A GIS based approach for prioritizing dams for potential removal

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A B S T R A C T

Dam removal has proven to be an effective mechanism for quickly restoring in-stream habitat and returning stream systems to a free flowing state in a wide range of settings. Identification of dam removal projects can be a tedious task that often accounts for multiple social, ecological and hydrologic criteria. Here, a GIS based approach for prioritizing dams for removal based on eco-hydrologic and social metrics is presented. The tool uses a hierarchical decision-support framework to rank dams for removal based on criteria such as good habitat and water quality connectivity, larger streamflow at the dam, improved dam safety and longer stream mile connectivity. The tool is applied for three commonly considered prioritization scenarios that rank dams based on their suitability for removal using: ecological criteria, both social and ecological criteria together, and habitability of anadromous fish criteria. Results show that highest ranking dams from an ecological prioritization are located on reaches of high habitat quality and longer connected river miles. In contrast, social plus ecological prioritization yields higher ranks to dams that are primarily used for recreation, but are also in areas of high habitat quality. Dams in close proximity to anadromous fish spawning areas with high river mileage and few downstream dams are ranked higher by anadromous fish prioritization. Notably, some dams rank high in all criteria. These dams should be paid particular attention to, as they could potentially provide the best benefit if removal is possible. The top 20 ranked dams, as predicted by the tool, includes dams that had been pre-identified by resource managers as potential dam removal projects, indicating that the tool is performing as intended. The tool and presented results should be used as a screening tool in conjunction with the expert knowledge of resource managers to further investigate the influence of site-specific factors, thereby determining the final priority of projects.

1. Introduction

Dams can provide many human benefits such as flood control, hydropower and water supply. In North Carolina, a large number of dams were constructed to power mills up until the mid 1900s. Many of them are now outdated and no longer serve their originally intended purpose (Walter and Merritts, 2008). These dams do, however, have the potential to negatively impact river ecosystems (Gregory et al., 2002; Bednarek, 2001; Poff et al., 1997). Small dams (height smaller than 25 ft.) degrade habitat quality and fragment the river network, making the survival of anadromous and resident lotic species more difficult. Without connected river networks, anadromous fish struggle to gain access to important spawning grounds (Saunders et al., 2006). This is of both ecological and economic concern in coastal communities, especially in North Carolina where anadromous fishes such as river herring (\textit{Alosa pseudoharengus}, \textit{Alosa aestivalis}) and American shad (\textit{Alosa sapidissima}) have been important in commercial and recreational fisheries throughout history to present (Watson, 1996). Other lotic species, such as the federally endangered Cape Fear shiner (\textit{Notropis mekistocholus}), a small fish species endemic to the basin, and rare freshwater mussels are also impacted by changes in connectivity of the river network, and fragmentation and transformation of habitat due to the presence of dams (Master et al., 1998). Dams transform the upstream habitat to a more lentic environment (Hayes et al., 2006), thus reducing fish species richness upstream (Helms et al., 2011; Gardner et al., 2013). Dams can also drastically alter the flow regime (Poff et al., 1997), water temperature and dissolved oxygen (Gregory et al., 2002; Poff and Hart, 2002). In North Carolina, three large dams have been identified by the NC Division of Water Quality as the direct cause of impairment to the upstream segment of the river by reducing dissolved oxygen, and thus affecting fish and benthic communities (NCDWQ, 2012). Dams can also alter sediment transport (Bushaw-Newton et al., 2002; Poff et al., 1997). Sediments, particularly coarser grained sediment, are important for in-stream habitat in general, and particularly

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important for certain species during spawning, like salmon. Dams can slow this transport, creating a buildup of sediment upstream and sediment-starved areas downstream (Walter and Merritts, 2008).

