Single-Stream Recycling Inspires Selective Fish Passage Solutions for the Connectivity Conundrum in Aquatic Ecosystems

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Barrier removal is a recognized solution for reversing river fragmentation, but restoring connectivity can have consequences for both desirable and undesirable species, resulting in a connectivity conundrum. Selectively passing desirable taxa while restricting the dispersal of undesirable taxa (selective connectivity) would solve many aspects of the connectivity conundrum. Selective connectivity is a technical challenge of sorting an assortment of things. Multiattribute sorting systems exist in other fields, although none have yet been devised for freely moving organisms within a river. We describe an approach to selective fish passage that integrates ecology and biology with engineering designs modeled after material recycling processes that mirror the stages of fish passage: approach, entry, passage, and fate. A key feature of this concept is the integration of multiple sorting processes each targeting a specific attribute. Leveraging concepts from other sectors to improve river ecosystem function may yield fast, reliable solutions to the connectivity conundrum.

Keywords: selective connectivity, connectivity conundrum, fish passage, barriers, invasive fish management

Centuries of road construction and waterways engineering have resulted in a network of barriers that fragment freshwater ecosystems worldwide (Nilsson et al. 2005, Liermann et al. 2012). Nearly 60% of all global rivers (1293 river basins) contain at least one large dam (Grill et al. 2015). Fragmentation impairs animal movements and ecosystem processes that society depends on for many forms of economic activity (Foley et al. 2005, Shepard et al. 2008, McRae et al. 2012, Woodroffe et al. 2014, Jakes et al. 2018, Pekor et al. 2019). Barrier removal is the most recognizable solution for reversing the fragmentation of aquatic ecosystems (McRae et al. 2012), but restoring connectivity is not always straightforward. Restoring connectivity can have consequences for both desirable and undesirable species (McLaughlin et al. 2013, Rahel 2013) that affect ecological and human economic activity in unintentional ways. Restoration of ecological connectivity (Ward and Stanford 1995, Pringle 2003, Berger et al. 2010) therefore presents a conundrum. In watersheds that face the risk of invasion from nonnative species or deleterious impacts of co-occurring species on an endangered population, the term *connectivity conundrum* refers to the tension between improving

passage for desirable species while decreasing or eliminating passage by invasive or undesirable species (Fausch et al. 2009). We seek to break conceptually and technologically from past approaches to reconnect the waterscape only for desired (usually native) species.

Selectively passing desirable taxa beyond barriers while restricting the movement of undesirable taxa (selective connectivity) could provide a solution to the connectivity conundrum in fragmented systems managed primarily to support human society. The concept of selective connectivity aligns with the societal push for dam removal (Foley et al. 2017) that has heightened tensions between barrier removal for rehabilitation and barrier retention for controlling invasive species (Novinger and Rahel 2003, McLaughlin et al. 2013, Starrs et al. 2017, Zielinski et al. 2019). Although the idealized condition of fully selective connectivity may not exist in natural ecosystems and may be challenging to attain, even partial fulfillment of the goal can significantly enhance ecosystem function (Pratt et al. 2009, Gates et al. 2012). Partial connectivity is already employed in terrestrial wildlife management using fence gaps to permit movement along migration corridors while still segregating animals

from people (Dupuis-Désormeaux et al. 2016). Because of the ubiquity of fragmented ecosystems and large numbers of organisms requiring movement among habitats to complete their lifecycles, restoration efforts raise a few immediate questions: How are species determined to be desirable versus undesirable for passage? And where on the spectrum of complete connectivity versus complete blockage are the most positive outcomes achieved? Ascribing values to certain species and identifying desired outcomes require an understanding of the ecology and biology of the animals, local and regional economic activity, social and cultural trends, and likely responses of the ecosystem to environmental change.

The challenge of selective fish passage is fundamentally one of sorting an assortment of things. Sorting a stream of objects with variable attributes is not unique to fish passage. Attribute-based sorting technologies have been successfully developed in other industries, such as material recycling. The processes and innovations developed by the materials recycling sector provides useful guidance and lessons learned for the development and implementation of new and existing techniques and technologies to achieve selective fish passage. In single-stream material recycling, a stream of mixed products is collected and passed through a network of technologies that sort each material according to its attributes (Stessel 1996). The process is often recursive in that outgoing material streams may be sorted iteratively until a required purity is obtained. Material recycling is successful, in part, because of the application of unit processes, a single operation or group of operations that achieves simple sorting tasks. Unit processes help reduce the overall complexity of the sorting process by isolating individual sorting tasks, each targeted on individual attributes of the materials within the stream. Targeting single attributes makes sorting processes easier to optimize and reconfigure. In the present article, we provide the rationale and theory for selective fish passage based on lessons borrowed from the recycling industry.

The implementation of single-stream recycling principles to fish passage differs from material recycling in several ways. The biggest difference is that fish have agency; that is, the objects make their own choices. The probability of a fish passing through a fishway is dependent on its internal state and the environmental stimuli. Such complexity has made fish passage a challenging problem. Although fish decision-making abilities introduce complexity to the sorting operations, they also provide an opportunity to exploit behavioral tendencies and abilities to achieve selective sorting; that is, the fish's behavior can be used to develop opportunities in which the individuals sort themselves.

Porting single-stream recycling processes and innovations to selective fish passage requires an approach that mimics eco design (Pioch et al. 2018). Understanding the ecology and biology of targeted fishes and ecosystem must be integrated with engineering designs. To outline our vision of how single-stream recycling principles can achieve selective connectivity in managed ecosystems, we

first synthesize the historical use of single-factor methods to block or remove undesirable fishes as well as pass desirable species. Furthermore, we highlight where past methods have succeeded and failed and reason how our approach could yield improved results. Second, we outline the single-stream recycling process and its analogy to fish passage as an integrated concept for developing selective connectivity. Finally, we lay out expectations for the efficiency and application of selective connectivity for fisheries management. The management of invasive species in the context of enhanced connectivity for habitat and fishery restoration is a global issue—the connectivity conundrum—for which our vision of selective connectivity could provide a solution.

Historical use of single-factor methods to achieve selective fish passage

Fish blockage, guidance, and passage methods are generally focused on a single physiological, morphological, phenological, or behavioral attribute for a single species or group of similar species (table 1). The technologies include physical impediments or catalysts to movement and environmental stimuli altered to guide, facilitate, or deter passage. The available technologies for blockage, guidance, and passage also range from permanent to temporary and operate on time scales ranging from individual encounters to annual deployments. Below, we provide examples of the most commonly deployed technologies for fish blockage, guidance, and passage and highlight some key limitations (figure 1).

Barriers that intentionally block fish passage are common tools used to control invasive fish. The fixed-crest barrier is one of the most prevalent and effective physical impediments to invasive fish passage used around the world to block invasive species such as sea lamprey (*Petromyzon marinus*; Zielinski et al. 2019), European perch (*Perca fluviatilis*; Starrs et al. 2017), goldfish (*Carassius auratus*; Morán-López and Tolosa 2017), and rainbow trout (*Oncorhynchus mykiss*; Novinger and Rahel 2003). Although fixed-crest barriers can be designed to exploit interspecific differences in fish locomotion, they often impede passage of nonnative species with overlapping locomotor attributes (McLaughlin et al. 2013).

