Journal of Environmental Management 92 (2011) 3112–3120

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Open rivers: Barrier removal planning and the restoration of free-flowing rivers

Jesse R. O'Hanley*

Kent Business School, University of Kent, Canterbury, Kent CT2 7PE, United Kingdom

ARTICLE INFO

Article history:
Received 10 December 2010
Received in revised form
11 May 2011
Accepted 28 July 2011
Available online 30 August 2011

Keywords:
Dams
Culverts
Fish passage barriers
Flow barriers
Barrier removal
River restoration
Optimization

ABSTRACT

Restoration of unobstructed, free-flowing sections of river can provide considerable environmental and ecological benefits. It removes impediments to aquatic species dispersal and improves flow, sediment and nutrient transport. This, in turn, can serve to improve environmental quality and abundance of native species, not only within the river channel itself, but also within adjacent riparian, floodplain and coastal areas. In support of this effort, a generic optimization model is presented in this paper for prioritizing the removal of problematic structures, which adversely affect aquatic species dispersal and river hydrology. Its purpose is to maximize, subject to a budget, the size of the single largest section of connected river unimpeded by artificial flow and dispersal barriers. The model is designed to improve, in a holistic way, the connectivity and environmental status of a river network. Furthermore, unlike most previous prioritization methods, it is particularly well suited to meet the needs of potamodromous fish species and other resident aquatic organisms, which regularly disperse among different parts of a river network. After presenting an initial mixed integer linear programming formulation of the model, more scalable reformulation and solution techniques are investigated for solving large, realistic-sized instances. Results from a case-study of the Pike River Watershed, located in northeast Wisconsin, USA, demonstrate the computational efficiency of the proposed model as well as highlight some general insights about systematic barrier removal planning.

© 2011 Elsevier Ltd. All rights reserved.

1. Introduction

River infrastructure, such as dams, road crossings (e.g., culverts) and flood control barriers (e.g., levees, weirs and tide gates), while important in providing a range of socioeconomic goods and services (e.g., water supply, transportation, renewable hydropower and flood control), are well known for having considerable negative impacts on freshwater ecosystems and the hydrologic processes which sustain them (Dynesius and Nilsson, 1994; Stanford et al., 1996; WCD, 2000; Bednarek, 2001). As a consequence of this, removal of artificial in-stream structures is being increasing seen as a viable option for sustainable watershed management (Roni et al., 2002; Bednarek, 2001; Bernhardt et al., 2005). To this end, an optimization model is presented in this paper for prioritizing the removal of problem structures, which adversely affect aquatic species dispersal and river hydrology (e.g., flow, sediment transport and nutrient supply). In order to restore free-flowing river conditions over the widest extent possible, the specific aim of the model is to decide which artificial passage and flow barriers to remove in order to form the single largest, contiguous section of unimpeded river.

The effects of river infrastructure on native freshwater fish are particularly well documented in the literature. In-stream structures often form physical barriers that prevent or otherwise reduce access to essential breeding and rearing river habitats. The direct consequences of habitat loss and fragmentation on fish usually include reduced productivity and abundance, restricted range size, and even changes in fish community composition (Santucci et al., 2005; Catalano et al., 2007; Spens et al., 2007; Slawski et al., 2008). Hydromodifications in the Pacific Northwest and Atlantic Northeast of the United States, for example, have resulted in the loss of 40–80% of prime anadromous salmon spawning grounds (Sheer and Steel, 2006; WWF, 2001).

Apart from impeding fish dispersal, in-stream barriers can act in other ways to disrupt the natural hydrology and ecology of fluvial systems. Dams and other structures designed to regulate flow often alter, both temporally and spatially, the basic physical and chemical profile of rivers and nearby coastal areas (Stanford et al., 1996; Campo and Sancholuz, 1998; Bednarek, 2001; Shaffer et al., 2008). Notable examples include: (i) stream discharge, depth and temperature; (ii) dissolved oxygen content; (iii) suspended and bed load sediment transport; (iv) nutrients and large woody debris supply; (v) substrate composition; and (vi) river and coastal morphology. Environmental changes caused by the presence of

* Tel.: +44 1227 824286; fax: +44 1227 761187.
E-mail address: j.ohanley@kent.ac.uk.

0301-4797/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jenvman.2011.07.027

river infrastructure can extend many kilometers in both the downstream and upstream directions. Especially problematic is the catastrophic failure of in-stream structures during large storm events, which can lead to flooding, channel scouring, large sediment deposition, channel realignment, bank destabilization and damage to riparian vegetation.

Hydrologic changes associated with flow regulation, in turn, commonly trigger a collateral reduction in the structural complexity and overall quality of natural in-stream habitats (Beechie et al., 1994). Not only does this impact on the productivity of fish and the wider the aquatic community directly within a regulated river, but also dependent semi-aquatic and terrestrial biota found in adjacent riparian zones, wetlands and coastal areas (Bednarek, 2001). Reduced variability of season discharge cycles and elimination of stochastic flow events (i.e., flooding) can dramatically alter vegetation structure in floodplain areas (Hughes and Rood, 2003). Additionally, barriers often create conditions favorable to the establishment and expansion of non-native, invasive species (Stanford et al., 1996; Clavero et al., 2004). The end result of all this is a cascading reorganization of a river system's biophysical structure, typified in most cases by a reduction in the abundance and diversity of native species and a proliferation of non-native species.

Given the enormous environmental problems created by river infrastructure, it is not surprisingly that barrier removal and mitigation is often seen as a valuable form of restoration (Roni et al., 2002; Hughes and Rood, 2003; Pess et al., 2008; Kemp and O'Hanley, 2010). In spite of this, relatively little work has been published regarding the development of systematic methods for efficiently removing multiple barriers over wide geographic areas. In most cases, prioritization methods have focused predominately on restoring access to upstream spawning grounds of migratory (diadromous) fish and have usually employed overly simple *scoring-and-ranking* type procedures (Kemp and O'Hanley, 2010). Scoring-and-ranking, as used by Taylor and Love (2003), Kocovsky et al. (2009), and WDFW (2009), has been shown to produce ineffective and inefficient solutions as a consequence of ignoring the cumulative, non-additive impacts that barriers have on fish passage success (O'Hanley and Tomberlin, 2005).

In only a few cases have more robust optimization based methods been examined. This includes work by Paulsen and Wernstedt (1995), Kuby et al. (2005), O'Hanley and Tomberlin (2005), and Zheng et al. (2009). An extensive review of barrier prioritization methods is provided in Kemp and O'Hanley (2010). For readers unfamiliar with optimization modeling and solution techniques, two comprehensive and well written primers on this topic are Pardalos and Resende (2002) and Winston (2003).

In this article, an optimization model, as advocated by Kemp and O'Hanley (2010), is used to efficiently prioritize the removal of problematic barriers. Structurally, the model is most closely related to Kuby et al. (2005) and Zheng et al. (2009) in that it does not take into account the variability that artificial barriers have on fish passage and river hydrology. Rather, in-stream structures are *implicitly* treated as equal: they either have an impact or not. Furthermore, removal is assumed to completely eliminate any negative effects a structure may have on river system processes.