As a result, both scientists and environmental managers consider selective dam removal to be an ecologically effective and, in many instances, a cost-effective method of restoration (returning the ecosystem to its flowing state), when the appropriate conditions are met (Keller et al., 2011). For instance, removing a dam can improve habitat quality for fishes that do best in lotic environments, and boost the water quality and connectivity of the ecosystem (Kanehl et al., 1997). However, several considerations arise when evaluating dam removals, and projects often have unique conditions that require thoughtful planning and implementation. For example, if a large load of fine sediments has built up behind the dam, dam removal may lead to re-suspension of sediments for a period of time (Gregory et al., 2002). In nutrient-sensitive waters, dam removal should also consider nutrient dynamics (Doyle et al., 2003; Stockner et al., 2000). Although these issues may add complexity and specificity to individual dam removal projects, dam removal is still generally considered a viable and beneficial option to restore the river system over the long term (Pejchar and Warner, 2001; American Rivers, 2002).

This paper presents a GIS based, Barrier (dam) Prioritization Tool (BPT) for prioritizing possible dams for removal within the state of North Carolina. We note that in this paper, the term “barrier” and “dam” are used interchangeably. First we present an objective hierarchy framework that organizes relevant ecological, social and anadromous fish criteria to rank dams as potential removal projects. Next, we discuss the barrier and criteria data sets that are used to calculate prioritization ranks. The applicability of the toolkit is then demonstrated using three prioritization scenarios, and differences between them are highlighted based on the selection of criteria sets and their corresponding weights. The sensitivity of the tool to different criteria weighting schemes is also evaluated.

2. Dam removal prioritization: a multi-criteria issue

The Barrier Prioritization Tool uses Multi Attribute Utility Theory (MAUT) to prioritize dams for removal. MAUT is a decision making framework that uses an objectives hierarchy to organize the prioritization (Dyer, 2005). First, the fundamental objective to solve the problem is identified. Here, the fundamental objective is to identify the best dams to remove. Then sets of specific subsidiary objectives called criteria are identified, which determine if the primary objective is being met (Clemen, 1996). In this paper, six criteria that grade a dam’s suitability for removal are used: (a) connect high quality stream habitat, (b) connect areas of high water quality as well as the ability to improve areas with poor water quality directly attributable to the dam, (c) avoid social conflict, (d) improve public safety, (e) improve flow downstream, and (f) improve stream habitat connectivity (Fig. 1). Finally, measurable indicators that determine how well a criterion is met are established. A variety of measurable indicators for each of the criteria are selected. Measurable indicators are given a rank from 0 to 1 based on the level of utility, or satisfaction gained from one additional unit of an indicator. Due to the differing motivations for prioritization, users can choose different criteria and indicator sets depending on their prioritization objectives, much like a menu. For instance, if prioritization is considered for a specific group of aquatic species (e.g. anadromous fishes), in order to evaluate the criteria called “connect high quality habitat,” habitat indicators for only anadromous fishes can be used. While utility for each indicator is generally evaluated through formal solicitation processes (McNutt, 2002), such solicitation was not performed in this work as the intention of the developed tool is to allow assignment of indicator ranks by decision makers, who can carry their own utility solicitation. It is to be acknowledged, however, that given the large number of criteria and indicators, a formal solicitation process in this case is expected to be resource intensive. Here, indicators are ranked based on empirical evaluation of qualities and inputs from a group of stakeholders.
Next, cumulative indicator rank (CIR) of each criterion is obtained by calculating the weighted sum of individual ranks. Final objective rank is then calculated by weighted sum of CIRs. It is to be noted that percent weight given to indicators within their respective criteria, as well as percent weight given to each criterion should individually add to 100% (Fig. 1) (Clemen, 1996).