Fish guidance technologies are ideal for applications where the goal is to guide individuals toward or away from a specific location without impeding flow or navigation. Popper and Carlson (1998) and Schilt (2007) provide detailed histories on the development and theory of many fish guidance systems. The most prevalent guidance stimulus is pulsed direct current voltage, which has been shown to block up to 99% and guide up to 75% of adult invasive sea lamprey and common carp (*Cyprinus carpio*) into traps (Johnson et al. 2014, 2016, Bajer et al. 2018). Unfortunately, these electrical systems are not species specific. Systems targeting physiological differences in fish (e.g., sound) have greater potential for species specificity. Acoustic deterrents (figure 1a), sometimes paired with air bubbles or strobe lights, have been shown to be 42%–99% effective at guiding

Table 1. Summary of single-factor fish passage, guidance, and blockage technologies.

Attribute category	Fish attribute	Technology	Description	Examples
Physiological	Jumping	Fixed-crest barrier	Blocks passage of fishes with limited leaping ability or propensity to leap.	Zielinski et al. (2019) Starrs et al. (2017) Morán-López and Tolosa (2017) Novinger and Rahel (2003)
		Williams-Trap	Mechanical trap that selectively captures common carp *Cyprinus carpio* based on jumping behavior at barriers.	Stuart and Conallin (2018) Stuart et al. (2006)
	Swimming	Velocity barrier	Generate velocities that some or all fish cannot overcome.	Castro-Santos (2005)
		Technical fishways	Series of pools, slots, or baffles that control velocities and water levels to permit volitional fish passage.	Bunt and Castro-Santos (2012), Bunt et al. (2016) Katopodis and Williams (2012)
		Louvers	Vertical slats that create local velocity fields that prevent impingement and fish can avoid.	Scruton et al. (2003)
		Turbulence plumes	Induced turbulence to attract or deter fish passage.	Coutant (2001)
	Climbing	Eel style ladder	Inclined channel with pegs or studs spaced that anguilliform fishes can climb.	Reinhardt and Hrodey (2019)
		Bristle pass	Inclined channel with bristles that anguilliform fishes can climb.	Kerr et al. (2015)
		Inclined ramp	Wetted surface designed to promote lamprey attachment for passage or discourage lamprey attachment for blockage.	Reinhardt et al. (2008) Sherburne and Reinhardt (2016)
Morphology	Size	Screens	Openings in a mesh or spacing between bars that restrict fish passage.	French et al. (1999)
	Shape color	Image capture	Human- or computer-based visual recognition of targeted species.	Garavelli et al. (2019)
Phenology	Diel or seasonal movement	Seasonal barrier	Block or provide passage on the basis of movement timing of targeted species.	Vélez-Espino et al. (2011) Klingler et al. (2003) Taylor et al. (2012)
Behavioral	Tactical	Direct current (DC) voltage	Submerged electrodes create an electrical field that immobilizes or deters fish passage.	Johnson et al. (2014, 2016) Bajer et al. (2018)
	Visual	Lights	Fish are attracted or deterred by continuous or strobe lights.	Popper and Carlson (1998)
	Auditory	Sound projector	Some fish avoid propagating sound pressure waves and the associated acoustic particle motion field.	Dennis et al. (2019) Gurshin et al. (2014) Zielinski and Sorensen (2017)
	Multisensory	Sound projector and air bubbles	Air bubbles augment sound propagation to enhance fish guidance.	Dennis et al. (2019) Welton et al. (2002) Perry et al. (2014) Zielinski and Sorensen (2016)
	Chemical	CO_2	Fish avoid regions of increased CO_2 concentrations and reduced pH.	Kates et al. (2012) Cupp et al. (2017)
	Olfaction	Pheromones	Natural odorants that attract fish.	Hume et al. (2015)
		Alarm cues	Natural odorants that repel fish.	Wagner et al. (2011)

passage of a wide range of species including Atlantic salmon smolt (*Salmo salar*; Welton et al. 2002), juvenile Chinook salmon (*Oncorhynchus tshawytscha*; Perry et al. 2014), blueback herring (*Alosa aestivalis*; Gurshin et al. 2014), and bigheaded carp (*Hypopthalmichtys* spp.) and common carp (Zielinski and Sorensen 2016, 2017, Dennis et al. 2019). Despite the large number of stimuli that have been investigated (table 1), the efficacy of single-factor barrier or guidance technologies for blocking or removing invasive fishes is generally less than 100% (Rahel and McLaughlin 2018).

Technical (e.g., vertical slot, pool and weir, Denil) and nature-like fishways are commonly used to provide fish passage at barriers (figure 1d). To date, passage of fish around anthropogenic barriers in North America and Europe is generally between 28% and 62% (including salmonine and nonsalmonines; Bunt and Castro-Santos 2012, Bunt et al. 2016). Multispecies fish passage in the presence of undesirable (e.g., invasive) species remains elusive, in part, because fish assemblages and their life histories and behaviors vary by site and species. Unlike invasive
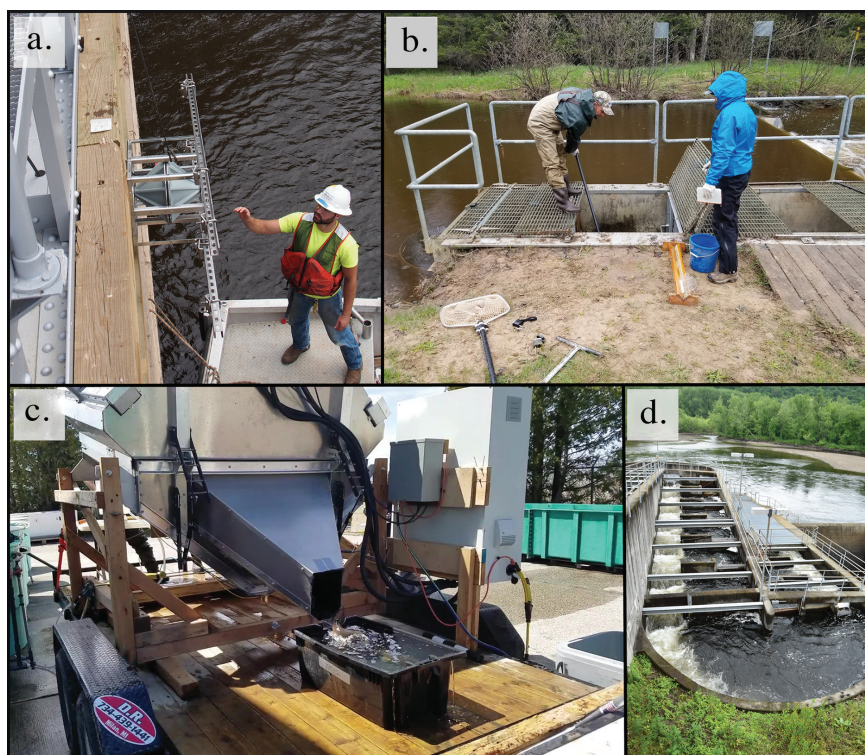
Figure 1. Examples of existing fish sorting technologies. (a) Acoustic deterrent installation at a Mississippi River lock and dam. (b) Seasonally operated trap-and-sort fishway on the Big Carp River, Ontario, with sea lamprey fixed-crest barrier located in the background. Photograph: Gale Bravener, Fisheries and Oceans Canada. (c) Fish imaging system, FishLTM Recognition System, developed by Whooshh Innovations being tested to identify sea lamprey from other Great Lakes species. Photograph: Andrea Miehls, Great Lakes Fishery Commission. (d) Cabot Station fish ladder at the Turners Falls Hydroelectric Project on the Connecticut River, Massachusetts. Photograph: Andrea Miehls, Great Lakes Fishery Commission.

