA removal: Lake George, NY. *Aquat. Conserv. Mar. Freshw. Ecosyst.* **2009**, *19*, 703–713. [CrossRef]
168. Claudi, R.; Mackie, G.L. *Practical Manual for Zebra Mussel Monitoring and Control*; Lewis Publishers, CRC: Boca Raton, FL, USA, 1994.
169. Wong, W.H.; Gerstenberger, S.; Watters, A. *Using Pressurized Hot Water Spray to Kill and Remove Dreissenid Mussels on Watercraft: Field Testing on the Efficacy of Water Temperature, High Pressure, and Duration of Exposure*; US Fish and Wildlife Service: Washington, DC, USA, 2014; p. 20.
170. Culver, C.; Lahr, H.; Johnson, L.; Cassell, J. *Quagga and Zebra Mussel Eradication and Control Tactics*; University of California: Oakland, CA, USA, 2013.
171. Waller, D.L.; Bartsch, M.R. Use of carbon dioxide in zebra mussel (*Dreissena polymorpha*) control and safety to a native freshwater mussel (Fatmucket, *Lampsilis siliquoidea*). *Manag. Biol. Invasions* **2018**, *9*, 439–450. [CrossRef]
172. Cook, G.D. Marine Excavation. *Encycl. Archaeol. Sci.* **2018**, 1–4. [CrossRef]
173. Goggin, J.M. Underwater archeology: Its nature and limitations. *Am. Antiq.* **1960**, *25*, 348–354. [CrossRef]
174. Viduka, A.J. Unit 10: Intrusive techniques in underwater archaeology. In *Training Manual for the UNESCO Foundation Course on the Protection and Management of Underwater Cultural Heritage in Asia and the Pacific*; UNESCO Bangkok: Bangkok, Thailand, 2012; p. 29.
175. Bass, G.F.; Hope-Simpson, R. Archaeologists, sports divers, and treasure-hunters. *J. Field Archaeol.* **1985**, *12*, 256–260. [CrossRef]
176. Liou, Y.C.; Herbich, J.B. *Sediment Movement Induced by Ships in Restricted Waterways*; Texas A&M University: College Station, TX, USA, 1976.
177. Wang, P.; Rivera-Duarte, I.; Richter, K.; Liao, Q.; Farley, K.; Chen, H.-C.; Germano, J.; Markillie, K.; Gailani, J. *Evaluation of Resuspension from Propeller Wash in DoD Harbors, Project ER-201031*; SSC Pacific: San Diego, CA, USA, 2016; p. 325.
178. Wood, P.J. Biological effects of fine sediment in the lotic environment. *Environ. Manag.* **1997**, *21*, 203–217. [CrossRef] [PubMed]
179. Mouton, A.M.; Buysse, D.; Stevens, M.; Neucker, T.; Coeck, J. Evaluation of riparian habitat restoration in a lowland river. *River Res. Appl.* **2012**, *28*, 845–857. [CrossRef]
180. Kailing, P.J.; Tucker, R.L. An innovative device for stream bedload sediment removal and measurement. In Proceedings of the Seventh Federal Interagency Sedimentation Conference, Reno, NV, USA, 25–29 March 2001; pp. 34–40.
181. Lipscomb, C.M.; Darrow, A.; Thornton, C.I. *Removal Efficiency Testing of Streamside Systems' Bedload Monitoring Collector*; Engineering Research Center, Colorado State University: Fort Collins, CO, USA, 2005; p. 87.
182. Thomas, R.C.; McArthur, J.; Braatz, D.; Welp, T. *Sediment Management Methods to Reduce Dredging: Part 2, Sediment Collector Technology*; US Army Engineer Research and Development Center: Vicksburg, MS, USA, 2017; p. 11.
183. Geiling, D. Construction of self-cleaning substrate. In *Methods of Modifying Habitat to Benefit the Great Lakes Ecosystem. CISTI (Canada Institute for Scientific and Technical Information) Occasional Paper No. 1*; Kelso, J.R.M., Hartig, J.H., Eds.; National Research Council of Canada: Ottawa, ON, Canada, 1995; pp. 32–38.
184. Sayce, C.S.; Larson, C.C. Willapa oyster studies—Use of the pasture harrow for the cultivation of oysters. Comm. *Commer. Fish. Rev.* **1966**, *28*, 21–26.
185. MacKenzie, C.L. Development of an aquacultural program for rehabilitation of damaged oyster reefs in Mississippi. *Mar. Fish. Rev.* **1977**, *39*, 1–13.
186. Perret, W.S.; Dugas, R.; Roussel, J.; Wilson, C.A.; Supan, J. Oyster Habitat Restoration: A Response to Hurricane Andrew. In *Oyster Reef Habitat Restoration: A Synopsis and Synthesis of Approaches; Proceedings from the Symposium, Williamsburg, Virginia, April 1995*; Luckenbach, M.W., Wesson, J.A., Eds.; Virginia Institute of Marine Science, College of William and Mary: Gloucester Point, VA, USA, 1999; pp. 93–99.