3. Relevant datasets: data compilation and pre-processing

3.1. Barriers

A barrier dataset of dams is the primary input to BPT. The dataset is a point shapefile that contains both locational and attribute information for dams. Important attributes include information regarding dam ownership, use, structural dimensions and date of construction. The dataset is compiled from the North Carolina Dam Inventory, the National Inventory of Dams (NID) and the North Carolina Aquatic Obstruction Inventory (AOI). All the three datasets are publically available, but must be obtained by contacting the source agencies. The NC Dam Inventory is the primary database used by water resource managers in North Carolina, and is maintained by the North Carolina Dam Safety Program (NCDENR, 2012). This dataset was created by the North Carolina Dam Safety Program, and consists of dams regulated by the program. The Program regulates dams that are 25 feet in height or greater and with impoundment size of 50 acre feet or greater, or that are designated “high hazard”. The NID dataset from the US Army Corps of Engineers is a national dataset that includes dams that meet one of the following criteria: (a) high hazard classification – loss of one human life is likely if the dam fails; (b) significant hazard classification – possible loss of human life and likely significant property or environmental destruction, (c) equal or exceeding 25 feet in height and 15 acre-feet in storage, and (d) equal or exceeding 50 acre-feet storage and 6 feet in height. The NID dataset used for this project is from 1996 and only includes dams that are greater than or equal to 10 feet in height (NID, 2010). The Aquatic Species Obstruction Inventory, initiated in October of 2006 and released in 2007, is an undertaking by the US Army Corps of Engineers, US Fish and Wildlife Service (USFWS), and North Carolina Division of Water Resources to identify (often smaller) dams that were not part of the NC Dam Safety database. In the process of compiling these three datasets, redundant dams were removed and attributes combined into one data point. A source field was added to the final barrier dataset to identify the source dataset from which each dam came.

The final compiled barrier dataset for this project has a total of 5120 dams. Of these, 3263 (≈64%) are used primarily for recreation (Table 1). Many of these dams also furnish secondary functions such as water supply and hydropower. Other dams are used for a range of purposes such as flood control and irrigation. 84% of 5120 dams are privately owned, 10% of them are owned by federal, local or state governments, while 6% of dams do not have any assigned owner (Table 1).

3.2. Criteria and indicators

3.2.1. Criterion 1: connect high quality habitat

Habitat indicator data consists of Significant Natural Heritage Area (SNHA) polygons from the North Carolina Department of Environment and Natural Resources (NCDENR) Natural Heritage Program, High Quality and Outstanding Resource Waters lines (HQW/ORW) from the Division of Water Quality, Bio classification lines from the Division of Water Quality, Habitat Predictor lines from USFWS, and anadromous fish spawning area data from the NC Division of Marine Fisheries. SNHAs are areas identified by the state as being important for conservation due to their level of biodiversity. They contain either rare species communities or important habitats. Twenty five percent of SNHAs are currently conserved, and the rest are privately owned. The SNHA GIS polygon file was produced by NCDENR in 2011 under NCDENR Natural Heritage Program (NCDENR, 2011b). ORW and HQW are surface water classifications assigned by the NC Division of Water Quality (DWQ). These classifications designate surface water areas as being of high quality based on biological, physical, and chemical characteristics. The data used in this tool is from January 2011 (NCDWQ, 2011). The biological classification dataset is a measure of health of the river system and its ability to support fish and macroinvertebrate communities. Bioclassification data used here are from 2011 (NCDWQ, 2011). Habitat predictor data are from the USFWS. USFWS synergistically uses species locational data and environmental variable data describing characteristics of the rivers to predict river reaches where species may be found (Endries, 2011). Species locational data used by USFS came from NC Natural Heritage element-occurrence data (where endangered species are known to be located), North Carolina Museum of Natural Sciences Research and Collections Section Dataset, North Carolina Wildlife Resource Commission Priority Species Monitoring Dataset, NCWRC Trout Distribution Dataset, NC DWQ Benthos Macroinvertebrate Assessment data, and NCDWQ Stream Fish Community Assessment Program Data. Environmental variable data consists of attributes such as flow, velocity and drainage area from the National Hydrography Dataset (NHD) plus (NHD, 2013), as well as land cover data from the Southeast Gap Analysis Project Land Cover Dataset (USGS, 2013).

Multiple habitat data shapefiles (SNHA, HQW/ORW lines, and bio-classifications) are associated with the dams via a spatial join operation with a search distance of 300 m. A 300 m threshold is observed to be conservative enough such that it does not exclude any dams that should have correctly joined to habitat data. The habitat predictor data and the NHD plus river network are joined to the dams using a search distance of 100 m to keep in line with Northern Aquatic Connectivity Assessment Project. The Euclidean Distance function in GIS is used to calculate a raster with distances of each dam to the anadromous fish spawning areas. These distances are joined to the barrier dataset and ranked; the closer the distance of the dam to the anadromous fish spawning area, the higher is the rank. It is to be noted that the user need not always use all the indicators, and may select one or multiple indicators to use within the habitat criterion. For example, anadromous fish habitat indicators can be substituted for the statewide habitat indicators in order to prioritize specifically for anadromous fish.

