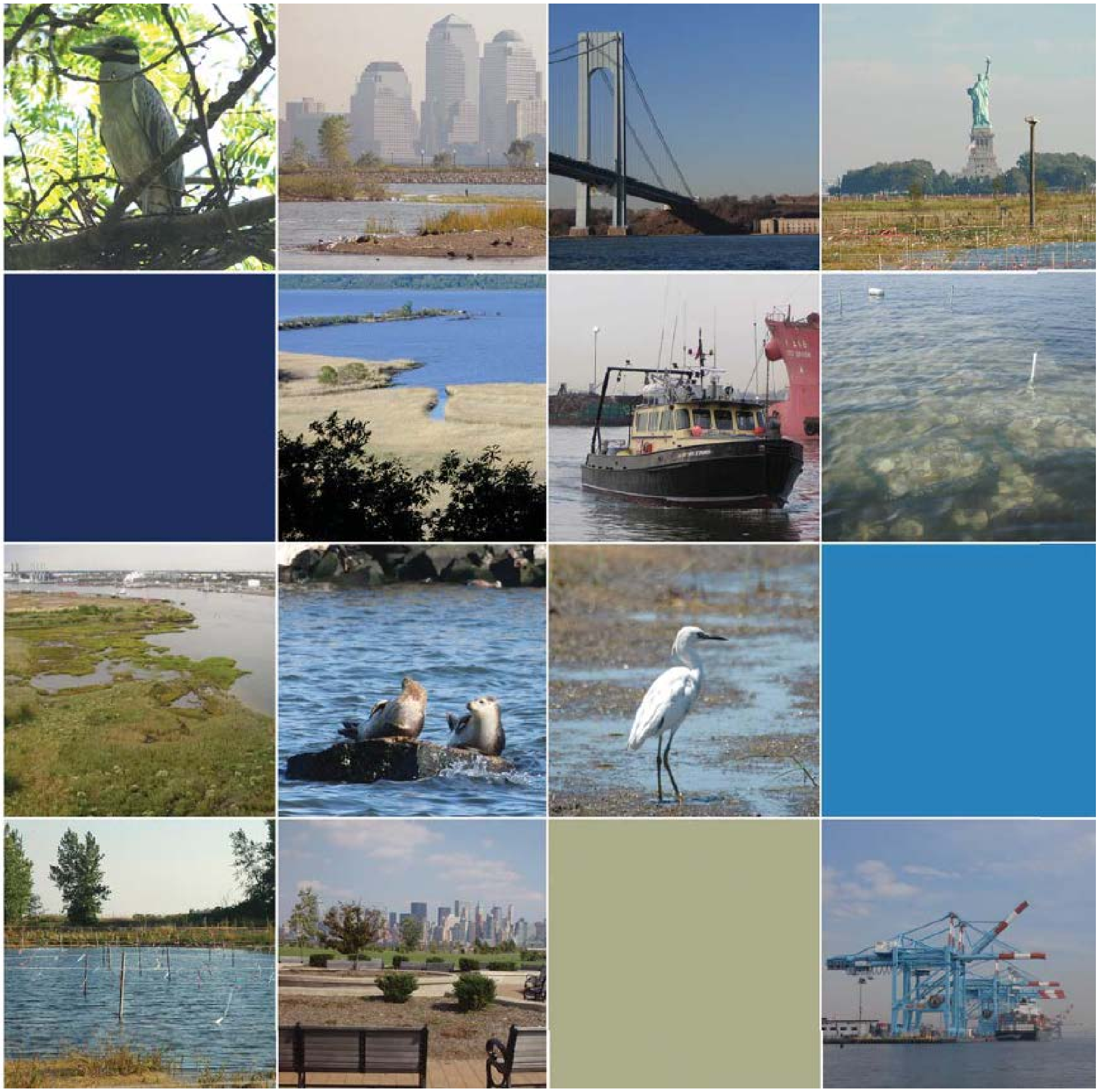
Hudson-Raritan Estuary Ecosystem Restoration Feasibility Study

Appendix C
Fish Passage

Draft Integrated Feasibility Report & Environmental Assessment
February 2017

Prepared by the New York District,
U.S. Army Corps of Engineers



ERDC TN-EMRRP-SR-??
February 2017

Barrier Prioritization in the Tributaries of the Hudson-Raritan Estuary (DRAFT – September 20, 2016)

