OPTIMIZING FISH PASSAGE BARRIER REMOVAL USING MIXED INTEGER LINEAR PROGRAMMING

Carla P. Gomes Ashish Sabharwal
Dept. of Computer Science, Cornell University, Ithaca, NY 14853-7501, U.S.A.

Extended Abstract, CROCS-09 Workshop, Sep 2009

We study the problem of minimizing the impact of man-made stream barriers on the upstream and downstream movement of migratory fish. A good example is anadromous fish such as salmon, which need upstream accessibilty from the ocean water to high quality rearing and spawning habitat in side channels or upper tributaries of a river. Various studies have shown that small barriers such as dams, culverts, dikes, levees, floodgates, and weirs have a dramatic impact on the natural movement of fish, resulting in significant decrease in fish population due to factors such as increased mortality and predation on one hand and decreased egg production on the other [cf. 1, 2]. E.g., salmon stocks have been reduced by over 40% of their historical range in the Pacific Northwest and over 80% in the Atlantic Northeast. While barriers such as dams and levees completely block upstream fish movement, others such as floodgates and many culverts result in partial or temporal barriers. Barriers have indirect impacts as well, such as increasing the level of inbreeding among resident (i.e., non-migratory) fish, lowering nutrient inputs to upstream reaches provided by the carcasses of anadromous adults, and causing artificial selection for stronger swimming fish species [2].

While several factors contribute to fish population decline, man-made barriers have been identified both as one of the main causes and, at the same time, one of the most cost-effective opportunities to address the situation [5]. Extensive engineering guidelines have been developed for the building of new barriers and the retrofitting of existing barriers in order to enhance fish passage [e.g., 6]. However, as with many conservation related problems, planners and decision makers must work with a *limited budget*, which leads to the need for prioritization in terms of (1) which barriers within a river system to target and (2) which of several possible repair and restoration projects to undertake at each targeted barrier. This work treats this problem as a combinatorial optimization problem and studies the use of Mixed Integer (Linear) Programming as a solution method. Specifically, it addresses the question: *Given a budget, a stream topology, a set of barriers, and a set of corresponding possible repair/restoration projects, which projects should one undertake at which barriers in order to maximize the net habitat accessibility of fish within the given budget?*

Informally, in most of the current approaches, including ours, expert knowledge is used to assign a (*cost*, *benefit*) pair to each possible repair and restoration project that may potentially be performed at any given barrier. The *benefit* is often represented in terms of the resulting "passability" score, a real number in the range $[0, 1]$ that may be thought of the fraction of fish that will be able to pass through the barrier if the project were to be undertaken. Most of the initial work on this problem was based on a *scoring and ranking* approach [e.g., 4]. Here each barrier is considered individually and chosen (or not) based on the cost to utilty ratio as a metric. As expected, this approach is highly scalable and easy to implement, but misses the key spatial relationship between barriers—and hence can be substantially sub-optimal [2]. E.g., undertaking a high-utility high-cost project at a barrier in the upstream regions without ensuring that its downstream barriers also have a reasonably high passability is wasteful. In the context of stream structures with a "tree-like" topology and for the "upstream" accessibility variant of the problem, O'Hanley and Tomberlin [2] addressed this issue by formulating this as a structure-aware combinatorial optimization problem. They represented the constraints of the problem in terms of an Integer *Non-linear* Programming model, where the degree of the constraints was as high as the number of barriers along a root-to-leaf path of the underlying tree structure (i.e., the number of barriers downstream from any given point). As a solution method, they proposed a *dynamic programming* approach, which was shown to scale well for the instance sizes they considered. At the same time, their study recognized that dynamic programming may not scale to problem sizes that one would like to address in practice, and also proposed a heuristic solution approach.

Contribution. We extend this line of work by proposing the use of stronger and yet more flexible Mixed Integer *Linear* Programming techniques (referred from now on simply as "MIP" techniques) for optimal solutions to the fish barrier removal and restoration problem. This is expected to have several advantages over the specialized dynamic programming or heuristic methods proposed earlier: a MIP formulation will result in (1) better scalability which is highly desirable [3], (2) flexibility of incorporating additional constraints if and when needed, (3) incorporating the important but less well understood "downstream" accessibility problem [3] in addition to the currently studied "upstream" accessibility, and (4) providing opportunities to relax the "tree-like" topology assumption, which does not hold in many real scenarios [3].

We propose a linearization of the high-degree model considered by O'Hanley and Tomberlin [2] for the upstream accessibility problem on tree-like stream topology. Furthermore, we also extend this linearized model to take into account both upstream and downstream fish migrations. While similar sounding, the downstream problem even on a tree-like stream topology poses design decisions and modeling choices not present in the original upstream problem. For example, rather than assuming a single large fish mass in the ocean wanting to migrate upstream, one must work with several smaller fish masses in upstream regions and consider their accessibility downstream. This necessitates working with actual fish masses rather than simply with fractions or proportions of a single fish mass. Another issue to consider is the utility value of "slightly" downstream regions vs. the extreme downstream region composed of the sea or ocean. For example, being able to reach a region very close to the sea could be much more rewarding for certain fish than being able to reach a region already relatively close to their usual upstream habitat.

Our ongoing work involves an experimental evaluation of the proposed approach on both real and synthetic data, especially with regard to scaling issues. The initial real data considered is based on what was used by O'Hanley and Tomberlin [2], namely, several culvert network datasets in the State of Washington, which were created based on GIS data obtained from the SSHEAR database and information from Washington Department of Fish and Wildlife's Fish Program and the Snohomish County Surface Water Management department.

Extensions. One would like to relax the assumption that the stream structure has a tree-like topology, i.e., that streams only merge as they go downstream, they never split into multiple sub-streams and then merge later. Allowing for streams to split leads to a directed acyclic graph (DAG) topology, which immediately raises several design and implementation issues. For instance, when an upstream region A is connected to a downstream region B through two paths with barriers of different passabilities and different habitat volumes, how should the net accessibility of region B for fish from region A be defined? Should a path of better overall passability but poor initial passability dominate? Our ongoing work is beginning to address some of these questions and the associated scalability issues, while still trying to keep the model compact and linear.

Acknowledgments. Supported by NSF Expeditions in Computing award for Computational Sustainability (grant 0832782), NSF IIS award (grant 0514429), and IISI (AFOSR grant FA9550-04-1-0151).

References

[1] W. Meehan (ed.). Influences of forest and rangeland management on salmonid fishes and their habitats, American Fisheries Society, special publication 19, Bethesda, Maryland, 1996.

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

[3] A. P. Olivero. The Nature Conservancy, personal communication, 2009.

[4] G. Pess, M. McHugh, D. Fagen, P. Stevenson, and J. Drotts. Stillaguamish salmonid barrier evaluation and elimination project phase III, final report to the Tulalip tribes, Marysville, Washington, 1998.

[5] P. Roni, T. Beechie, R. Bilby, F. Leonetti, M. Pollock, and G. Pess. 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, 2002.

[6] WDFW (Washington State Department of Fish and Wildlife). Fish passage design at road culverts: a design manual for fish passage at road crossings, WDFW, habitat and lands program, environmental engr. div., 1999.