Following association of indicator data to dams, indicator rank fields are assigned. Generally, these indicators are binary, meaning if a dam is on an area of high habitat quality, it is given a 1, and if not, it is given a 0. However, varying levels of significance are given different ranks. In the case of SNHAs, if the area was of national

<table>
<thead>
<tr>
<th>Use of dams in the organized barrier dataset</th>
<th>Number of dams</th>
<th>Ownership of dams in the organized barrier in dataset</th>
<th>Number of dams</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recreation/Fishing only</td>
<td>3263</td>
<td>Private</td>
<td>4319</td>
</tr>
<tr>
<td>Primarily Recreation, with secondary use</td>
<td>449</td>
<td>State or Local</td>
<td>365</td>
</tr>
<tr>
<td>Water Supply as only or first use</td>
<td>129</td>
<td>Government</td>
<td>308</td>
</tr>
<tr>
<td>Hydropower as only or first Use</td>
<td>77</td>
<td>Federal</td>
<td>47</td>
</tr>
<tr>
<td>Other</td>
<td>1202</td>
<td>Utility</td>
<td>81</td>
</tr>
<tr>
<td>Total</td>
<td>5120</td>
<td>Total</td>
<td>5120</td>
</tr>
</tbody>
</table>
significance it is given a 1, if regional, a 0.87, if local, a 0.33. Along similar lines, if the dam is located on a stream classified as being Outstanding Resource Waters, it is given a 1, and if it is on High Quality Waters, it is given a 0.8. For bio classifications, if the dam is on a stream segment classified as having an excellent benthic or fish community it is given a 1, and if good, a 0.5. Species existence data was pre-ranked by USFWS from 0 to 1; a 0 if the dam is on a stream which is not predicted to have endangered species, up to a 1, meaning it is predicted to have the highest number of threatened or endangered species. Anadromous fish indicators consisted of evaluating if the dam was within the contributing area of a watershed that is part of the historical spawning area or current spawning area. If the dam is in a historical area, it is given a 1. Dam on or closer to a current spawning area are assigned a 1 as well. It should be noted that the tool allows users assignment of their own indicator ranks based on empirical observations or management constraints.

3.2.2. Criterion 2: connect High Quality Waters/Improve Water Quality

Two indicators were used for this criterion. The first is whether a dam is located on an impaired water body. These data are derived from impairment lines obtained from the NC Division of Water Quality (NCDWQ, 2012). A body of water is classified as impaired if they no longer meet a specific use due to poor water quality. Listing a body of water as impaired is a management scheme created by the EPA through the Clean Water Act, which gives states the power to manage non-point source pollution in the United States through listing impairment of water bodies (USEPA, 2013). The impairment data shapefile is associated with the dams by first selecting the dams within 300 m of impairment lines and then hand checking each to ensure that only those dams on stream segments that are impaired for low dissolved oxygen, high chlorophyll-a, and high temperatures located immediately upstream and downstream of the dams are included. Also, stream segments designated as Integrated Report Category (IRC) rating of 4C, meaning the dam is causing water quality impairment, are included. The second indicator used for this criterion is the percent impervious surface within each watershed. These data are calculated from the National Land Cover Database updated in 2006 (Fry et al., 2011).

Indicator ranks are then assigned based on the data associated with each dam. If a dam is on an area of impairment, specifically impaired due to low dissolved oxygen, high chlorophyll a, high water temperature, or an area identified as being of low water quality due to the dam it was given a positive rank of 1; if the dam was on a segment labeled as not yet being impaired but having a potential water quality standard violation, it was given a rank of 0.5. These ranks were given assuming that removing the dam would alleviate some of these issues. If the dam was in a watershed that had a low impervious surface (less than 5%), it was given a rank of 1 and considered to be healthy. If the impervious surface ranged between 6 and 10%, it was given a rank of 0.67, between 11 and 20% a 0.33, and finally a 0 for any dam in the watershed having more than 20% impervious surface. The assumptions here are that dams with lower impervious surface areas in their watersheds would have higher water quality and therefore greater potential for restoring the stream community following removal.