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OVERVIEW: The Hudson-Raritan Ecosystem Restoration Feasibility Study is a large multi-objective, watershed-scale ecosystem restoration initiative led by the US Army Corps of Engineers (USACE) New York District in cooperation with its non-federal sponsors (Port Authority of New York and New Jersey, State of New Jersey, New York City Department of Environmental Protection, and Westchester County Department of Planning). One study outcome was development of a Comprehensive Restoration Plan (CRP) that serves as a master plan and blueprint for future restoration in the HRE. The CRP goal is to develop a mosaic of habitats that provide society with renewed and increased benefits from the estuary. The CRP provides the framework for an estuary-wide ecological restoration program by utilizing restoration targets –Target Ecosystem Characteristics (TECs) – developed by the region's stakeholders. One TEC focuses on the restoration of tributary environments and reconnection of rivers to coastal environments to benefit impacted or imperiled migratory fishes (e.g., Alewife, blueback herring, Striped bass, American shad, American eel). This technical note describes a procedure developed to prioritize removal of major migratory barriers, specifically dams. These methods are demonstrated in one of eight planning regions, the Harlem River, East River, and Western Long Island Sound Planning Region, where they were applied to prioritize potential barriers for removal over a range of costs. The prioritization scheme is based on four primary components: habitat quantity upstream of a dam, habitat quality upstream of a dam, the effects of multiple dams in sequence in the context of diadromous fish (i.e., if a fish cannot pass the most downstream dam, then upstream dam removal provides no benefits), and a rapid, screening-level relative cost estimate. This technique is then applied to examine 49 potential dam removal sites. A combinatorial algorithm was applied to develop plans with more than 489,000 combinations of removal sites (e.g., remove barrier-A, barrier-B, neither, or both). From this analysis, 49 proposed sites were screened and refined to a recommended plan containing 12 sites, which provides 66% of the total potential habitat gain at 19% of the relative cost. The advantages and challenges of barrier prioritization are then discussed more broadly with an emphasis on efficacies that can arise as a result of spatial prioritization methods.

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HUDSON-RARITAN ESTUARY ECOSYSTEM RESTORATION FEASIBILITY STUDY: The Comprehensive Restoration Plan (CRP) provides a multi-objective vision for ecosystem restoration actions in the region (USACE 2016). This master plan was developed in coordination with a variety of agency and non-governmental partners to provide a collaborative and comprehensive framework for estuary-wide restoration. The framework is designed to facilitate restoration actions by governmental, non-profit, and private entities. This "living" document is periodically updated to reflect ongoing activities, accommodate any shifts in priorities, and facilitate incorporation of new technologies and methods. The plan divides restoration actions into eight planning regions to facilitate analyses and structure locally specified actions (Figure 1).