Despite this similarity, the modeling approach adopted herein, is designed for an entirely different purpose. The main focus is on improving connectivity and environmental conditions within the river corridor as a whole, including the river channel, riparian zone, and floodplain. Hence, the model is more general in comparison to previous approaches, which have been primarily designed to mitigate barrier impacts on migratory (diadromous) fish dispersal. The benefits of this are twofold. First, the model is especially well suited to meet the life-cycle requirements of potamodromous fish species and other resident aquatic organisms, which regularly disperse on a seasonal basis among habitats (e.g., for breeding and rearing) located in different parts of a river network. Second, removal of problematic river infrastructure is also likely to partially restore the normal hydrologic regime and allow natural channel recovery process to occur. When extended over a suitably large area, this can help improve habitat quality and ecosystem productivity to a significant portion of the river corridor.

An additional benefit of the model is it low data requirements. In an effort to keep the model as simple as possible, no attempt has been made to incorporate the variable effect that barriers may have on fish passability and river hydrology. In many cases, reliable data of this kind do not exist or may be costly and time consuming to gather. Publicly available data from the Oregon Department of Fish and Wildlife (ODFW 2011), for example, do not include numerical estimates of fish passability for any of the more than 28,000 natural and artificial physical barriers found throughout the state. Such estimates usually require the subjective judgment of qualified fisheries biologists or more systematic statistical modeling using structural and hydrological data collected from on-the-ground surveys. Given only basic geospatial data pertaining to river length/quality and the location and removal cost of barriers, the modeling approach presented in this article can be applied in a straightforward way to any watershed. This points to the model's usefulness as a generic restoration planning tool.

The remainder of the paper is organized as follows. In Section 2 the basic problem we consider is discussed in more detail. A mathematical formulation of the problem is also presented as well as some techniques for efficiently solving large problem instances. Section 3 provides results of a case-study from the Pike River Watershed, located in northeast Wisconsin, USA. Finally, in Section 4 a summary of the main contributions of the paper, some basic insights based on case-study, and a discussion of suggested areas of future research are given.

2. Methods and materials

2.1. Problem description

In the following, the aim is to decide which artificial passage and flow barriers to remove from a river, subject to a limited budget, in order to maximize the size of the single largest contiguous section of unimpeded river, termed a *connected river subnetwork* or simply *subnetwork* for short. To better understand this basic structure of this problem, consider the illustrative example shown in Fig. 1.

In this example, 4 artificial barriers (1–4) and river confluences separate a hypothetical basin into a total of 7 river segments (S1–S7), depicted as alternating solid and dashed curves (Fig. 1a). The value in parentheses next to each segment indicates the amount of available habitat in quality-adjusted river kilometers. The river segments, in turn, combine to form 5 subnetworks (N1-N5). Currently, the highlighted subnetwork N2 is the largest with a combined total of 5.3 km of river habitat. In the simplest case where the cost of removal is equal for all barriers, barrier 2 would be the single best one to remove (Fig. 1b). This would reconnect subnetworks N2 and N3 resulting in a newly formed 7.7 km subnetwork (N2′). If two barriers can be removed, then the optimal solution would be to remove barriers 3 and 4 (Fig. 1c), resulting in an 8.8 km subnetwork (N2″) formed by reconnecting subnetworks N2, N4 and N5.

Note here the lack of nestedness between solution 1 (Fig. 1b) and solution 2 (Fig. 1c). Specifically, solution 1 does not form a subset of solution 2, meaning that barrier 2 is not included in solution 2. As a rule, the set of barriers targeted for removal at one budget level may not all be contained among those given a higher budget. In practical terms, this implies that an optimal solution cannot be constructed in an iterative fashion by simply selecting

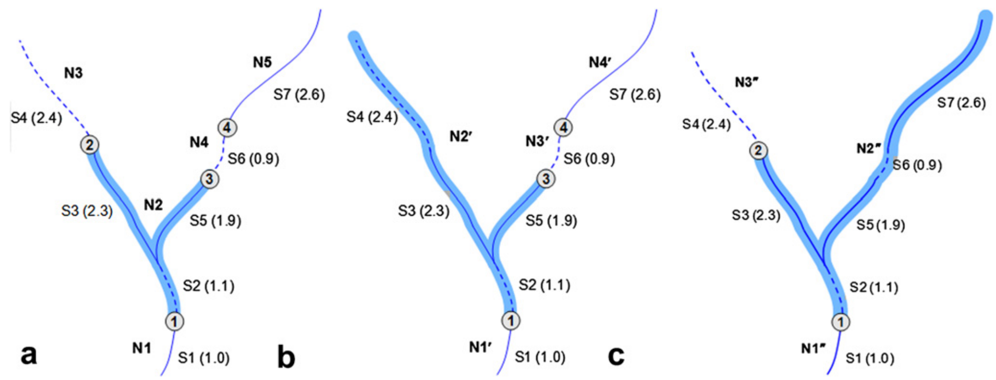

Fig. 1. Hypothetical river barrier network showing all connected river subnetworks formed by existing barriers (a) and following the optimal removal of either 1 barrier (b) or 2 barriers (c). Barriers, which are depicted as circular nodes, numbered 1–4, initially separate the basin into 7 confluence bounded river segments, labeled S1–S7 and depicted as alternating solid and dashed curves. The current largest connected river subnetwork (N2) and those formed following the removal of one (N2′) or two (N2″) barriers are denoted with a light blue shade. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

barriers in turn to form larger and larger subnetworks. Hence, simple scoring-and-ranking procedures most often used for barrier prioritization by environment and transportation agencies (Taylor and Love, 2003; Kocovsky et al., 2009; WDFW, 2009) will generally fail to give the biggest bang for the buck in terms of the amount of restored river habitat. In contrast, optimization based methods (Kemp and O'Hanley, 2010), like the one presented below, easily overcome this difficulty.