3.2.3. Criteria 3 and 4: avoid social conflict and improve safety

Dam use and safety criteria indicator data are obtained from the NC Dam Safety Program and the NID datasets. If a dam is used for recreation only, it is given a rank of 1, as the assignment of “recreation” often does not represent an actual functional use of the dam. If dams are primarily used for hydropower or water supply, they are given a rank of 0, as these represent important social uses. Other uses such as irrigation and flood control fall in between 0 and 1, with the idea being that these uses could possibly be derived from other sources or replaced if the dam were to be removed. It should be noted that the dam “use” attribute is often outdated, so this should be confirmed by further investigation before a high priority potential project is either discarded from consideration or initiated. Dams with “mill” in their names were given a binary rank of 1, because mill dams generally are no longer in use. Dams with “lake” in their names were given a binary rank of 0, because lake dams tend to be in highly populated areas and valued esthetically, making them harder to remove from a social perspective.

3.2.4. Criterion 5: select dams with higher streamflow

Flow data in the form of mean annual flow velocity are obtained from the NHD plus dataset. They are associated with the dams using a spatial join operation in GIS by using a search distance of 100 m. A rank of 0 is given to dams with flow velocity below 0.4 m/s, and a 1 is assigned to those with flow velocity greater than or equal to 0.4 m/s. This velocity threshold is critical for spawning of American Shad (Dutterer et al., 2011).

3.2.5. Criterion 6: improve connectivity

 Connectivity data are created using the Barrier Assessment Tool (BAT). This tool uses the NHD plus flow lines to calculate connectivity metrics (Martin, 2011). The flowlines are first edited to remove loops/bifurcations and intermittent streams, to aid connectivity analyses. An additional reason for editing out intermittent streams is because they provide little benefit in the movement of species. Barrier point file is then snapped to the river network. Dams on very small headwater streams do not snap to any river network and were excluded from this ranking. Out of the 5120 dams, 2295 (~45%) remained after this process and were prioritized. Three connectivity indicators are calculated for all barriers that successfully snap to the network. These are: (a) upstream functional connectivity, which is the number of miles upstream of a dam to the next barrier, (b) total upstream and downstream functional connectivity, which is the combined number of functional miles upstream and downstream of the dam, and (c) downstream barriers, which is the number of barriers downstream of a dam. A higher indicator rank is assigned for higher upstream mileage and total connectivity. For anadromous fish prioritizations, a higher rank is assigned for a lower number of downstream barriers.

It is to be noted that all or a subset of the six criteria may be used in analysis depending on user goals.

4. Barrier Prioritization Tool

The Barrier Prioritization Tool is designed in the model builder function of ArcGIS 10 (Fig. 2). It begins with a selection-by-attribute field so the user can select a geographic boundary. It then clips the dataset by the boundary, and adds criteria and indicator fields to the new clipped barrier dataset. Each criterion field uses the calculate field tool so that the user can use indicator ranks, weight them, and weight the criteria within the rank field. The user is also able to manually select specific indicators to weight within criteria. The tool calculates the criteria fields, and a final rank field. BPT then automatically sorts the attribute table from highest to lowest rank, outputs a new shapefile, and symbolizes the dataset using an algorithm of the user’s choice (e.g. “equal interval” or “natural breaks”) in ArcGIS 10. The user may then zoom in to specific locations on the map to individually explore higher ranking dams, or open the attribute table of the shapefile and view the dams from highest to lowest rank.
5. Results and discussions

5.1. Final barrier prioritization results

In this paper, three dam removal prioritization scenarios are implemented; a social plus ecological prioritization which includes the ecological, safety and the social criteria (Fig. 3), an ecological prioritization which includes only ecologically based criteria (Fig. 4), and an anadromous fish prioritization (Fig. 5) which includes indicators specific to anadromous fish.