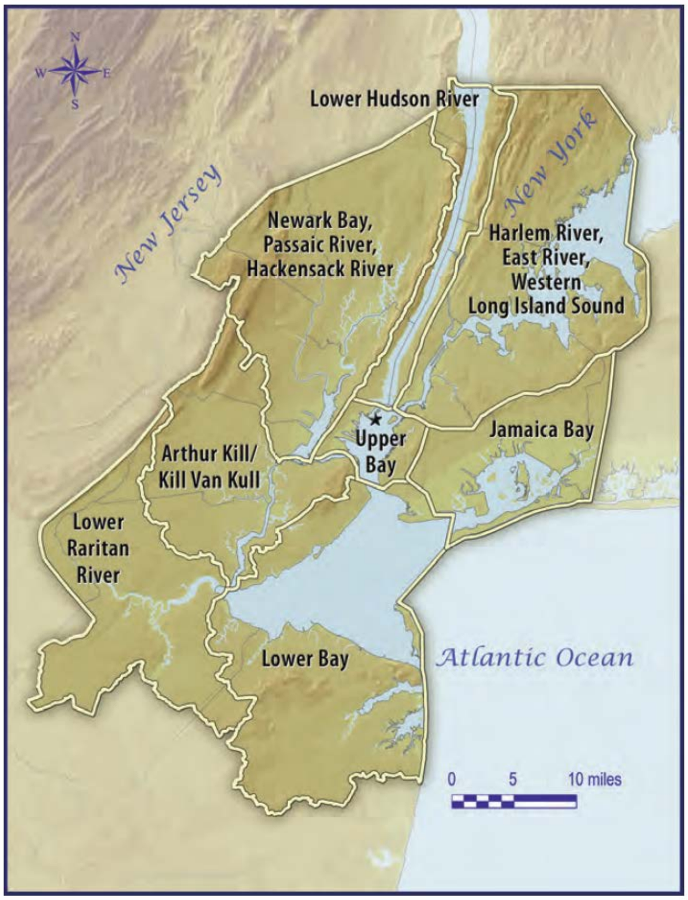

Figure 1. Eight planning regions of the Hudson-Raritan Estuary study area. The Statue of Liberty is represented by the star (USACE 2016, Figure 1-2).

Project Objectives. From its inception, the HRE study has worked collaboratively with a large diversity of stakeholders to identify and refine goals and objectives. The overarching goal of the project is "to develop a mosaic of habitats that provides society with renewed and increased benefits from the estuary environment" (USACE 2016). This goal is further refined into twelve Target Ecosystem Characteristics (TECs) ranging in scope from oyster reefs to contaminated sediments. One of these TECs focuses on "tributary connections" and is guided by the following objectives:

- Increase connectivity of riparian habitats to reduce fragmentation in migratory corridors.
- Improve the hydrologic connectivity of the floodplain and the river/estuary to improve the function of riparian habitat; reduce velocities, increase infiltration and improve natural sediment processes.
- Enhance basin and tributary bathymetry reconfiguration to promote optimal circulation.
- Reduce shoreline erosion.
- Remove invasive species and replace with diverse native vegetation.
- Increase habitat available for migratory fish through removal of fish passage impediment.

The HRE study required a scientifically defensible, analytical approach for estimating potential costs and benefits of alternative barrier removal plans in HRE tributaries (e.g., removal of barrier-A, barrier-B, neither, or both). The following sections describe development and application of a family of models to screen potential restoration sites in this large region. As a demonstration, we apply these models to the watersheds within the Harlem River, East River, and Western Long Island Sound Planning Region, which we refer to as the East Harlem-Bronx region (EHB, Figure 2).