187. Wesson, J.; Mann, R.; Luckenbach, M.W. Oyster Restoration Efforts in Virginia. In *Oyster Reef Habitat Restoration: A Synopsis and Synthesis of Approaches; Proceedings from the Symposium, Williamsburg, Virginia, April 1995*; Luckenbach, M.W., Wesson, J.A., Eds.; Virginia Institute of Marine Science, College of William and Mary: Gloucester Point, VA, USA, 1999; pp. 117–129.
188. Binkowski, F.P. Utilization of artificial reefs in the inshore areas of Lake Michigan. In *Artificial Reefs: Marine and Freshwater Applications*; D'itri, F., Ed.; Lewis Publishers, Inc.: Chelsea, MI, USA, 1985; pp. 349–362.
189. Kevern, N.R.; Biener, W.E.; VanDerLann, S.; Cornelius, S.D. Preliminary evaluation of an artificial reef as a fishery management strategy in Lake Michigan. In *Artificial Reefs: Marine and Freshwater Applications*; D'itri, F., Ed.; Lewis Publishers, Inc.: Chelsea, MI, USA, 1985; pp. 443–458.
190. Environnement Illimité Inc. *Investigation of Lake Sturgeon Spawning Activities at Xxxxxxxxxxxx on the St. Lawrence River in 2008—Final Report*; White Plains: New York, NY, USA, 2009; p. 33.
191. Peck, J.W. Dynamics of reproduction by hatchery lake trout on a man-made spawning reef. *J. Gt. Lakes Res.* **1986**, *12*, 293–303. [CrossRef]
192. Kim, C.G.; Kim, H.S. Post-placement management of artificial reefs in Korea. *Fisheries* **2008**, *33*, 61–68. [CrossRef]
193. Yoon, H.S.; Dongha, K.; Na, W. Estimation of effective usable and burial volumes of artificial reefs and the prediction of cost effective management. *Ocean Coast. Manag.* **2016**, *120*, 135–147. [CrossRef]
194. Sheng, Y.P. Physical characteristics and engineering at reef sites. In *Artificial Reef Evaluation with Application to Natural Marine Habitats*; CRC Press: Boca Raton, FL, USA, 2000; pp. 51–94.
195. Mumby, P.J.; Harborne, A.R.; Raines, P.S.; Ridley, J.M. A critical assessment of data derived from Coral Cay Conservation volunteers. *Bull. Mar. Sci.* **1995**, *56*, 737–751.
196. Toft, J.D.; Ogston, A.S.; Heerhartz, S.M.; Cordell, J.R.; Flemer, E.E. Ecological response and physical stability of habitat enhancements along an urban armored shoreline. *Ecol. Eng.* **2013**, *57*, 97–108. [CrossRef]
197. Collier, J.S.; Brown, C.J. Correlation of sidescan backscatter with grain size distribution of surficial seabed sediments. *Mar. Geol.* **2005**, *214*, 431–449. [CrossRef]
198. Dumont, P.; D'Amours, J.; Thibodeau, S.; Dubuc, N.; Verdon, R.; Garceau, S.; Bilodeau, P.; Mailhot, Y.; Fortin, R. Effects of the development of a newly created spawning ground in the Des Prairies River (Quebec, Canada) on the reproductive success of lake sturgeon (*Acipenser fulvescens*). *J. Appl. Ichthyol.* **2011**, *27*, 394–404. [CrossRef]
199. Foster, N.R.; Kennedy, G.W. Patterns of egg deposition by lake trout and lake whitefish at Tawas artificial reef, Lake Huron, 1990-1993. In *The Lake Huron Ecosystem: Ecology, Fisheries, and Management*; Leach, J.H., Edsall, T.A., Munawar, M., Eds.; SPB Academic Publishing: Amsterdam, The Netherlands, 1995; pp. 191–206.
200. Diegues, A.; Pinto, J.; Ribeiro, P.; Frias, R. Others Automatic habitat mapping using convolutional neural networks. In Proceedings of the 2018 IEEE OES Autonomous Underwater Vehicle Symposium, Porto, Portugal, 6–9 November 2018; pp. 1–6.
201. Bonin-Font, F.; Burguera, A.; Lisani, J.-L. Visual discrimination and large area mapping of *Posidonia oceanica* using a lightweight AUV. *IEEE Access* **2017**, *5*, 24479–24494. [CrossRef]
202. Brown, C.J.; Smith, S.J.; Lawton, P.; Anderson, J.T. Benthic habitat mapping: A review of progress towards improved understanding of the spatial ecology of the seafloor using acoustic techniques. *Estuar. Coast. Shelf Sci.* **2011**, *92*, 502–520. [CrossRef]
203. Kaeser, A.J.; Litts, T.L. A novel technique for mapping habitat in navigable streams using low-cost side scan sonar. *Fisheries* **2010**, *35*, 163–174. [CrossRef]
204. Katz, S.; Barnas, K.; Hicks, R.; Cowen, J.; Jenkinson, R. Freshwater Habitat Restoration Actions in the. Pacific Northwest: A Decade's Investment in Habitat Improvement. *Restor. Ecol.* **2007**, *15*, 494–505. [CrossRef]
205. Jensen, A.; Ken, C.; Peter, L. Current issues relating to artificial reefs in European seas. In *Artificial Reefs in European Seas*; Springer: Berlin, Germany, 2000; pp. 489–499.



© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).