2003, Januchowski-Hartley et al. 2013). The number of species affected may be higher as barriers block nonmigratory movements as well. A more effective approach and one that accounts for variability within a desirable fish assemblage is to view the multispecies assemblage holistically—that is, grouping species into guilds with similar attributes. Then, passage and blockage schemes can be formulated on the basis of differences and commonalities among guilds, such as large, strong swimmers versus small, weak swimmers. Although Rahel and McLaughlin (2018) viewed selective fish passage through a multidimensional niche space to identify sortable differences between species, no framework exists for integrating multiple technologies that operate on multiple attributes for the purpose of achieving selective passage of a fish assemblage within a river. The principles of movement ecology, behavior, and engineering must be merged to develop an approach capable of sorting and selectively passing a mixed fish assemblage by predetermined categories of desirable and undesirable species. We suggest that selective connectivity will require exploiting or overcoming differences in phenological, behavioral, physiological, social, and morphological attributes among guilds within a fish assemblage that can vary through space and time.

sea lamprey in the Great Lakes, where nearly 60 years of research has been dedicated toward understanding their physiological and behavioral attributes (Siefkes 2017), little information on fish attributes relative to passage are available for species not targeted by commercial or recreational fisheries. The paucity of data is a legacy of engineering designs for fish passage devices that have historically focused on a single attribute such as the swimming performance of a single target species or group of physiologically, behaviorally, or morphologically similar species. Rarely do fishway designs exploit multiple attributes of the full fish assemblage in the river system.

Developing solutions for selective fish passage using an approach in which all species are independently and exhaustively studied is untenable. For example, a network of nearly 250,000 barriers on tributaries to the Laurentian Great Lakes of North America affect the movement of an estimated 121 fishes known to show migratory movements between lakes and rivers or within a river (Mandrak et al.

Single-stream recycling as an integrated model for developing selective connectivity

The evolution of single-stream recycling is similar to that of our proposed approach to selective fish passage. Over time, single-stream recycling moved away from single-factor sorting to a centralized system of integrated technologies that target a suite of attributes in an incoming assemblage to achieve the desired sorting goals (i.e., ultimately passing only a desirable fraction of that assemblage). We are unaware of any examples in the natural sciences of engineered multiattribute sorting systems for passage of living organisms. We explore the field of single-stream recycling to help inform the future development and expectations for selective fish passage. Below, we outline a brief history of single-stream recycling and key features of single-stream recycling systems to highlight the potential areas where it has direct translation to selective fish passage.

History of single-stream recycling. Recycling is a key component of modern management practices for municipal solid

waste, which is generally composed of wet food waste and dry recyclables. The development of the modern municipal solid waste management system started in the 1970s, in part, because of growing environmental awareness, government policies (the 1965 Federal Solid Waste and Disposal Act, the 1969 National Environmental Policy Act, the 1976 Resource Conservation and Recovery Act), and consolidation of waste management companies (USEPA 2002). Early municipal recycling programs relied on homeowner separation of recyclable materials into separate bins that were either collected curbside or dropped off at small-scale collection sites. The drawbacks of early recycling programs were high collection costs and high residue rates—that is, loads with comingled materials or nonrecyclables. As a result, communities began switching to single-stream recycling systems in which all recyclable materials are collected in a single bin to reduce collection costs and are then transported to large, regional material recovery facilities for processing. The move to single-stream recycling was driven by the development of more sophisticated sorting technology, as well as the desire for greater processing capacity and the improved quality of the recoverable material.

The recycling industry has overcome several key social and technological problems in the implementation of single-stream recycling; how these issues were solved can benefit the development of selective fish passage. Initial participation in recycling was low (Gershman, Brickner, and Bratton 2015), so concerted outreach and education efforts were pursued to increase public participation and awareness of recycling (Read 1999). The adoption of packer trucks to collect, package, and deliver material to the facility also helped increase the amount of material that could be efficiently collected and delivered to the facility (Stessel 1996). Increased sensor sensitivity, reconfigured sorting processes, and technological improvements to sorting devices helped reduce residue rates. For example, a primary source of residue was plastic bags, which quickly wrap around disk screens and entwine in conveyors. Bag breakers were developed to rip open the bags so the workers could pick them off and feed them into vacuum system (Kessler Consulting 2009). Because of the success of contemporary sorting technologies in obtaining efficient and effective material sorts, the United States recycling industry now supports over 1.1 million jobs and generates $236 billion in annual revenue (USEPA 2002). The process has become so efficient that some companies and communities are even exploring one-bin systems in which recyclables are combined with regular refuse (Cimpan et al. 2015).

The motivation and development of single-stream recycling through shifts in community desires and governmental policy mirror, in several ways, the recent globalized movement toward dam removal and increased connectivity and the shift in fisheries from single-species management to ecosystem-based management. Political and social forces drive the need for solutions to fish passage that require selective capability, which is especially critical when unfettered

passage is not a desirable outcome, such as in the presence of invasive species. The expansion of fisheries management beyond commercially important species to ecosystem-based management is similar to the desire to recover a greater diversity of materials from municipal solid waste streams that, in turn, helped drive innovation and wider implementation of single-stream recycling. Finally, a shift away from manual trapping and sorting of fishes at fishways to automated sorting processes will also likely improve the efficiency and sustainability of selective fish passage solutions.

Key features of single-stream recycling. Single-stream recycling systems follow a process train composed of many unit operations, each optimized to perform a basic sorting task. The concept of subdividing the recycling process into separate unit processes is central to single-stream recycling development and necessary to address the inherent complexity of a diverse incoming waste stream (Stessel 1996). Much like fishes but far exceeding their observed diversity, municipal solid waste is composed of hundreds of thousands of unique items that fit into fewer than 30 general attribute-based descriptive categories (Staley and Barlaz 2009). In single-stream recycling, the complex material stream is separated into approximately 11 output streams (e.g., paper, clear glass, aluminum; Gershman, Brickner, and Bratton 2015). The output streams in recycling are analogous to guilds of similar fishes targeted for passage. The unit operations can be independently modified to improve performance without changing the entire process train, and a single unit process can be used repeatedly in the process train to increase the encounter rate of different materials with their designated sorting process.