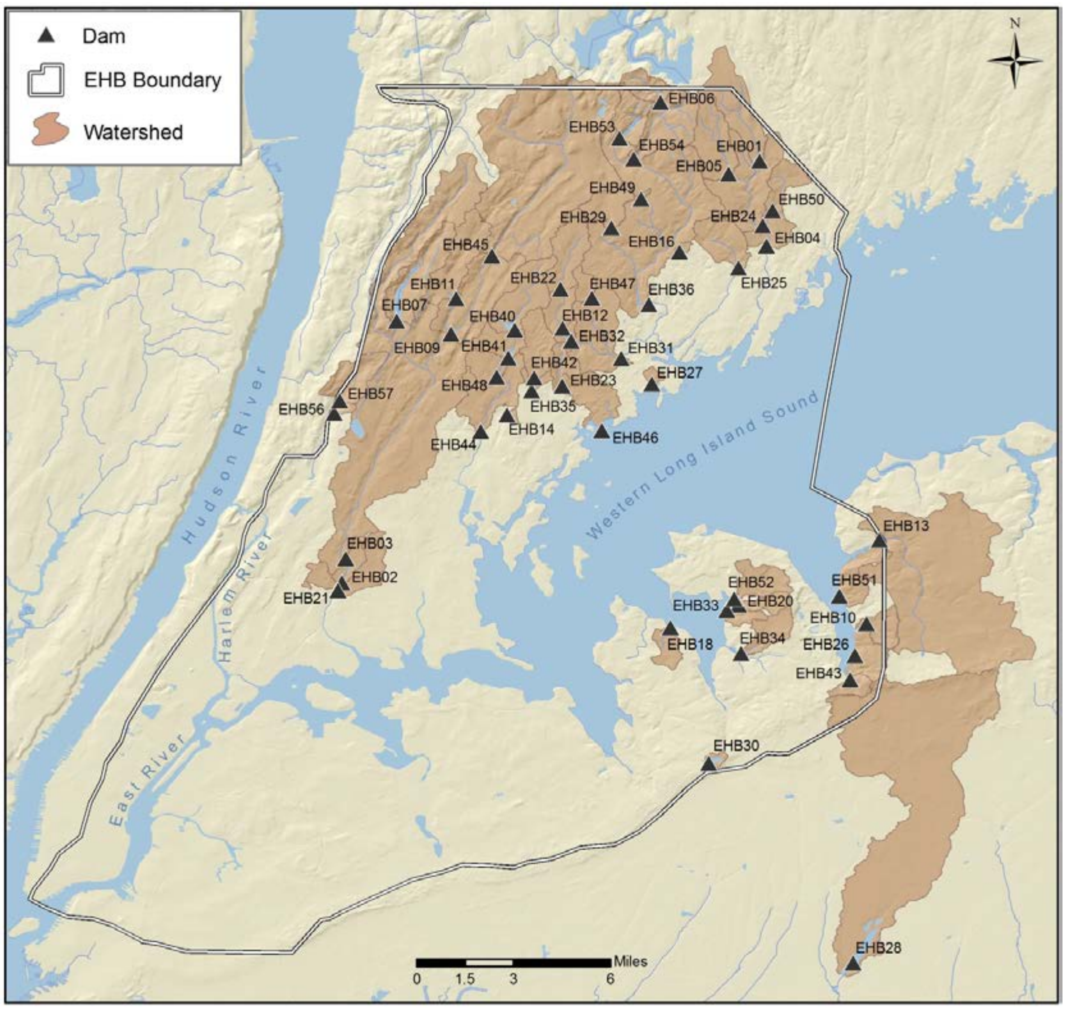

Figure 2. Harlem River, East River, and Western Long Island Sound planning region, which we refer to as the East Harlem-Bronx region (EHB).

BARRIER PRIORITIZATION MODEL: To develop a barrier prioritization model, a common ecological model development process of conceptualization, quantification, evaluation, and application was followed (Grant and Swannack 2008, Swannack et al. 2012). Notably, model development was constrained by the need for rapid development and application under the USACE Smart Planning paradigm as well as the need for an approach that relied on readily available, large-scale datasets applicable across the entire HRE program. This study drew heavily from methods applied in multiple USACE planning studies such as the Truckee River fish passage project (Conyngham et al. 2011, McKay et al. 2013) and the Proctor Creek Ecosystem Restoration study (underway by Mobile District).

Model Conceptualization. An enormous array of models has been developed for stream corridor assessment and barrier prioritization. In addition to differing in technical complexity and application time, these models also vary based on factors such as the disciplinary perspective (e.g., hydrologic, geomorphic, ecological), the hierarchical level of ecological element addressed (e.g., individuals, populations, communities, ecosystems), the basic approach to modeling (e.g., statistical, theoretical), input requirements (e.g., few parameters vs. extensive geospatial layers), the treatment of time and space (e.g., lumped vs. distributed), and the degree of development (e.g., long history vs. new tool). Here, we take a common approach to ecological modeling based on quantity and quality of habitat. These "index" models (Swannack et al. 2012) were originally developed for species-specific applications (e.g., slider turtles), but the general approach has also been adapted to guilds (e.g., salmonids), communities (e.g., floodplain vegetation), and ecosystem processes (e.g., the Hydrogeomorphic Method).

This component of the HRE study emphasizes the restoration of hydrologic connectivity, which refers to the "water-mediated transfer of matter, energy, and/or organisms within or between elements of the hydrologic cycle" (Pringle 2001). In a recent review of barrier prioritization decision support models, McKay et al. (2016) identify three basic elements common to a diversity of connectivity prioritization applications: habitat quantity, habitat quality, and connectivity. Each of these components can be assessed relative to multiple species (e.g., shad vs. eel), habitat requirements (e.g., tolerant vs. intolerant to pollution), life histories (e.g., anadromous vs. catadromous), and even units of measure (e.g., habitat quantity as length along a river vs. the wetted area of the river). Here, a simple view of each of these components was adopted that prioritizes reconnecting tributaries to the ocean (rather than reconnecting fragmented riverine stretches to one another), long reaches of rivers (over short), and patches of high quality habitat (over low). Although the HRE study examines other tributary taxa (e.g., freshwater mussels), this analysis focuses only on anadromous fish (American shad, alewife, blueback, herring, striped bass, and American eel). In addition to ecological outcomes, this model also captures the relative costs of potential barrier removals, such that given two barriers with the same ecological benefit, the barrier with the lowest relative cost is favored. Relative cost is used to conduct a preliminary cost effectiveness and incremental cost analysis.