2.2. Optimization model

To formulate mathematically the problem of removing barriers in order to create a maximal river subnetwork, consider the following notation. It is assumed there are total of n artificial problem barriers, indexed by j, each of which at least partially restricts fish passage or the natural flow of a river. For each barrier j, it costs c_j to remove it. In what follows, we will use the term "removal" in the broadest sense to mean any mitigation action, including physical removal and repair, which completely eliminates (or to the greatest extent possible given logistical, financial and political constraints) all negative effects of a barrier on aquatic species movements and or river hydrology. The total budget available for removing artificial barriers is denoted by b. Artificial barriers separate a given focal river basin/subbasin into m confluence bounded river/stream segments, indexed by s and t. The amount of quality-weighted habitat for each river segment s is given by $w_s = q_s v_s$, where q_s is a measure of habitat suitability, in the range [0, 1], and v_s is the length or area (e.g., m or m^2) of the river segment. Let us define B_{st} as the set of artificial barriers j lying along the path between segment s and t. Finally, we include the following decision variables:

$$x_j = \begin{cases} 1 & \text{if barrier } j \text{ is selected for removal} \\ 0 & \text{otherwise} \end{cases}$$

$$y_{st} = \begin{cases} 1 & \text{if the path between river segments } s \text{ and } t \text{ is unimpeded by barriers} \\ 0 & \text{otherwise} \end{cases}$$

z_s = amount of quality-weighted habitat within the river subnetwork containing segment s

$\bar{z}$ = amout of quality-weighted river habitat for the largest river subnetwork

$$u_s = \begin{cases} 1 & \text{if the subnetwork with } s \text{ as the focal river segment is maximal} \\ 0 & \text{otherwise} \end{cases}$$

With this in place, a mixed integer linear programming (MILP) model for optimally removing barriers is given below. Formally, this model is referred to as the *maximum edge-weighted connected subgraph problem.*

$$\max \bar{z} \quad \text{s.t.} \tag{1}$$

$$\bar{z} \le z_s + M(1-u_s) \quad s = 1,\ldots,m \tag{2}$$

$$\sum_{s=1}^{m} u_s = 1 \tag{3}$$

$$z_s = \sum_{t=1}^{s-1} w_t y_{ts} + w_s + \sum_{t=s+1}^{m} w_t y_{st} \quad s = 1,\ldots,m \tag{4}$$

$$y_{st} \le \begin{cases} 1 & B_{st} = \varnothing \\ x_j & \forall j \in B_{st} \neq \varnothing \end{cases} \quad s = 1,\ldots,m-1, t = s+1,\ldots m \tag{5}$$

$$\sum_{j=1}^{n} c_j x_j \le b \tag{6}$$

$$u_s \in \{0,1\} \quad s = 1,\ldots,m \tag{7}$$

$$x_j \in \{0,1\} \quad j = 1,\ldots,m \tag{8}$$

The objective (1) maximizes the size of the largest river subnetwork. Inequalities (2) and equality (3) collectively form a set of *either-or* constraints that enforce $\bar{z}$ to be bounded above by the largest river subnetwork. Specifically, equality (3) ensures that only one of the m inequalities in (2), one for each river segment, will be active. The value M in (2) is a sufficiently large number such that if the subnetwork containing a particular segment s is not specified as being maximal ($u_s = 0$), then the corresponding constraint in (2) allows $\bar{z}$ to be unrestricted ($\bar{z} \le z_s + M$). On the other hand, if the subnetwork containing s is specified as being maximal ($u_s = 1$), then the corresponding constraint from (2) becomes binding ($\bar{z} \le z_s$). Given the maximization of $\bar{z}$, the corresponding variable u_s will be equal to 1 for this particular segment s, resulting in $\bar{z} = z_s$, as it should. Note that if the maximal subnetwork is made up of multiple segments, then the choice of which individual segment s to specify as being maximal is arbitrary.

To continue, equations (4) calculate the total amount of quality-adjusted river habitat connected through a particular segment s. This is equal to the sum of habitat contained in segments having indices less than s ($\sum_{t=1}^{s-1} w_t y_{ts}$), greater than s ($\sum_{t=s+1}^{m} w_t y_{st}$), and including s (w_s). Note that only those segments t *connected* to s by a barrier-free path ($y_{st} = 1, \ \forall t < s$, and $y_{st} = 1, \ \forall t > s$) are counted in the summation. Constraints (5), meanwhile, determine whether or not any pair of segments s and t ($s \neq t$) are indeed connected by a barrier-free path. Specifically, for all segment pairs s and t unimpeded by intervening barriers ($B_{st} = \varnothing$), variable y_{st} is simply required to be bounded above by 1. Conversely, for all segments s and t separated by one or more intervening barriers ($B_{st} \neq \varnothing$), all such barriers must be removed ($x_j = 1, \ \forall j \in B_{st}$) in order for the segments to be connected ($y_{st} = 1$). Constraint (6) ensures the total cost of barrier removal is less than or equal to the available budget. Lastly, constraints (7) and (8) place binary restrictions on all of the u_s and x_j variables, respectively. Note that due to the structure of the model, the y_{st} variables are automatically guaranteed to take on binary values.

As an aside, it should be noted that model (1)–(8) (and variants discussed below) is actually quite broad in its applicability. With a suitable redefinition of terms, the model could be used to plan the installation and expansion of various types of public utility infrastructure, including road and rail transport networks, irrigation, water supply and sewer system networks, and cable telecommunication networks, just to name a few.

2.3. Incorporation of additional biological factors

The model presented above focuses solely on quality-adjusted habitat. In some circumstances, however, a decision maker may wish to include other biological criteria within the planning framework. For example, an endangered species or rare communities may be present in some stream segments, which ideally should be targeted for protection. This can be incorporated into the model in one of two ways, either 1) including an additional weight in the w_s terms that provides extra incentive for reconnecting portions of a river where a biological target (i.e., a species/community of concern) is located or 2) using constraints that strictly require the maximal river subnetwork to include a biological target a specified number of times.

Let Ψ be the set of stream segments where a biological target is located. Using the former (and simpler) approach, an additional weight $h > 0$ can be defined representing the added value of including a biological target in the maximal subnetwork. The w_s terms specified in Equations (4) would then need to be changed to $w_s = q_s v_s + h$ for all segments in Ψ. The rest of the model would remain exactly the same. Different initial values for h could be assigned, such as the size of the maximum quality-adjusted stream segment (*i.e.*, $h = \max_s\{q_s v_s\}$) or some fraction of the maximum subnetwork size $\bar{z}^*$ corresponding to the particular budget value of interest. The value $\bar{z}^*$ can be found by first solving the basic model without any added biological weights. One could then perform a sensitivity analysis by changing the weight h up or down to see how this influences the results. For problems with multiple biological targets (i.e., several different species/communities of concern), a series of additional weights could be used. Given a total of r targets, aggregate weights in Equations (4) would need to be specified as $w_s = q_s v_s + \sum_{i=1}^{r} a_{si} h_i$ for all segments $s = 1,\ldots,m$, where coefficient a_{si} is equal to 1 if biological target i is present in stream segment s, 0 otherwise.

The alternative approach for including biological factors in the model would be to add the following set of constraints, which expressly require that at least one segment in Ψ be included in the maximal river subnetwork.

$$\sum_{\substack{t \in \Psi \\ t < s}} y_{ts} + \sum_{\substack{t \in \Psi \\ t > s}} y_{st} \geq u_s \qquad \forall s \notin \Psi \tag{9}$$

Constraints (9) state that if a segment s is chosen as the focal segment ($u_s = 1$), which does not itself include the target ($s \notin \Psi$), then it must be connected to a segment t that does contain the target (i.e., $\sum_{t \in \Psi, t<s} y_{ts} \geq 1$ and or $\sum_{t \in \Psi, t>s} y_{ts} \geq 1$). The advantage of this constraint form over say a much simpler one like $\sum_{s \in \Psi} u_s \geq 1$ is that it can be easily extended to require protection of a target multiple times. Assuming a biological target is found in more than one segment and a decision maker would like the target to be represented in at least $d > 1$ segments of the maximal subnetwork, constraints (9) can be replaced with:

$$\sum_{\substack{t \in \Psi \\ t < s}} y_{ts} + \sum_{\substack{t \in \Psi \\ t > s}} y_{st} \geq \begin{cases} du_s & s \notin \Psi \\ (d-1)u_s & s \in \Psi \end{cases} \qquad s = 1,\ldots,m \tag{10}$$

Note that adding constraints (9) for multiple biological targets and or (10) by itself may result in problems that are infeasible (i.e., no solution exists which satisfies the constraints). If this occurs, one can either try dropping/modifying the constraints or resort to the weighting method discussed previously.