Fig. 6 shows the output of the BPT using a statewide social plus ecological prioritization scheme. Integration of the tool within the GIS allows seamless visualization and analyses of results, without the need of any post-processing. For example, classification of 2295 dams into four intervals using an equal interval algorithm immediately highlights 97 dams (as seen in dark blue in Fig. 6) with higher ranks. These dams should be explored first by the user as potential dam removal projects. Zooming-in on the figure also indicates that majority of the lower ranked dams (shown in yellow and green in Fig. 6) tend to be on small tributaries that are used as agricultural ponds and have less functional upstream connectivity. Of the top 20 ranked dams (Fig. 7), most are primarily used for recreation (Table 2) and are located on higher order streams, and on areas of high habitat quality. 19 of the top 20 ranked dams are located on Significant Natural Heritage Areas. It is to be noted that out of the top 20 dams, eight were pre-identified by resource managers as potential projects (Table 3). In fact, the third ranking dam is in the process of being removed, and funding for the removal of the fourth has been recently approved (Piedmont Conservation Council, 2012). Two other dams were identified for removal by American Rivers, however in both cases the land owner did not want to remove the dam (Table 3). This underscores an important underlying issue with ranking of dams for removal by the BPT. None of the data used in BPT considers information about land owner’s receptiveness to dam removal. There is always a possibility that dams that are owned privately may not have a willing owner. The tool, however, can still be used for filtering through large number of dams in order to identify potential projects (Fig. 8).

Within the ecological prioritization (social and safety criteria excluded), the top 20 ranked dams (Fig. 7) include those that are used primarily for water supply and hydropower (and are therefore unlikely removal candidates), but are on the areas of highest habitat quality. For instance, in contrast to the social plus ecological prioritization, which has 19 of the top 20 dams being primarily used for recreation, in this scenario only 12 dams are used primarily for recreation (Table 2). It is to be noted that none of the eight dams used primarily for a use other than recreation figure in the top 20 list obtained from social plus ecological prioritization scenario. Because many of these dams are used for hydropower and water supply, they are ranked poorly in social criteria. For instance, Jordan Lake and Falls Lake, which are very large dams operated by the US Army Corps of Engineers and are depended on for municipal water sources, rank high in the ecological prioritization. While these dams may be extremely beneficial to remove for ecological reasons, they would not be feasible to remove from a social perspective. However, the ecological prioritization still highlights the possible advantages that could be incurred from removal of these dams and could encourage modifications at the dam site, such as installation of fish ladders to accommodate for anadromous fish passage. Within the ecological prioritization, 5 out of 20 are current projects identified for removal (Table 3). It is to be noted that between the ecological and social plus ecological prioritizations, 11 out of 20 top ranked dams overlap, though they are in different orders. There are primarily two reasons for overlap between

<table>
<thead>
<tr>
<th>Use of top 20 dams</th>
<th>Number of dams associated with their corresponding usages</th>
<th>SEP</th>
<th>EP</th>
<th>AFP</th>
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<tr>
<td>Recreation/fishing only</td>
<td></td>
<td>13</td>
<td>7</td>
<td>8</td>
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<td>Primarily recreation, with secondary use</td>
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<td>Hydropower as only or first use</td>
<td></td>
<td>0</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Other (e.g. navigation)</td>
<td></td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

Fig. 2. Interface of the Barrier Prioritization Tool.
Fig. 3. Indicator and criteria percentages for a statewide social plus ecological prioritization.

Fig. 4. Indicator and criteria percentages for a statewide ecological prioritization.
Fig. 5. Indicator and criteria percentages for a coastal anadromous fish prioritization.

Fig. 6. Barrier Prioritization Tool output from a statewide social plus ecological prioritization. (For interpretation of the references to color in text, the reader is referred to the web version of the article.)
top 20 rankings from the two prioritizations. First, a dam that has a use other than recreation can rank high in both the ecological prioritization and the social plus ecological prioritization, such as the Tar River Dam. This dam is used for water supply and recreation, and it ranks very high in the habitat criterion also, making it appear in both top 20 lists. Second, dams that have extremely high habitat quality and also exhibit the best social safety attributes are also ranked highly in both the prioritizations. An example of this is Lassiter Mill Dam. This dam is located on a Significant Natural Heritage Area, and also has been classified as having an excellent benthic community at the dam, has a high number of upstream miles, and is considered a millpond with its only potential use being recreation. As a result, Lassiter Mill Dam is present in the top 20 ranking in both prioritizations, and is a pre-identified potential project that is currently in the process of being removed. Dams like Lassiter Mill Dam that rank high on both the social plus ecological

### Table 3
Top 20 ranked dams using a social plus ecological, ecological and anadromous fish prioritization. AFP, active fish passage; AP, active project; ULO, unwilling land owner; CPP, current potential project.