Model Quantification. The four components of the HRE tributary barrier prioritization (habitat quantity, habitat quality, connectivity, and cost) required three separate analyses, which are described below. The numerical models are described, which were used to combine these variables and prioritize potential barrier removal sites.

Barrier Location and Passability. The foundation of any barrier prioritization is an accurate dataset of the location and properties of potential barriers. Sites were compiled from state and federal dam datasets in which the most accurate location and attribute information were combined into a single record (i.e., the USACE National Inventory of Dams and the New York State Inventory of Dams). All locations were visually verified using current aerial photography and other online resources, and some sites were manually moved to more accurately reflect the location of the structure. In addition to location, other attributes were compiled for future HRE projects. Sixty dams were initially included in the dataset. However, eleven sites were removed from analyses because of infrastructure value (e.g., water supply) or unverifiable location. The remaining 49 dams are owned and operated by a variety of private and public entities and range significantly in age (20-201 years), height (4-40 feet), and width (50-7,000 feet). Removed sites were maintained as barriers in the river network.

Even relatively small barriers can impede movement or migration of fish. For instance, the maximum jumping height of alewife (*Alosa pseudoharengus*, one of the HRE focal species) is less than 1.5 feet, which would make all of the EHB barriers impassable (Meixler et al. 2009). Without structure-specific hydraulic data, knowledge of fish passage structures, or local studies of fish movement, we make the conservative assumption that all dams are total barriers to movement, and 0% of fish are capable of passing these structures.

A barrier prioritization could be made based solely on the number of miles of river upstream of a structure. However, the cumulative impact of multiple barriers in series can have dramatic effects on the outcome of a prioritization (O'Hanley and Tomberlin 2005). For instance, if barrier-A has 2 miles upstream and barrier-B has 10 miles upstream, a site-by-site scoring system would recommend the removal of barrier-B. However, if barrier-A is downstream of barrier-B, reconnection to the ocean first requires the removal of barrier-A. The sequential impacts of barriers has been well-described elsewhere (McKay et al. 2016), and a variety of metrics exist to quantify the effects of a barrier on watershed connectivity (e.g., O'Hanley and Tomberlin 2005, Cote et al. 2009, Martin and Apse 2011). This analysis adopts the approach of McKay et al. (2013), who use a graph theoretic approach for summarizing upstream connectivity at watershed scales.

Geospatial Habitat Analyses. The primary geospatial focal point is the drainage area for each dam site since that is the immediate area contributing to habitat quality. For each dam site, the watershed was delineated using the "Watershed Tool" in the ArcGIS software (version 10.1). Some delineations were inaccurate due to complexities of the highly urbanized region (e.g., piped segment, land grading, low relief coastal zones). Those cases required each watershed to be visually inspected and manually delineated based on a digital elevation model. These watersheds were then cross-referenced to the National Hydrography Dataset (NHD) for a final validation of watershed shape and topology.

Dam IDs were assigned to each watershed area (EHB01, EHB02, etc.). The NHD Plus Flow Lines were used to compute the overall quantity of habitat in a given watershed. Additionally, the Environmental Protection Agency's (EPA) 303d listed waters (2012 version), the 2011 National Land Cover Database (NLCD) polygons (converted from grid format), and The Nature

Conservancy's secured lands polygons were clipped and/or intersected to the watershed areas using Geo-processing tools in ArcGIS. These three datasets were aggregated to derive proxies of habitat quality, as described below. Data for each watershed were then compiled into a centralized Microsoft Excel database (Appendix A).

The EHB region is highly urbanized, resulting in large changes to watershed hydrology, stream morphology, water quality, and other factors. This "urban stream syndrome" is well-documented globally (Walsh et al. 2005), and the ecological changes associated with urban development are well-described (Wenger et al. 2009). Developed watershed area was used as a surrogate for overall changes in stream health as shown below (Figure 3A).

$$SI_{lu} = 1 - \frac{A_{dev}}{A_{da}}$$

Where SI_{lu} is a quality index related to land use development pressure, A_{dev} is the area of developed land uses in the 2011 NLCD (specifically, the sum of land use codes 21, 22, 23, and 24), and A_{da} is the drainage area for this barrier.