2.4. Revised formulation

As a further refinement to the optimization model presented above, we can substitute constraint set (5) with the following, functionally equivalent set of inequalities.

$$y_{st} \leq \begin{cases} 1 & t \in \Gamma(s), B_{st} = \varnothing \\ x_j & t \in \Gamma(s), B_{st} = \{j\} \\ y_{sk} & t \notin \Gamma(s), k = link_{s \to t} \\ x_j & t \notin \Gamma(s), k = link_{s \to t}, B_{kt} = \{j\} \end{cases} \qquad s = 1,\ldots,m-1, t = s+1,\ldots m \tag{11}$$

Here, $\Gamma(s)$ specifies the set of river segments directly adjacent to segment s, while $link_{s \to t} = \operatorname{argmin}_{\ell \in \Gamma(t)}(d_{s\ell})$ determines the river segment k adjacent to t that is closest to s (i.e., the river segment k along the direct path from s to t that would be traversed immediately before arriving at t).

Constraints (11) state that if segments s and t are adjacent ($t \in \Gamma(s)$) and have no artificial barrier separating them ($B_{st} = \varnothing$), then y_{st} is bounded above by 1 (Case 1). If the two segments are separated by a barrier ($B_{st} = \{j\}$), however, then the barrier j lying between them must be removed ($x_j = 1$) in order for y_{st} to take on a value of 1 (Case 2). In the case where segments s and t are not adjacent to each other ($t \notin \Gamma(s)$), variable y_{st} can be 1 only if the path from s to the nearest segment k adjacent to t is free ($y_{sk} = 1$) (Case 3). Furthermore, if segments k and t are separated by a barrier ($B_{kt} = \{j\}$), then this barrier must also be removed ($x_j = 1$) to allow

y_{st} to be 1 (Case 4). With reference to Fig. 1, each of the four different cases specified in (11) is given below for a subset of river segment pairs.

(Case 1)	$y_{S2,S3} \le 1$	$S3 \in \Gamma(S2),\ B_{S2,S3} = \emptyset$
(Case 2)	$y_{S3,S4} \le x_2$	$S4 \in \Gamma(S3),\ B_{S3,S4} = \{2\}$
(Case 3)	$y_{S4,S5} \le y_{S3,S4}$	$S5 \notin \Gamma(S4),\ S4 = link_{S4\to S5},\ B_{S4,S5} = \emptyset$
(Case 4)	$y_{S4,S6} \le y_{S4,S5}$	$S6 \notin \Gamma(S4),\ S5 = link_{S4\to S6},\ B_{S5,S6} = \{3\}$
	$y_{S4,S6} \le x_3$	

The main advantage of (11) over (5) is that it is considerably more compact in size. Whereas in (5) a constraint of the form $y_{st} \le x_j$ is required for all barriers $j \in B_{st}$ lying between two nonadjacent, unconnected segments s and t ($t \notin \Gamma(s)$, $B_{st} \ne \emptyset$), in (11), this can be represented with just two constraints: $y_{st} \le y_{sk}$, $k = link_{s\to t}$, and $y_{st} \le x_j$, $k = link_{s\to t}$, $B_{kt} = \{j\}$. Consequently, given networks with a sufficiently large number of barriers and river segments, the use of (11) will invariably produce models having far fewer numbers of constraints. As an example, for the watershed used in the case-study (details described below), there are 544 river segments with an average of 4.16 artificial barriers between each of the 147,696 segment pairs. Based on (5), this produced a total of 623,402 connectivity constraints; using (11), there were just 194,030, less than a third of the number. As a result of its very large size, in fact, the original model had very large optimality gaps for all budget values (e.g., 97.8% given a $1M budget) even after 6 h of solution time.

2.5. Solution methodology

The revised model: (1)–(4), (6)–(8) and (11) was coded in C++ using CPLEX version 12.1 callable libraries (IBM ILOG 2009). CPLEX is a state-of-art commercial software package that employs a branch and bound algorithm to solve MILPs. All experiments reported below were run on the same quad-core (2.53 GHz per chip) HP Z600 workstation with 6 GB of RAM.

As opposed to solving the optimization model directly, however, a "divide and conquer" approach, referred to as *problem decomposition*, was employed as follows. For any given budget amount, the size of the maximum river subnetwork connected through a particular segment s can be determined by solving the model with $u_s = 1$. By repeating this for all m segments, it is a simple matter to find the largest overall subnetwork (i.e. a global maximum). Although this does necessitate solving m different *subproblems*, one for each segment, a major advantage of it is that each subproblem is considerably smaller in size than the full revised model and hence relatively easy to solve. Specifically, for any given subproblem involving focal segment s, all variables and constraints not pertaining to s (i.e., z_t, $t \ne s$, and y_{kt}, k, $t \ne s$) can simply be removed.

As an additional refinement, it is even possible to remove some stream segments from consideration if certain minimum requirements are not met. Specifically, consider the objective value of the best feasible solution found prior to solving the subproblem involving segment s as the focal river segment. This value provides a *lower bound* to the entire optimization problem. Further, consider the largest possible subnetwork connected through segment s, with s being located furthest downstream. The location of the focal segment in the maximum subnetwork is arbitrary so s can be specified as the one furthest downstream. An *upper bound* on the size of this network is equal to the amount of river habitat within s plus the amount upstream of or confluent with it. Consequently, if the upper bound for segment s does not exceed the current lower bound, then clearly s cannot be the maximum focal stream segment and there is no need to solve this particular subproblem.

Preliminary testing based on the case-study dataset (details described below) showed the decomposition approach to be much more efficient at solving instances with budget values in excess of $50 K compared to direct solution of the full model. Whereas the full model contained a total of 195,120 constraints, each subproblem had, in effect, at most 670 constraints. Further, not all of the subproblems needed to be solved. Consequently, whereas the full revised model still had a 76.4% optimality gap after 6 h of solution time given a $1 M budget, the decomposition method yielded an optimal solution in just over 100 s.