<table>
<thead>
<tr>
<th>Rank</th>
<th>Social plus ecological prioritization</th>
<th>Dam ID</th>
<th>CPP</th>
<th>Ecological prioritization</th>
<th>Dam ID</th>
<th>CPP</th>
<th>Anadromous fish prioritization</th>
<th>Dam ID</th>
<th>CPP</th>
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<tr>
<td>1</td>
<td>1</td>
<td>5167</td>
<td>Yes</td>
<td>13</td>
<td>Yes (AP)</td>
<td>5048</td>
<td>Yes (AFP)</td>
<td></td>
<td></td>
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<tr>
<td>2</td>
<td>2</td>
<td>13</td>
<td>Yes (AP)</td>
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<td>3</td>
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and ecological criteria should be given particular attention, as they are likely the most ideal candidates.

Within the anadromous fish prioritization, the top ranked dams are very different from the ones obtained from the other two prioritizations (Fig. 7). Top ranked dams in this prioritization are all located in the coastal plain region, and are in close proximity to current anadromous fish spawning areas and/or within the historical anadromous fish spawning area, have a high connectivity mileage and a low number of dams downstream. Since social and safety criteria were not considered in this prioritization, these dams tend to be used for multiple purposes including recreation, hydropower, and navigation (Table 2). The BPT automatically prioritizes these qualities by considering representative indicators that are unique to anadromous fish passage within habitat and connectivity criteria. Within this prioritization, 6 out of 20 were pre-identified as potential projects (Table 3). Of particular note is the number one ranked dam in this prioritization. While pre-identified as being very important for fish passage, removal of this dam is not possible, and a rock rapids fish passage structure is currently being constructed (Zlotnicki, 2012).

It is notable that roughly 30–35% of the top 20 dams in each prioritization scenario had been pre-identified as potential projects by resource managers. This indicates that the tool is performing as intended. However, the tool should be used with caution. The rankings should be synergistically used with expert knowledge of resource managers to further investigate the viability, landowner willingness, and other site-specific factors. This secondary investigation should determine the final priority of projects.

5.2. Sensitivity of rankings to criterion weights

The sensitivity of the top 20 ranked dams are evaluated, within each of the three prioritizations, by changing the criterion weights by 5, 15, 45, and 75%, and calculating the corresponding percent change in the top 20 dams. Expectedly, with increase in a criterion weight, dams that lack qualities of that specific criterion are scored lower and drop out of the prioritization. For example, in the social plus ecological prioritization, when social criterion is increased by 75%, dams that are used primarily for hydropower and water supply dropped out of the top 20. On the contrary, dams that align with the criterion qualities are rated higher. For example, when habitat weight is increased by 75% in a social plus ecological prioritization, the majority of dams in the top 20 are located in a significant natural heritage area. It is to be noted that since all criterion weights should add up to 100%, increase of a criterion weight during sensitivity analyses implicitly accounts for a decrease in all other criterion weights.

For both social plus ecological prioritization and the ecological prioritization, the top 20 dams are most sensitive to increase in the water quality criterion. This is because the impaired streams indicator within the water quality criterion is ranked highly. The indicator conflicts with others, in that it positively ranks a negative quality in a dam. Larger value of this indicator captures dams that are on impaired streams, and have the potential to markedly improve Water Quality on removal. Assignment of a higher weight to the water quality criterion causes a new set of dams which conform with conflicting impaired streams indicator to feature high in prioritization, thus resulting in a higher sensitivity. For the anadromous fish prioritization, the top 20 dams are most sensitive to changes in weight of the connectivity criterion. This is attributable to a large criterion weight of connectivity criteria.