The recycling process encompasses four sequential stages: collecting a comingled mixture of items, loosening the mixture and preparing materials for sorting (material disintegration and conditioning), sorting materials on the basis of particle (e.g., size, density, shape) and material (e.g., color, magnetism) attributes (Stessel 1996), and determining the fate of recyclable material (i.e., the output streams). The primary stages of the single-stream recycling process train are analogous to the four sequential stages of fish passage: approach, entry, passage, and fate (Silva et al. 2017). Each stage of fish passage can be directly compared with the primary stages of recycling (figure 2). The approach stage is similar to the material collection stage and involves fish detecting and being guided toward a fishway entrance from a distance. The entry stage is similar to the material disintegration and conditioning stage and involves fish detection and guidance toward a fishway entrance from close range and ultimately entering the fishway. The passage stage is similar to the material sorting stage and involves fish moving through the fishway and interacting with sorting technologies. Finally, the fate stage involves fish being directed into one of three output streams: blocked but not removed (undesirable), blocked and removed (invasive), and passed (desirable). Each stage
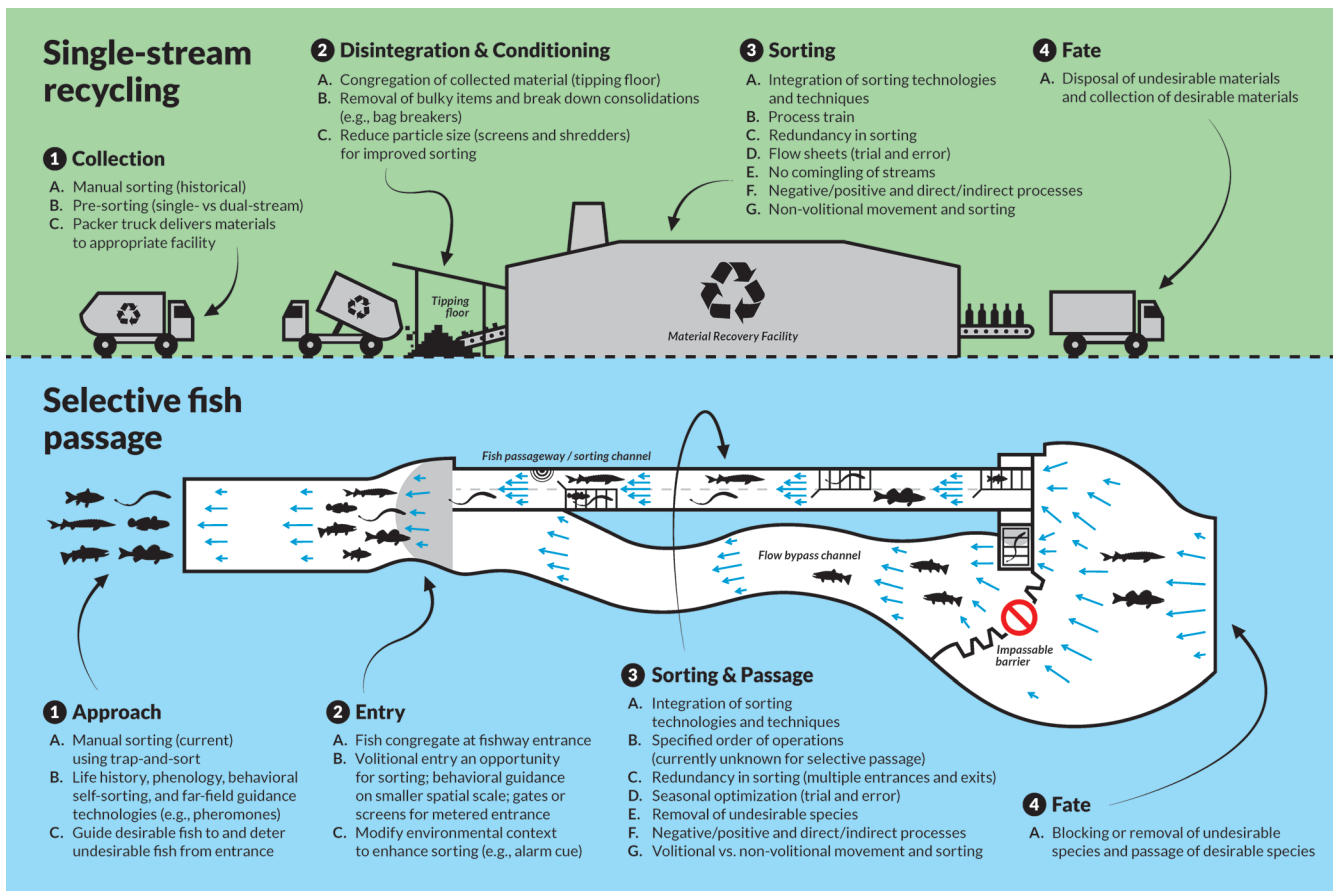
Figure 2. Parallel mechanics of selective fish passage and single-stream recycling processes. The key processes involved in selective fish passage are identified and similar processes are identified for single-stream recycling. Bottom image: Arrows indicate approximate stream velocity and direction and grey zones indicate entrances into the fish passageway or sorting channel. The fish-sorting channel is shown with a conceptual series of traps and environmental stimuli (radial contours) to sort a hypothetical fish assemblage. Selective passageway design modified with permission from FishPass (www.glfc.org/fishpass.php).

of the sorting process presents an opportunity to introduce a suite of technologies and techniques, similar to single-stream recycling that exploits or overcomes attributes and behaviors of fishes to effectively guide, sort, and pass or block individuals in a mixed fish assemblage. Next, we describe the primary features of the four stages of single-stream recycling and their analogy to the four stages of fish passage. Although the parallels drawn in figure 2 highlight similarities between the basic mechanics of the two sorting processes, key lessons from single-stream recycling (box 1) help reveal important insights and research questions that will help facilitate the design of selective fish passage technologies (box 2). Many of the key questions regarding selective fish passage development pertain to whether and how best to partition fish populations to apply targeted sorting processes.

Recycling stage 1: Collection. The collection of municipal solid waste is the first stage of any recycling process. The abundance and content of municipal solid waste varies by country, region, season, and economics (Stessel 1996). Public outreach and legislative actions influence community value judgments, creating a feedback loop influencing what materials are disposed and how they are disposed. Single-stream systems only collect the trash recyclables component of the waste stream, which is either a fully comingled mixture or, in dual-stream systems, waste coarsely separated between fibrous material (e.g., paper, cardboard) and containers (e.g., plastic, metal, glass). Packer trucks collect waste from a large area following tightly scheduled routes for which the delivery time and content entering a material recovery facility is forecasted. Standardized sampling is then applied at the collection stage (Newenhouse and Schmit 2000, Staley and Barlaz 2009) to confirm the forecasts and to better understand the composition and temporal dynamics of the waste stream. Engineers can decide what technologies may be required to sort the contemporary material stream.

Box 1. Key lessons from single-stream recycling that could inform selective passage for fishes.

General

1. Integration of multiple sorting technologies each targeting a specific sortable attribute is required.

2. Adaptive infrastructure is critical to meeting changing market demands and a variable material stream.

3. Understanding the composition, size distribution, timing, variability, and variables influencing variability is critical to determining appropriate technologies and the order of sorting operations.