2.6. Study area

To examine its performance and critically analyze proposed barrier removal strategies for different budget amounts, the optimization model was run on barrier and river network data obtained from the Pike River Watershed (PRW), located in northeast Wisconsin, USA. The PRW, which empties into Lake Michigan, is a predominately forested area covering 284.7 square miles (73,747.5 ha). Anthropogenic impacts are minimal for the most part; the Pike River is one of only four state designated wild rivers protected from development and designed to be maintained in a natural, free-flowing condition (WDNR 2010). Areas along tributaries and the main stem of the river, which can reach over 100 feet (30.5 m) in width, are characterized by a wide range of habitats, including aspen and northern hardwood stands, swamp conifer, wetlands and rocky outcrops (WDNR 2010).

In spite of its protected status, however, a fair number of barriers are nonetheless present in the PRW. Extensive field surveys conducted by the US Fish and Wildlife Service have identified a total of 125 artificial river barriers in the PRW (Fig. 2), all of which at least partially restrict fish movements and or natural surface flows. The vast majority of these barriers consist of small road crossings, mainly improperly installed and undersized culverts. The estimated cost to remove all existing artificial barriers is $7,750,248. On an individual basis, removal costs (rounded to the nearest $1000) range from just $2000 for minor repairs to $500,000 each to remove two medium-sized dams.

Natural barriers, namely waterfalls, of which there are 11 in total in the PRW, are assumed to be regular, permanent features of the landscape and, thus, not subject to removal. Furthermore, natural barriers have been assumed not to have any undue impact on baseline river connectivity, meaning that river segments separated by a natural barrier are nonetheless regarded as being effectively connected. The end result is that natural barriers have been entirely excluded from consideration within the present case-study.

It should be noted, however, that there is nothing intrinsic to the model that would prevent one from treating natural barriers the same as artificial barriers. Natural barriers could be included in set B_{st} along with artificial barriers if so desired. The primary justification for this is to prevent the objective value of the model from becoming capped and so encourage removal of all artificial barriers within a given watershed. If natural barriers are

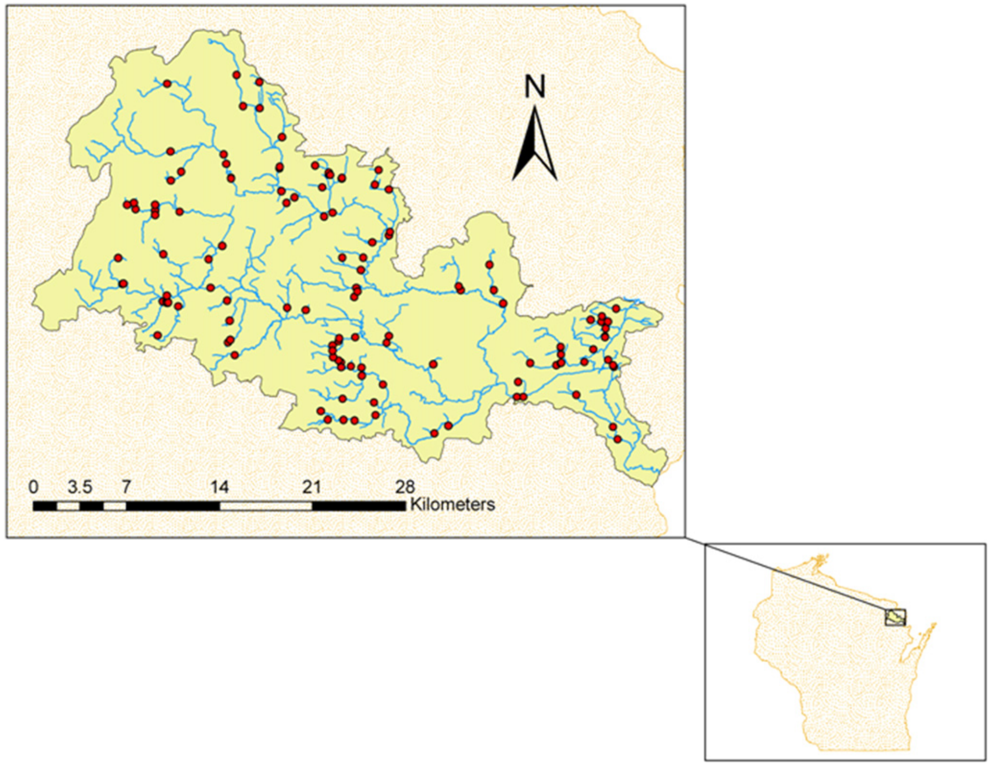

Fig. 2. The Pike River Watershed. Known artificial river barriers are shown as solid red circles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

included but cannot be removed (i.e., because they are natural features), then the stream network becomes permanently separated into distinct subnetworks. With a sufficient budget, one will be able to remove all barriers within the largest of these subnetworks. For larger budgets, however, there is no impetus to remove more artificial barriers in other subnetworks as the size of maximum subnetwork can only be further increased by removing the set of natural barriers which isolate it from the other subnetworks.

Data pertaining to river segments were compiled by the US Forest Service using procedures developed by Diebel et al. (2010). In short, this was carried out within a geographic information system (GIS) by taking a 1:24,000-scale river network layer derived from the National Hydrography Dataset (Simley and Carswell, 2009), adding additional stream segments that had not been previously mapped and then correcting for spatial errors in the data. Next, the geographic coordinates of all known artificial and natural barriers were imported into the GIS and snapped onto the river network layer. As a final step, the river network was split into 544 confluence-bounded river segments. Primary data for each segment includes an estimate of its length (L_s) in meters. For lack of data, habitat suitability indices (q_s) were assumed to be 1.0 for all segments. Lack of such data here does not detract from the main conclusions of the paper nor does it indicate that such data may not be easily obtainable in general. Suitability values can be calculated in straightforward way with remotely sensed data (Tiner, 2004). Hence the increased data requirements of using quality-adjusted river length instead of river length alone are modest.

Geospatial barrier and river segment data were kindly supplied by the US Forest Service (M. Fedora, USDA Forest Service, E6248 US Highway 2, Ironwood, MI 49938, USA, unpublished data) and subsequently reprocessed by the US Fish and Wildlife Service (C. Soucy, 4R Fundy Rd., Falmouth, ME 04105, USA).

3. Results

Table 1 provides some basic computational results generated with the optimization model across a range of budget values. Reported values in Table 1 include the optimal objective value (size of the maximum connected river subnetwork in kilometers), solution time (in seconds), the total number of simplex iterations and total number of branch and bound nodes. Overall, the model was deemed to be highly efficient. Optimal solutions were always found in less than 2 min (maximum 101.3 s). For high budget values ($\geq$\$6 M), solution time was considerably less, under 30 s in all cases, with reading of input files accounting for more than half of the total (results not shown). The amount of branching, another indication of how difficult a problem is to solve, was quite small (109.6 nodes on average) and tended to decrease with increasing budget.

Table 1
Computational results for the optimization model.