Water quality is a multi-faceted ecological issue, not easily addressed through readily available, remotely sensed data. The relative number of miles identified as impaired by the EPA's 303d list was used as a surrogate for overall water quality (Figure 3B). For instance, if 13 of 20 miles of river in a watershed were listed for any reason (e.g., bacteria, metals), the overall water quality suitability score would be 0.35. For EHB, this ratio ranged from 0-100% (median = 54%).

$$SI_{WQ} = 1 - \frac{L_{303d}}{L_{da}}$$

Where SI_{wq} is a quality index related to water quality, L_{303d} is the length of streams listed for contamination by the EPA, and L_{da} is the length of streams in the drainage area for this barrier.

Barrier removal benefits migratory fishes but also a host of other aquatic, riparian, and terrestrial taxa such as birds, mammals, and invertebrates as well as other ecological processes. As such, a habitat quality index was developed to assess the ability of a removal to reconnect potentially valuable patches that create conservation corridors. The Nature Conservancy (TNC) maintains a regional database of "secured" lands such as parks and reserves. For the highly developed EHB, 20% secured lands would be a very large proportion (range = 0-66%, median = 2%, 3 sites > 20%), and thus, we assume best attainable habitat quality for any conservation connections beyond this threshold (Figure 3C).

$$SI_{cons} = \begin{cases} 1 & \frac{A_{cons}}{A_{da}} > 0.2 \\ 0.5 + 2.5\frac{A_{cons}}{A_{da}} & \frac{A_{cons}}{A_{da}} < 0.2 \end{cases}$$

Where SI_{cons} is a quality index related to conservation areas, A_{cons} is the area of conservation lands given by the TNC secured lands dataset.

An overall habitat quality index (*HQI*) was derived by the arithmetic mean of the three suitability indices described above (Figure 3D). Other combination algorithms are often used in index-based model construction (e.g., geometric means). However, an arithmetic mean was deemed appropriate given the preliminary nature of this barrier screening.