4. Fate of materials is driven by market demand, society, and policy.

Collection

5. Material compaction can make delivery of sortable materials to a material recovery facility much more efficient.

6. Opportunities exist during material collection for pre-sorting.

Disintegration and conditioning

7. Removal of large or bulky items is the first step in the sorting process.

8. Disintegration of the material stream breaks up conglomerates (i.e., material collected in plastic bags).

9. Homogenization of the size distribution of materials simplifies sorting technology operations.

10. Conditioning aims to change or enhance the particle properties to better facilitate technology to sort it.

Sorting

11. Each technology or device targets a single property or attribute on which it sorts.

12. Facilities are typically designed and optimized through trial and error whereby a basic process train is installed and unit operations are adjusted over time or new operations are added until the desired output is achieved.

13. Probabilistic tools have been developed to predict which order of operations is optimal given a number of sorting processes and recovery rates.

14. System performance is tracked using flow sheets, which identify the waste stream composition throughout the material recovery process train.

15. Specificity of each consecutive unit process is increased, thereby reducing the volume of non-desirables as the waste stream advances through the facility.

16. Individual unit processes are used at multiple points in the process train. That is, a sortable attribute is targeted multiple times as the stream moves through the facility.

17. Adjustability of unit processes allows adaptation to a constantly varying waste stream.

Fate

18. Material recovery facilities must produce an end product that meets quality and quantity of industry demand.

Fish passage stage 1: Approach. The abundance and diversity of fish that require passage at any barrier varies by ecoregion, movement phenology, and a suite of environmental factors (Dolinsek et al. 2014). Feedback loops affect fish assemblages on the basis of the outcomes of previous passage attempts. For example, if fish are unable to reach critical spawning habitat above a barrier, then the abundance or diversity of the fish attempting to pass in subsequent years could be reduced (Freeman et al. 2003).

The approach stage of fish passage initiates at some distance from the fishway and involves the fish encountering physical signals (e.g., water velocity, turbulence, temperature) that identify the location and conditions generated by the fishway (Silva et al. 2017). The range of the approach stage depends on the propagation of each environmental stimulus and sensitivity of the targeted fish but generally encompasses fish movement outside of the fishway entrance (i.e., from 1–2 meters to approximately 100 meters away). For sorting purposes, physical signals could be used to guide desirable fish toward a fishway while guiding undesirable fish away from the fishway or toward a trap. The approach stage differs from waste collection in that the fish are not packed into trucks and brought to a sorting facility, although, in some scenarios, fish are indeed loaded into trucks for passage around dams (Harris et al. 2019). Rather, we envision that discrete arrivals of fish at a fishway, on the basis of their

Box 2. Key questions relating single-stream recycling lessons to selective fish passage development.

General

1. Can selective passage be designed to meet changing management objectives?

2. What species and how many should pass to achieve optimal fishery production and diversity?

3. What data are required to understand variation in the fish assemblage moving upstream in a river?

Collection

4. Can we compress in time or space the fish assemblage encountering a selective passage facility?

5. Can physical structures, such as a weir or baffle, provide crude sorting prior to fishway encounter?

6. Can fish movement phenology, which tends to be triggered by environmental conditions, lead to pre-sorting?

7. Can environmental or conspecific cues be used to alter the internal state of fish, effectively biasing their response to later sorting processes?

Disintegration and conditioning

8. Can large, solitary species such as sturgeons (Acipenseridae spp.) or carps be passed separately from groups of smaller species.

9. Can the fish assemblage be broken up in time or space such that it is less mixed or bottle necks caused by large movement events are minimized?

10. Can movement triggers cause only portions of the assemblage to move through the facility at a given time?

11. Can the fish assemblage be sorted on the basis of size, such that small, medium, and large fishes encounter appropriate subsequent sorting or passage conditions?

12. Can maturation status of animals encountering the facility be altered by delaying access to the sorting facility?

Sorting

13. Can an inventory of sortable attributes of fishes be inventoried at the species or guild level and mapped onto available sorting and passage technologies and to identify new technologies?

14. What does the basic process train for selective fish passage look like? Where do we start?

15. Do we have enough data on the responses of many fish species to sorting technologies to predict performance using probabilistic models?

16. How does the composition of a mixed fish assemblage change as it moves thorough the facility?

17. How does redundancy in sorting technologies maximize encounter, entry, retention, and removal of undesirable species?

18. Do sorting technologies for fishes have to be static, or can technologies or their operation be altered in season to account for varying environmental conditions or the phenology of fish movements?

19. Can fish be triggered to exhibit unusual or new behaviors that facilitate self-sorting?

Fate

20. What are the watershed specific goals for fish passage (e.g., species, movement rates, timing)?

21. What ecological or social tolerance is there for passage of undesirable species?

22. Do desirable species exit the passageway in good condition and complete their life history stage?

movement phenology, are analogous to the arrival of packer trucks at a material sorting facility. Rivers provide the mode of transportation by which the fish approach barriers and fishways, and they self-sort to an extent on the basis of arrival times (e.g., seasonal diadromous migrations). Phenological differences inherent to species are already exploited by seasonal barriers, for example (table 1 and figure 1b).

Perhaps the greatest similarity between fishway approach and waste collection is the need to understand the composition and temporal dynamics of the incoming assemblage to determine what suite of tools can and should be considered in later sorting stages. Routine fish sampling and movement studies can help assess the timing and composition of fish assemblages approaching a fishway. If movements

have strong correlations to environmental conditions (e.g., water temperature, time of day, discharge, water level), fish approaches could be predicted to an extent or modified for sorting purposes (Vélez-Espino et al. 2011, Dolinsek et al. 2014). For example, Workman and colleagues (2002) found the probability of upstream migration of adult steelhead rainbow trout in the St. Joseph River, Michigan, to increase with increasing stream temperature above a minimum threshold temperature.

Recycling stage 2: Disintegration and conditioning. The disintegration and conditioning of the waste stream is the second stage of the recycling process and the first stage within the material recovery facility. All of the materials collected by the packer trucks are unloaded onto the tipping floor, where bulky objects and contaminants are manually removed from the waste stream. The materials are combined and directed to conveyor systems that transport the waste and recovered materials throughout the facility. Material disintegration includes the removal of plastic bags and agitation to break the waste stream and any large consolidations into individual particles on which subsequent sorting systems can operate. Conditioning changes or enhances particle attributes to increase the probability of separating them from the waste stream. For example, one common conditioning tactic is to reduce the maximum particle size using screens to remove large materials or shedders to break those large materials down to a size compatible with all unit processes. Disc screens are commonly used to remove large items and to coarsely separate a single stream into separate fiber (e.g., paper and cardboard) and container (e.g., plastics, glass, and metal) streams (Peer Consultants 1991). Therefore, size is the first order of operations in the sorting process for recyclable materials.

Fish passage stage 2: Entry. On locating the fishway entrance, fish detect and respond to entrance conditions and decide whether to enter or not within a range that is often 1–2 meters from the entrance. Volitional entry into fishways continues to be a challenge. Strategic placement of entrances relative to spillways and supplemental attraction flows are common approaches to improve entrance probabilities. Alternatively, environmental conditions at entrances can be adjusted to discourage entrance of undesirable fish. Chemosensory cues from conspecifics can be used to attract (e.g., pheromones) or deter (e.g., pheromone antagonists, alarm cues, necromones) animals at passageway entrances (Wagner et al. 2011, Hume et al. 2015).