Budget	Objective (km)	Time (sec)	Iterations	Nodes
$0	140.64	55.88	0	0
$1,000,000	322.54	100.86	14305	413
$2,000,000	402.38	100.97	11801	19
$3,000,000	457.26	101.30	12328	286
$4,000,000	505.94	68.17	6032	257
$5,000,000	542.48	39.98	2286	0
$6,000,000	560.91	27.00	587	0
$7,000,000	567.70	21.63	305	11
$7,750,248	569.06	18.77	0	0
Avg	-	59.40	5293.8	109.6

"Time" denotes the number of CPU seconds CPLEX took to solve a particular budget level, "Iterations" refers to the total number of simplex algorithm iterations and "Nodes" indicates the total number of nodes searched within the branch and bound tree.

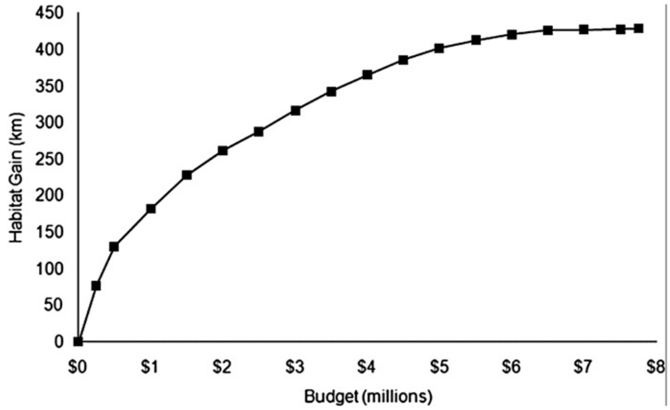

Fig. 3. Broad-scale pattern of habitat gain (km) versus large budget increments ($M).

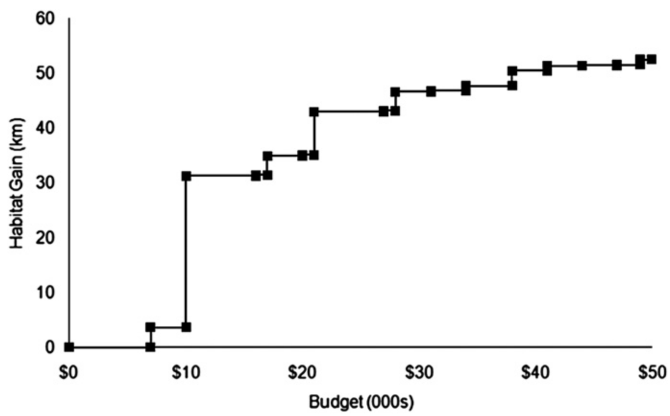

Fig. 4. Fine-scale pattern of habitat gain (km) versus small budget increments ($K).

Looking at the range of objective values, one clear pattern is a decreasing marginal gain in terms of the investment in barrier removal required to increase of the size of the largest river subnetwork. With a budget of $1 M, the maximum subnetwork more than doubled in size from 140.64 river km to 322.54 km (net gain of 181.90 km). Increasing the budget by an additional $1 M to $2 M, the gain was 79.83 km, equating to about a 25% improvement. At higher budget values, gains were markedly less. Increasing the budget from $6 M to $7 M, for example, produced only 6.79 km of additional connected habitat (approx. 1% gain).

The general pattern of habitat gain versus budget is more clearly shown in Fig. 3. Looking at the graph, it is clear that there is a large increase in habitat for the first $500 K investment in barrier removal: a gain of 130.68 km. Beyond this, increases are more modest, becoming approximately linear between $1 M and $4 M and then tapering off sharply after $5 M.

Fig. 3, however, gives an incomplete picture of the complex relationship between the cost and benefit of barrier removal. There are, in fact, clear thresholds in terms of the budget, below which little or no habitat gain may be observed. Fig. 4 shows, in detail, how small incremental changes in the budget actually produce a step-wise pattern of habitat gain. The graph shows that habitat gain is actually zero until the budget reaches $7 K, yielding a relatively small 3.67 km net increase. The total amount of open, connected habitat then remains constant until the budget reaches $10 K, whereupon a considerably larger 27.60 km net gain is produced. Similar small and medium discrete changes in habitat gain are seen for higher budget amounts.

Detailed analysis of this kind can be especially useful in strategic planning and decision making within governmental agencies and other nonprofit organizations involved in watershed planning and management. First of all, it focuses attention on the importance of setting cost-effective restoration goals by highlighting the critical levels of financial investment needed to produce comparatively large restoration gains. Second, it also provides a firm evidence base in supporting all levels of budget planning, including proposal, negotiation and allocation processes.

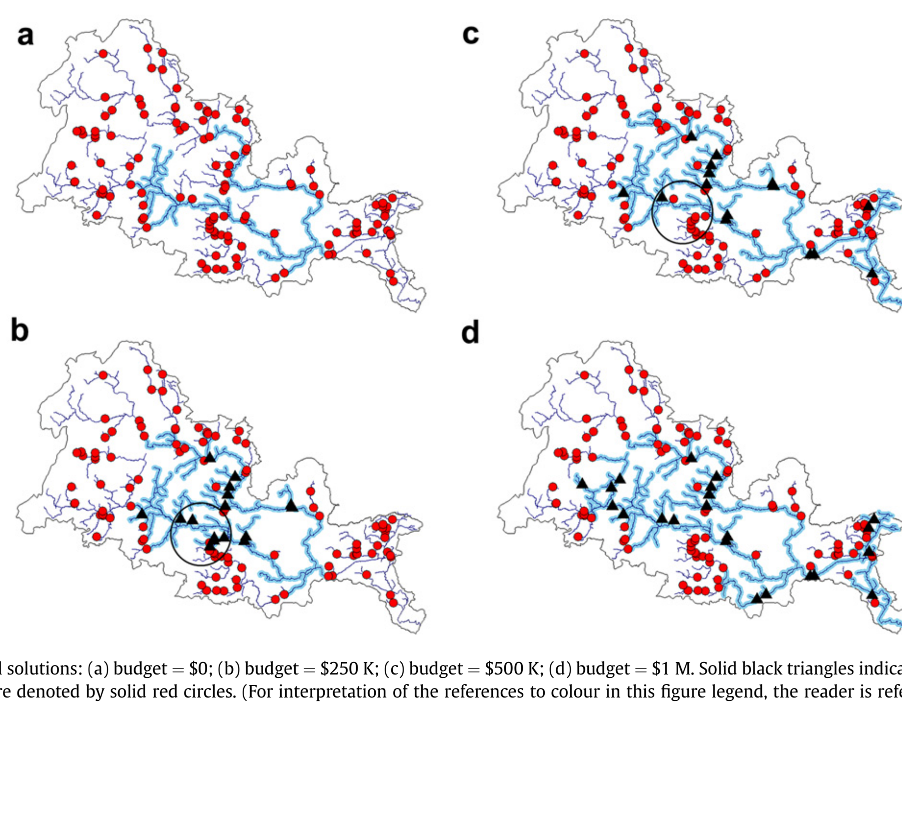

Fig. 5. Optimal barrier removal solutions: (a) budget = $0; (b) budget = $250 K; (c) budget = $500 K; (d) budget = $1 M. Solid black triangles indicate artificial barriers selected for removal. Remaining barriers are denoted by solid red circles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Finally, it can be instructive to analyze the spatial structure of solutions generated by the optimization model. Fig. 5 shows how the size and spatial layout of the maximum river subnetwork changes for a range of different budget amounts. Given no barrier removal (Fig. 5a), the largest existing river subnetwork is situated in the central part of the watershed, mostly along the middle portions of the main North and main South branches of the Pike River. This existing maximal subnetwork forms a primary backbone around which barrier removals are targeted in order to reconnect isolated upstream and downstream sections. For example, with a budget of $250 K (Fig. 5b), a number of barriers are removed in the central part of the watershed in order to open various small, upstream tributary areas in the center and toward the west. Increasing the budget to $500 K (Fig. 5c), a large stretch of river is opened downstream toward the east all the way toward the mouth of the Pike River. Increasing the budget further still to $1M mostly results in the opening up of upstream tributaries along the South branch of the Pike River.