Interestingly, a select few dams consistently score high and remain in the top 20 in both the original and altered weight configuration. Notably, these dams are also already identified potential projects for removal, indicating that the tool successfully distinguishes extremely desirable projects. The ability of a certain number of dams to remain in the top 20 regardless of alteration in criteria weights also indicates that many of these dams furnish multiple criteria simultaneously. For instance, dams that score high in the habitat criterion, either because they are in significant natural heritage areas or where species of interest exist, also tend to be in areas with low impervious surface. As a result they score highly in the water quality criterion as well. Many of these dams are mill dams that were built for the purpose of aiding the agriculture and forestry industries. These mill dams score higher in the connectivity criterion than dams located in urban centers. This is due to a higher concentration of dams in cities, which results in fragmentation of connectivity of the river there.

6. Sources of errors in the results

In this work, a formal solicitation was not performed to evaluate the utility of each indicator, as the intention of the developed tool is to allow assignment of indicator ranks by decision makers. Notably, the solicitation process is expected to be resource intensive, given the large number of criteria and indicators. Ideally, mapping of how a unit increase of an indicator’s utility impacts the amount of satisfaction gained by the decision maker is needed. Although an elicitation approach was not used, ranks were discussed with a group of stakeholders and hence reflected professional and practitioner knowledge. Given the high percentage of dams within the top 20 from prioritizations that were already pre-identified as active or potential projects, it can be argued that the ranked indicators reasonably portray how they value attributes of good

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Fig. 5. Sensitivity of top 20 dams to varying changes in criterion weights within (a) social plus ecological prioritization, (b) ecological prioritization, and (c) coastal anadromous fish prioritizations.
dam removal projects. It is to be noted that the tool does not constrain users to the ranks used here, and the users have the flexibility to assign indicator ranks based on their respective utility elicitation process.

Another source of error is the way habitat and water quality criteria were associated with the dams using a spatial join. The methodology does not account for the quality of habitat and water quality within a certain distance upstream of the dam. This limits the analysis, because just beyond this distance there could be a significant natural heritage area, a certain endangered species, or an area of impairment. Therefore, in the future, an improved method of accounting for these indicators within a certain distance upstream and downstream is necessary.

The results may also be affected by inaccuracies in the data, such as (a) GPS location and snapping errors – this may translate to dams being wrongly assigned an indicator data not associated with them, and vice versa; (b) outdated attribute information such as use of owner information or safety hazard – these data sets evolve over time, and use of a more recent data is encouraged to reduce these errors as new data becomes available; and (c) the NHD plus river flow line dataset used for calculating connectivity indicators such as upstream mileage at times is too coarse to determine if dams are on the small streams of interest. The NHD plus data is still used because it has an enormous amount of data associated with it, such as flow velocity, elevation, and slope, which are useful in the prioritization process.

7. Conclusion

A Barrier Prioritization Tool to efficiently locate and prioritize potential dam removal projects in North Carolina is presented. While dam removal can be a controversial topic, this tool offers multiple criteria and indicator options that the users may use to prioritize dams for removal. The tool also offers flexibility in selection of one or multiple indicators or criteria in the prioritization process. Sensitivity analyses show that changes in weight to certain criteria does impact results of a prioritization, and therefore changing criteria weights when running custom analyses will result in alternate rankings. Notably, the top 20 list obtained from three prioritization scenarios contains dams that were pre-identified as current potential projects by resource managers. This indicates that the tool is able to successfully identify high-potential dam removal or passage projects from thousands of dams. It is important to note that a dam prioritization scenario created using the tool is only as accurate as the data and methodology that is used within it. So it is necessary that this tool be updated with the best and most updated available data. It is recommended that the ranking results be further investigated by resource managers to evaluate their site-specific constraints and viability, to determine a final set of project priorities. The tool has the potential to make river restoration, through the implementation of dam removal projects, a more efficient and effective process.

References

Martin, E., 2011. Barrier assessment tool (BAT) and dam prioritization tool (DPT). In: TNC Freshwater Conference, April 6–8, 2011.