Similar to disintegration, fishway entrances also permit large fish congregations to be sorted by limiting the opening size or manipulating their behavior. This benefits the sorting by reducing the number of fish that can move through a fishway at one time, reducing the risk of undesirable fish passing among congregations of desirable fish and ensuring that the sorting technologies do not get overwhelmed with large numbers of fish. Disintegration occurs naturally at fishways because the entrances are limited in size to maintain consistent attraction flow. Another method of disintegration that can be applied to fish passage is the separation of large and easily identified species such as sturgeons (*Acipenseridae*) or very small fishes such as cyprinid minnows from the wider assemblage. Sorting large and small fishes serves three purposes: First, large migratory fish are often imperiled by barriers and targets of conservation efforts in which their collection and passage are emphasized (Hay-Chmielewseki and Whelan 1997). Second, very small fishes are typically highly abundant among a migrating fish assemblage and serve a critical role as integrators of energy and nutrients from the base of food webs to top predators (Mallen-Cooper and Stuart 2007, Pompeu et al. 2012). And third, quantification of the maximum and minimum sizes of fish that must navigate and be evaluated at various stages of the sorting process. Similar to the material recovery process, size is a logical first attribute to sort fishes.

Conditioning also holds promise for selective fish passage. Conditioning targets fish behavior, a sortable attribute not applicable to material recycling. In the context of fish passage, conditioning would seek to alter context-dependent behavior to induce self-sorting or to increase the predictability of responses to future stimuli. Rather than focusing on the direct response to a stimulus, as is done in most fish guidance or deterrent studies, conditioning aims to influence how fish respond to subsequent stimuli. For example, Pacific lamprey (*Entosphenus tridentatus*) have been shown to exhibit both attraction and avoidance behaviors to turbulent intensities in a fishway depending on the background turbulence levels (Kirk et al. 2017). Kirk and colleagues (2017) found that lamprey avoided regions of relatively higher turbulent intensity when the background turbulence was high but were attracted to regions of relatively higher turbulence when the background turbulence was low. Attempts to quantify fish decision-making and movement responses to environmental attributes near passage structures are not new or trivial (Goodwin et al. 2014), because it requires consideration of multiple, interdependent physical and cognitive processes (Nathan et al. 2008). To assess what, if any, level of conditioning can influence fish sorting and passage, investigations will need to consider more than one stimulus at a time.

Recycling stage 3: Sorting. The definitive sorting and processing of the waste stream to salable materials is the third stage of the recycling process and forms the majority of activities at material recovery facilities. A variety of sorting processes are available, and process selection heavily depends on the ratio of desirable to undesirable materials. For example, it is more efficient to remove undesirables when the waste stream has a high proportion of a single desired material (Kessler Consulting 2009). Negative sorting, which targets the removal of undesirables from the waste stream, is applied when targeting removal of an undesirable from a largely recoverable waste stream (Kessler Consulting 2009).

Table 2. Summary of single-factor sorting technologies used in modern material recovery facilities.

Sorting application	Material attribute	Technology	Description	Examples
Direct sorting tools	Size	Screens	Vibrating, rotating (trammel), and disc screens separate large items and separate organic waste from recyclables.	Stessel (1996) Peer Consultants (1991) Kessler Consulting (2009)
	Density	Vibrating table	Oscillating plate that stratifies material on the basis of density.	Bonifazi and Serranti (2012)
		Air classifier	An air stream of sufficient velocity to carry away light material.	Kessler Consulting (2009) Dubanowitz (2000)
		Ballistic separator	Inclined grid of oscillating cleats that force heavy, rolling items to the bottom and light, flat items to the top.	Sigmund (2018)
	Electrical charge	Triboelectric separator	An electric charge is generated by allowing materials to contact each other in a rotating drum, then the materials are directed through a horizontal electric field that separates positively and negatively charged items.	Xiao et al. (1999)
	Magnetism	Magnetic separator	Magnetic field applied to waste stream to separate out ferrous metals. Can be used in a rotating drum or on a conveyor system.	Svoboda and Fujita (2003) Gundupalli et al. (2017) Bonifazi and Serranti (2012)
		Eddy-current separator	Magnetic flux applied to waste stream to separate non-ferrous metal from nonmetallic waste on the basis of conductivity.	Gundupalli et al. (2017) Bonifazi and Serranti (2012)
Indirect sorting tools	Magnetism	Eddy-current based sorting	Magnetic flux applied to waste stream and an electromagnetic sensor detects ferrous and non-ferrous material and uses compressed air to separate into bins.	Gundupalli et al. (2017)
	Chemical composition	Laser Induced Breakdown Spectroscopy (LIBS)	High powered laser pulse and optical spectroscopy to read and distinguish materials on the basis of chemical composition; compressed air or other mechanical system sorts the detected materials into bins.	Gundupalli et al. (2017) Bonifazi and Serranti (2012)
		X-ray based sorting	Sensor identifies different types of metal, plastics, and wood on the basis of absorption of X-rays; compressed air or other mechanical system sorts the detected materials into bins.	Gundupalli et al. (2017)
	Color	Optical sorting	Cameras are used to identify target materials on the basis of color, 3D shape, or light attenuation; compressed air or other mechanical system sorts the detected materials into bins.	Kessler Consulting (2009)

Alternately, positive sorting, which targets desired recoverable materials, is typically applied when targeting a desirable material from a largely undesirable waste stream (Kessler Consulting 2009).

Individual sorting technologies can be further characterized as direct or indirect processes. Direct sorting uses an external field (i.e., physical contact) to separate materials on the basis of material attributes, whereas indirect sorting uses sensors to locate and separate individual items (table 2; Gundupalli et al. 2017). The technological complexity of each sorting device varies greatly. For instance, screens simply sort material by size using different sized openings whereas optical sorting systems use high-resolution cameras and rapid computer processing to identify and select individual items. Nonetheless, sorting objectives of each device are simple and straightforward. Each technology or device targets a single attribute from among a host of potential properties inherent to different materials within the waste stream. The efficacy of the whole sorting system lies in the integration of multiple technologies, both simple and complex, that each targets a single attribute.

The design of material recovery facilities is inherently complex because of the interdependency between unit operations. The outgoing stream from one sorting process is the incoming stream of the next sorting process. There is a paucity of design guidelines because single-stream facilities have historically been designed and optimized through trial and error (Wolf 2011). Historically, the optimization of sorting involves installing a basic process train and adjusting unit processes during operation or adding new processes as required, whereas the efficiency of sorting (system performance) is tracked using flow sheets (i.e., sorting process road map). Using the road map, general strategies for process train development have been identified. Coarse separation helps ensure maximal yield of low concentration target materials. For example, ferrous and nonferrous materials are more readily collected by magnetic and eddy current separators when not covered by high volumes of nonmetallic material. In essence, recycling facilities improve the recovery of rare materials by removing materials that interfere with collection. Another strategy is to refine the sorting parameters of each consecutive unit process, ensuring the volume of undesirable materials decreases as the stream advances

through the facility. Facility designs also take advantage of similarities in sorting processes by using individual unit processes at multiple points in the process train. That is, a sortable attribute is targeted multiple times throughout the process. The ability to adjust unit processes is a key design feature that allows facilities to handle ever-changing waste streams. These design features yield relatively high recovery rates of desired material now around 90%–95% (in the United Kingdom) and residue rates around 3%–10% (Cimpan et al. 2015).