Of special note, as mentioned previously in Section 2.1, is the lack of perfect nestedness among the different solutions shown in Fig. 5. Focusing specifically on Fig. 5b and c, whereas with $250 K 6 barriers can be removed within the circled area, only 1 can be removed when the budget increases to $500 K. The consequence of this is that some tributaries opened up with a budget of $250 K, including the one behind the bottom (most southern) barrier in the circular area of Fig. 5b, are no longer reconnected to the main backbone subnetwork when the budget is increased to $500 K.

As a caveat, lack of nestedness is likely to be more pronounced at low budget values. In many instances, removal may become an essentially additive process at some critical budget level such that all barriers removed at one budget level will also be removed given higher levels of investment. For the PRW this is indeed the case. For budgets of $4 million and higher the solutions are all perfectly nested (results not shown).

4. Conclusion

Fluvial ecosystems in many parts of the world have been significantly degraded by the presence of river infrastructure, such as dams, weirs, culverts and levees. They often impede the dispersal of aquatic species like fish and disrupt flow, sediment and nutrient transport. This, in turn, can have a cascading affect on native species and ecosystem health, not only within the river corridor itself, but also in adjacent riparian, wetland and coastal areas.

As recognition of the environmental problems caused by river infrastructure has grown within public and policy circles, so too has the problem of how to remove problem structures in a systematic and cost-effective manner. In contribution to this, an optimization model is presented in this paper for prioritizing the removal of problematic river infrastructure (i.e., barriers), which impede aquatic organism dispersal or adversely affect natural hydrology. Its specific aim is to decide which barriers to remove, subject to a limited budget, in order to maximize the size of the single largest section of river unimpeded by barriers. Key features of the model include (i) its applicability to resident (potamodromous) fish species and other aquatic organisms by way of restoring expansive fully connected areas of river wherever possible (not just from the mouth of the river upstream) and (ii) its minimal data requirements – only basic data pertaining to river length/quality, barrier location and barrier removal cost and are required.

The model is formulated as a mixed integer linear program. Techniques for efficiently solving realistic, large-sized problem instances are also presented. Results based on a case-study from the Pike River Watershed in northeast Wisconsin, USA show that optimal solutions can be generated quickly, often in less than a minute. The results also show, as in other studies, a decreasing marginal gain in the amount of restored habitat that can be attained with increasing budget amounts. Importantly though, there are clear budget thresholds below which habitat gain may be quite modest or even negligible. Analysis of the spatial configuration of barrier removals at different budget amounts confirms that solutions may not be perfectly nested, meaning that barriers targeted for removal at one budget level may not be given a moderately higher budget.

With regard to future research, there are number of ways the modeling approach presented could be improved or extended. For example, instead of considering the single largest barrier-free subnetwork, one might want to optimize the combined size of two barrier-free sections, which though individually shorter than the longest are together much longer. Naturally, this could be extended up to combinations of three subnetworks and so on. Devising a linear integer programming model capable of handling this might be a considerable challenge and would almost certainly lead to problems that are much larger and harder to solve. Heuristic methods would seem a more tractable approach but would lack any guarantee of optimality.

Another alternative would be to work on the development of entirely new models which move away from using "fully connected" stream length to describe overall river connectivity status. One option, as employed in Cote et al. (2009), would be to incorporate barrier passability (assuming data exit) and assess how removal of barriers improves connectivity between each and every river segment. Research along this line is actively being pursued with colleagues.

More generally speaking, optimization and heuristic based solution methods could be coupled together with surface flow and sediment transport models (Stromberg, 1993; Burke et al., 2009; Brown and Pasternack, 2009), fish population and community dynamic models (Paulsen and Wernstedt, 1995; Zheng et al., 2009) and bioeconomic models (Johnson and Adams, 1988) in order to directly evaluate the range of potential environmental, ecological and economic benefits of barrier removal. Such models might adopt a multi-objective approach in which the size of the largest connected river network is traded-off with various hydrologic and ecological variables of interest, including mean water temperature, annual sediment yield, deviance from natural hydrograph peaks and troughs, and the abundance/richness of native aquatic and riparian species.

Acknowledgments

I am grateful to three anonymous referees and the editor for their very helpful comments on an earlier draft of this paper. I would also like to thank Mark Fedora from the USDA Forest Service Eastern Region, Ottawa National Forest for editorial comments as well as the provision of geospatial barrier and river network data used in the case-study. I would also like to thank Charles Soucy for reprocessing the GIS data and Sam Bordbar for his contributions to the literature review.

References

Bednarek, A.T., 2001. Undamming rivers: a review of the ecological impacts of dam removal. Environmental Management 27, 803–814.

Beechie, T., Beamer, E., Wasserman, L., 1994. Estimating coho salmon rearing habitat and smolt production losses in a large river basin, and implications for habitat restoration. North American Journal of Fisheries Management 14, 797–811.

Bernhardt, E.S., Palmer, M.A., Allan, J.D., et al., 2005. Synthesizing US river restoration efforts. Science 308, 636–637.

Brown, R.A., Pasternack, G.B., 2009. Comparison of methods for analysing salmon habitat rehabilitation designs for regulated rivers. River Research and Applications 25, 745–772.

Burke, M., Klaus, J., Buffington, J.M., 2009. Application of a hierarchical framework for assessing environmental impacts of previous dam term operation: changes in streamflow, bed mobility and recruitment of riparian trees in a western North American river. Journal of Environmental Management 90, S224–S236.

Campo, J., Sancholuz, L., 1998. Biogeochemical impacts of submerging forests through large dams in the Río Negro, Uruguay. Journal of Environmental Management 54, 59–66.

Catalano, M.J., Bozek, M.A., Pellett, T.D., 2007. Effects of dam removal on fish assemblage structure and spatial distributions in the Baraboo River, Wisconsin. North American Journal of Fisheries Management 27, 519–530.

Clavero, M., Blanco-Garrido, F., Prenda, J., 2004. Fish fauna in Iberian Mediterranean river basins: biodiversity, introduced species and damming impacts. Aquatic Conservation: Marine and Freshwater Ecosystems 15, 415–426.

Cote, D., Kehler, D.G., Bourne, C., Wiersma, Y.F., 2009. A new measure of longitudinal connectivity for stream networks. Landscape Ecology 24, 101–113.

Diebel, M., Fedora, M., Cogswell, S., 2010. Prioritizing road crossing Improvement to restore stream connectivity for stream-resident fish. In: Wagner, P.J., Nelson, D., Murray, E. (Eds.), Proceedings of the 2009 International Conference on Ecology and Transportation. Center for Transportation and the Environment, North Carolina State University, Raleigh, NC, pp. 647–660. Available online: <http://www.icoet.net/ICOET_2009/downloads/proceedings/ICOET09-Proceedings-Session411.pdf> (accessed 19.09.10).

Dynesius, M., Nilsson, C., 1994. Fragmentation and flow regulation of river systems in the northern third of the world. Science 266, 753–762.

Hughes, F.M.R., Rood, S.B., 2003. Allocation of river flows for restoration of floodplain forest ecosystems: a review of approaches and their applicability in Europe. Environmental Management 32, 12–33.

Johnson, N.S., Adams, R.M., 1988. Benefits of increased streamflow: the case of the John Day river steelhead fishery. Water Resources Research 24, 1839–1846.

Kemp, P.S., O'Hanley, J.R., 2010. Evaluation of barriers to fish migration and prioritisation of removal and mitigation projects. Fisheries Management and Ecology 17, 297–322.

Kocovsky, P.M., Ross, R.M., Dropkin, D.S., 2009. Prioritizing removal of dams for passage of diadromous fishes on a major river system. River Research and Applications 25, 107–117.

Kuby, M.J., Fagan, W.F., ReVelle, C.S., Graf, W.L., 2005. A multiobjective optimization model for dam removal: an example of trading off salmon passage with hydropower and water storage in the willamette basin. Advances in Water Resources 28, 845–855.

O'Hanley, J.R., Tomberlin, D., 2005. Optimizing the removal of small fish passage barriers. Environmental Modeling and Assessment 10, 85–98.

ODFW, 2011. Oregon Fish Passage Barrier Data Standard dataset, Version 2. Oregon Department of Fish and Wildlife (ODFW), Salem, OR. <http://nrimp.dfw.state.or.us/OregonPlan/default.aspx?p=134&XMLname=44.xml>.

Pardalos, P.M., Resende, M. (Eds.), 2002. Handbook of Applied Optimization. Oxford University Press, New York, NY.

Paulsen, C.M., Wernstedt, K., 1995. Cost-effectiveness analysis for complex managed hydrosystems: an application to the Columbia river basin. Journal of Environmental Economics and Management 28, 388–400.

Pess, G.R., McHenry, M.L., Beechie, T.J., Davies, J., 2008. Biological impacts of the Elwha River dams and potential salmonid responses to dam removal. Northwest Science 82 (Special Issue), 72–90.

Roni, P., Beechie, T., Bilby, R., Leonetti, F., Pollock, M., Pess, G., 2002. A review of stream restoration techniques and a hierarchical strategy for prioritizing restoration in Pacific Northwest watersheds. North American Journal of Fisheries Management 22, 1–20.

Santucci Jr., V.J., Gephard, S.R., Pescitelli, S.M., 2005. Effects of multiple low-head dams on fish, macroinvertebrates, habitat, and water quality in the Fox River, Illinois. North American Journal of Fisheries Management 25, 975–992.

Shaffer, J.A., Crain, P., Winter, B.D., McHenry, M.L., Lear, C., Randle, T.J., 2008. Nearshore restoration of the Elwha River through removal of the Elwha and Glines Canyon dams: an overview. Northwest Science 82 (Special Issue), 48–58.

Sheer, M.B., Steel, E.A., 2006. Lost watersheds: barriers, aquatic habitat connectivity, and salmon persistence in the Willamette and Lower Columbia River basins. Transactions of the American Fisheries Society 135, 1654–1669.

Simley, J.D., Carswell Jr., W.J., 2009. The national map – hydrography. Fact Sheet 2009-3054. US Geological Survey.

Slawski, T.M., Veraldi, F.M., Pescitelli, S.M., Pauers, M.J., 2008. Effects of tributary spatial position, urbanization, and multiple low-head dams on warmwater fish community structure in a Midwestern stream. North American Journal of Fisheries Management 28, 1020–1035.

Spens, J., Englund, G., Lundqvist, H., 2007. Network connectivity and dispersal barriers: using geographic information systems (GIS) tools to predict landscape scale distribution of a key predator (*Esox lucius*) among lakes. Journal of Applied Ecology 44, 1127–1137.

Stanford, J.A., Ward, J.V., Liss, W.J., Frissell, C.A., Williams, R.N., Lichatowich, J.A., Coutant, C.C., Stanford, J.A., Ward, J.V., Liss, W.J., Frissell, C.A., Williams, R.N., Lichatowich, J.A., Coutant, C.C., 1996. A general protocol for restoration of regulated rivers. Regulated Rivers: Research & Management 12, 391–413.

Stromberg, J.C., 1993. Instream flow models for mixed deciduous riparian vegetation within a semiarid region. Regulated Rivers: Research & Management 8, 225–235.

Taylor, R.N., Love, M., 2003. California Salmonid Stream Habitat Restoration Manual – Part IX Fish Passage Evaluation at Stream Crossings. California Department of Fish and Game, Sacramento, CA, 100 pp.

Tiner, R.W., 2004. Remotely-sensed indicators for monitoring the general condition of "natural habitat" in watersheds: an application for Delaware's Nanticoke River watershed. Ecological Indicators 4, 227–243.

WCD, 2000. Dams and Development: A New Framework for Decision-Making. World Commission on Dams (WCD), Earthscan Publications Ltd, London. 356 pg. Available online: <http://www.dams.org//docs/report/wcdreport.pdf> (accessed 1.12.10.).

WDFW, 2009. Fish Passage Barrier and Surface Water Diversion Screening Assessment and Prioritization Manual Washington. Department of Fish and Wildlife (WDFW), Olympia, WA, 240 pp. Available online: <http://wdfw.wa.gov/hab/engineer/fishbarr.htm> (accessed 06.06.10).

WDNR, 2010. Pike River Wild River. Wisconsin Department of Natural Resources (WDNR). Available online: <http://dnr.wi.gov/org/land/facilities/pikeriver/index.html> (accessed 15.11.10).

Winston, W.L., 2003. Operations Research: Applications and Algorithms, fourth ed. Duxbury Press, Belmont, CA.

WWF, 2001. The Status of Wild Atlantic Salmon: A River by River Assessment. World Wildlife Fund (WWF). 184 p. Available online: <http://assets.panda.org/downloads/salmon2.pdf> (accessed 22.11.10).

Zheng, P.Q., Hobbs, B.F., Koonce, J.F., 2009. Optimizing multiple dam removals under multiple objectives: linking tributary habitat and the Lake Erie ecosystem. Water Resources Research 45, W12417.