Overall improvements to a material separation process train can be accomplished through the technological advancement of unit processes, an increased number of steps, and the optimization of the operational parameters (Wolf et al. 2010). Parameter optimization remains an elusive improvement method for single-stream recycling because system designs have historically been site specific and accomplished through trial and error, and modeling solutions are restricted to very specific problems (Stessel 1996, Wolf 2011). Modeling approaches are hampered further by the paucity of detailed data from the scientific literature that describe process efficiency and output quality from material recovery facilities (Cimpan et al. 2015). Linear circuit analysis has been used to model multistage recycling systems, but these models are often restricted to binary material streams and static separation processes (Luttrell et al. 2004, Wolf 2011). More recently, Bayesian models have been suggested for more general analysis of multistage separation systems with recirculation of material streams and multiple target materials (Wolf et al. 2010, Wolf 2011).

Fish passage stage 3: Passage. The passage stage begins once a fish enters a fishway, attempts to advance through it, and encounters devices or stimuli that aim to facilitate or block passage. Fishways and invasive species control tools have historically targeted single attributes. For example, technical fishways provide passage on the basis of fish swimming or leaping abilities. Similar to the recycling industry, many single-attribute sorting technologies are available to fishway engineers. Most available fish sorting technologies (table 1) are considered direct sorting tools, where an external field (i.e., pheromone, turbulence, screen) is applied to separate fish on the basis of distinct attributes. To our knowledge, image-based sorting tools are the only existing tools that can sort indirectly whereby a targeted fish is acted on by some other device (e.g., opening a gate or trap entrance; Garavelli et al. 2019). Although current image-based sorting tools (figure 1c) have been used to assess fish biomass, count passage, or separate hatchery reared fish from wild (Garavelli et al. 2019, Li et al. 2019), further refinement of physical infrastructure and software architecture are still required for applications in selective passage of a mixed assemblage of fish. Imaged-based sorting of fish could be most effective as a final sorting process where the ratio of desirable to undesirable fish is conducive to identifying fish with lower abundance akin to application of image-based sorting in

material recycling. Existing sorting technologies could be implemented in both positive and negative sorting strategies depending on the composition of the fish assemblage entering the fishway. The efficacy of single-factor designs to pass or block desired species has been variable, depending on species, location, and targeted attribute (Bunt and Castro-Santos 2012, Bunt et al. 2016, Rahel and McLaughlin 2018). We propose that multiple single-factor designs be integrated in a configuration consistent with single-stream recycling design, which could greatly improve efficacy relative to the use of individual technologies. The integration of multiple single-factor technologies forms the basis of our concept for selective fish passage.

Development of selective fish passage tools must build on knowledge gained from past successes and failures and integrate traditional fish passage science with lessons learned from invasive species control. Engineered fishways provide a controlled environment to apply multiple sorting technologies. However, the standard fishway design may not be sufficient. Selective fish passage infrastructure should accommodate a multitude of different technologies amenable to precise monitoring and adjustment of environmental conditions. Historical fishway designs have commonly failed to meet performance expectations because the infrastructure is permanent and cannot be modified without complete replacement (Mallen-Cooper and Brand 2007). Not only does infrastructure flexibility follow the example of single-stream recycling facility design, it also provides researchers the ability to pursue an adaptive management approach where multifactor configurations can be tested, assessed, adjusted, and retested. Within the new flexible infrastructure, modeling tactics from the recycling industry (i.e., Bayesian models) can be applied to help identify optimal components and configurations to achieve selective fish passage.

The need for integrative automatic or semiautomatic solutions to selective fish passage is drawn from the desire to improve on the manual trap-and-sort approach, which is the current and only known method to selectively pass and block fishes. Although trap and sort has, for example, been 100% effective at preventing upstream movement of invasive sea lamprey in the Laurentian Great Lakes (figure 1b; Pratt et al. 2009), it has not been implemented widely. The percentage of native or desired fish passed, or passage efficiency, can vary widely, from as low as 7%–10% to as high as 88% (Pratt et al. 2009). Manual sorting of fish is time consuming and can be detrimental to fish health; therefore, selective fish passage solutions must arrange different sorting mechanisms in a configuration that automatically or semiautomatically passes desirable fishes and blocks undesirable fishes while minimizing the need for human intervention.

Optimizing the fish sorting process does not need to solely focus on technological improvements, but also identifying ways to alter fish behaviors that improve the abilities of existing technologies to sort fish (i.e., conditioning). In other words, a largely untapped potential for improving fish sorting lies

in understanding the potential additive effects to modify fish behavior through serial application of multiple existing technologies. The exact composition in type and order of technologies is likely site dependent because of differences in fish assemblages as well as the specific geology, hydrology, site development, and human use needs at a given location. Decisions on which sorting devices to include and where, should be cognizant of broader ecosystem objectives so as to maximize the exportability of a given solution to different systems.

Recycling stage 4: Material fate. The final stage of the single-stream recycling process involves reconsolidation of materials separated in the recycling facility for shipment and reuse by industry. The marketability of recyclable materials is highly dependent on product quality. Material with a high level of undesirables or contaminants can be costly to reintroduce in industry because of refinement costs, production of an inferior product relative to virgin material sources, and potential for damaging manufacturing equipment (e.g., glass particles in plastics can damage injection forms; Stessel 1996). The market for recyclable materials creates a feedback loop toward development of new sorting processes that produce materials with fewer undesirable components.

Fish passage stage 4: Fate. The final stage of fish passage addresses the condition and fate of fish sorted. In general, selective fish passage must contend with the fate of fish within one of three output streams: passed, blocked and removed, and blocked but not removed. Fish passed must be in good condition, in a timely manner, and able to complete their life history stage. Fallback of recently passed fish is a common issue with current fishways (Naughton et al. 2006) and should be avoided. The contribution of individuals to the upstream fish community is usually tied to factors acting on a much broader scale than just the fishway (i.e., amount and condition of upstream habitat). The fate of undesirable fishes, especially invasive species, is relatively straightforward in that they are removed and disposed of or repurposed for research. For example, the US Fish and Wildlife Service and Department of Fisheries and Oceans Canada transfer a portion of invasive sea lamprey trapped during spawning migrations to the Great Lakes Fishery Commission to support research, and communications and outreach programs. In Australia, invasive common carp (*Cyprinus carpio*) captured in Williams' cages are euthanized on site (Stuart and Conallin 2018). Removal of undesirable species can create a positive feedback by improving ratios of desirable to undesirable fish that need to be sorted. All remaining fish that are either intentionally blocked (i.e., undesired but not invasive) or do not advance through the fishway are returned downstream.

Expectations for selective connectivity and fish passage
The likelihood of success in developing selective connectivity for fish passage is goal dependent. Current fish passage

solutions have received increasing criticism for designs emphasizing passage of iconic diadromous species, such as Pacific salmonines, to the detriment of less mobile species resulting in an overall failure to meet conservation goals (Silva et al. 2017, Wilkes et al. 2018). Although full river connectivity at barrier sites can be accomplished through barrier removal and restoration where no natural impedance previously existed (Bednarek 2001), management decisions become more difficult in the presence of multiple barriers in a system (Rourke et al. 2019) or when barriers are unable to be removed and other technical means are required to pass fish. Furthermore, complicating the matter is the uncertainty about specific passage needs for each site. Although 90%–100% passage efficiency may be required for obligate migratory species to pass a barrier blocking access to critical habitat (Lucas and Baras 2008), there is greater uncertainty on the passage requirements for species with less motivation or mobility to traverse engineered fishways. Even low immigration rates between populations can reduce the risk of extinction (Hilderbrand 2003). Combinations of critical habitat assessment and metapopulation modeling can help establish effective fish passage goals for nonobligate migratory species (Wilkes et al. 2018).

Arguably, many of the tools required to achieve selective fish passage already exist in the form of single-factor fish guidance, passage, and trapping technologies (table 1). Although long hypothesized as the optimal approach (Popper and Carlson 1998, Coutant 2001), there are only a handful of examples of fish guidance or barrier systems employing multiple stimuli at a single location and none, that we are aware of, that employ different technologies in series. Learning from the development of single-stream recycling, it would be unrealistic to expect selective fish passage goals to be met using a single-factor process. A more realistic expectation is that an integrated and optimized set of ecological filters or novel filters (i.e., sorting technologies) will yield selective fish passage goals for a given system.

Fish behavior adds a layer of complexity to developing a sorting process that is not present in materials recycling. Manual sorting is effective at overcoming these complexities, but this is costly in terms of money and time, and not desirable or feasible at all locations. Selective fish passage solutions should capitalize on volitional behaviors to promote self-sorting, reducing the pressure on less efficient physical sorting techniques and need for human intervention. However, fish behaviors change over time and space, and differ across life stages and sexes. For example, the response to a given stimulus can habituate over time whereas a fish is unlikely to vastly change size or locomotor ability within a single season. Furthermore, fish attributes such as body shape and swimming capacity change with size and age. Single-stream recycling adapts to diverse input streams by incorporating multiple and often recursive sorting processes that can be adjusted on the basis of routine sampling of the input stream. Translating the processes developed for single-stream recycling to fish passage

offers a tangible solution to sorting the inherent diversity exhibited by living organisms.

Efforts to improve passage of desirable fishes and blockage of undesirable fishes must be tied to broader conservation goals such as restoring energy and nutrient cycles, increasing productivity, increasing the sustainability of fish species, preserving biodiversity, restoring genetic connectivity, and managing invasive species. Long-term impacts of increased connectivity take years to be realized; therefore, it is critical to identify passage priorities and monitoring strategies at the onset of a project. Typically, fish passage projects are judged by the number of fish to successfully attempt and pass the barrier. Contemporary studies have proposed time-to-event analysis to evaluate passage as a rate per unit time and distill the probability of passage and delay incurred while attempting to pass (Castro-Santos and Perry 2012, Silva et al. 2017). Although passage efficiency may be relatively straightforward to quantify and communicate, it does not capture the fate of fish passed or the impact of fish passage on other ecosystem services. For example, efficient upstream passage could still result in an ecological sink if downstream passage is lacking, upstream habitat is of poor quality, or habitat is not suitable for a species' reproductive needs (Pompeu et al. 2012). Evaluations of fish passage must also consider energy and nutrient pathways between lakes and their tributaries, because upstream migrants represent a significant nutrient subsidy for riverine habitats. The magnitude and form of nutrient delivery depends on species and life-history traits as semelparous species deposit nutrients as they spawn and die in rivers while iteroparous species deposit nutrients via eggs and excretions (Childress and McIntyre 2015, Wheeler et al. 2015). Barriers can lead to reduced genetic diversity in populations isolated by the barrier and intensify genetic differentiation between populations up and down stream of the barrier (Wofford et al. 2005). Therefore, assessments of fish passage must also consider the contribution of fish that traverse the barrier to gene flow between populations up and down stream. Recent advances in population genomics have made it possible to detect differences in genetic structure between subpopulations separated for an evolutionary short period of time (Larson et al. 2014).

The definition of success and failure in the context of selective connectivity is inherently complex with long-term goals needing to balance containment of undesirable species with passage of desirable species. The task is made more challenging by the lack of a singular definition of success for fish passage in the absence of undesirable species. For example, passage requirements for obligatory migrating species blocked by a barrier are far more straightforward than for less motivated or mobile species (Wilkes et al. 2018). Furthermore, systems partitioned by barriers could be considered novel ecosystems (Hobbs et al. 2009) and lack the necessary baseline ecological data on which to base any restoration or passage objectives (Magilligan et al. 2016). Definitions of success and failure will be driven by a combination of management objectives and the political and social values that shape those objectives. Of particular concern is the level of contaminants in undesirable, invasive species and whether they provide an upstream vector for contaminant movement. In the case of sea lamprey and big-headed carps in the Great Lakes watershed, blockage of all adults is required (McLaughlin et al. 2007) because of their high fecundity and potential ecological threats, respectively. Similarly, successful passage of obligatory migratory species may require passage of a large proportion of individuals encountering a barrier, whereas the goal for more resident species may be to pass enough to maintain gene flow to prevent population fragmentation (Pompeu et al. 2012) or demographic extinction due to upstream environmental stochasticity. A logical approach to selective connectivity in the face of evolving definitions of success and failure is adaptive management, which allows for planned, incremental advancements and modification of operations on the basis of results (Williams et al. 2007). We anticipate initial attempts at sorting fish to have low efficacy (i.e., low overall passage of desirable species or poor blockage or removal of undesirable species), but selective passage measures should improve progressively with each iteration. Much like single-stream recycling, the process train will require optimization for effective and efficient sorting. Ultimately, success and failure to achieve selective connectivity should be driven by management objectives that will subsume political or societal values and are not specific to a single system.

Conclusions

At first glance, the recycling industry and fisheries management have seemingly little in common. However, the goals of each field, sorting materials or fish for desirable outcomes, have remarkable commonalities. Our proposed concept capitalizes on the institutional knowledge gained from the development of single-stream recycling and applies it to the connectivity conundrum facing ecosystem management. Selective connectivity represents a responsible means for ecosystem restoration, when full connectivity could have significant unintended consequences. Because barriers can produce novel ecosystems both up and down stream of the barrier site, restoring systems to some previously undisturbed condition may not always be possible or desired, depending on the management goals. Our vision of selective connectivity could be viewed as a compromise between restoration and rehabilitation of ecosystems recognizing that global ecosystems have been irreversibly altered. The capacity for selective passage is also aligned with contemporary efforts for prioritizing ecological restoration efforts among sites in multistressor landscapes (Neeson et al. 2016), where considerations on barrier removal would no longer lead to binary responses of full connectivity versus full blockage. Ultimately, management of ecosystems fragmented by barriers will require continued research across ecology and engineering. Our vision for selective connectivity merges these fields of study to provide a more holistic solution to decisions regarding the connectivity conundrum.

Acknowledgments

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