$$HQI = \frac{SI_{dev} + SI_{WQ} + SI_{cons}}{3}$$

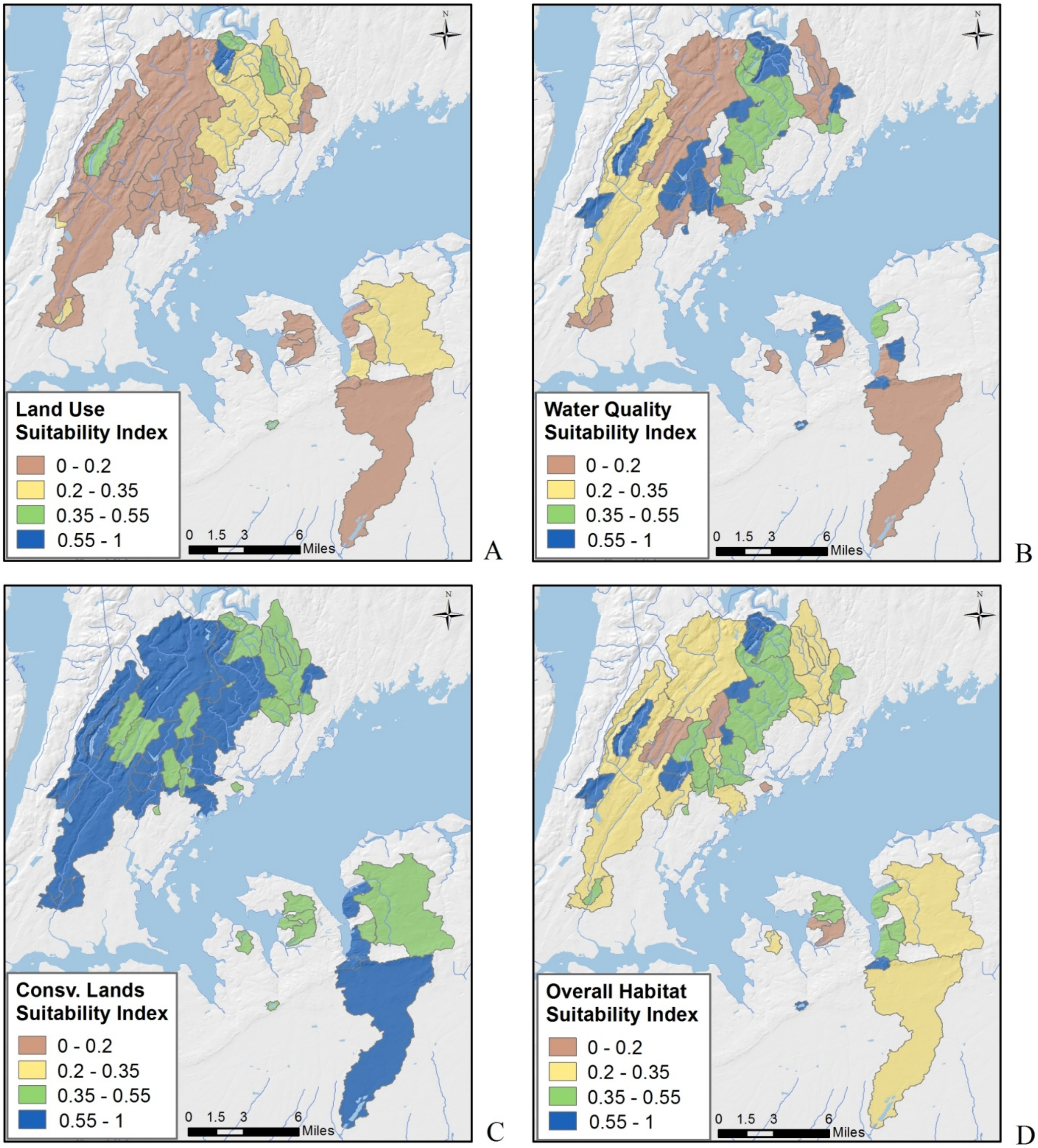

Figure 3. Habitat quality informing barrier prioritization in the EHB Planning Unit. (A) Quality index for developed land uses. (B) Quality index for water quality. (C) Quality index for conservation lands. (D) Aggregated quality score used to assess habitat in barrier prioritization.

Barrier Removal Cost. Barrier removal costs are highly case-specific due to factors such as equipment accessibility, sediment disposal, and infrastructure relocation, and thus, local cost estimates developed for a particular barrier are required to fully characterize restoration cost (Whitelaw and MacMullan 2002). However, regional studies prohibit the development of rigorous, site-specific cost estimates due to the large number of sites and goal of rapid screening. For this study, data on prior dam removals for the 12 state northeastern region[1] (CT, DC, DE, MA, MD, ME, NH, NJ, NY, PA, RI, VT) were used to develop a simple regression model between dam height and cost of prior removal projects. Because of the uncertainties surrounding local conditions, these cost estimates should be interpreted as relative and not absolute costs (all costs will be presented in relative cost units, CU), and future analyses will be required for site-specific estimates. These methods follow a growing body of studies using regional cost regressions for barrier prioritization (Kuby et al. 2005, Zheng et al. 2009, Zheng and Hobbs 2013, Neeson et al. 2015).

$$C_{rel} = 36{,}559 {H_{bar}}^{1.200}$$

Where C_{rel} is a relative estimate of cost (in \$2015) and H_{bar} is the height of the barrier in meters (R^2 = 0.263).

Numerical Model. The models described above required a diverse range of input parameters and data compiled from a variety of geospatial analyses, and a database was developed to compile all data into a single location for improved quality control. Appendix A provides a summary of all data used in the barrier prioritization. All computations were conducted in a script-based environment, which was used to compute ecological outputs for futures without and with restoration actions. Potential restoration actions at any site throughout the watershed can be "turned on and off" to analyze combinations of actions (e.g., barrier removal at site-A, site-B, neither, or both). All analyses were conducted using the R statistical software package (version 3.1.1, R Development Core Team 2014) [2].

Model Evaluation. Model evaluation is the process to ensure that numerical tools are scientifically defensible and transparently developed. Evaluation is often referred to as verification or validation, but in fact includes a family of methods ranging from peer review to model testing (Schmolke et al. 2010). The USACE has established an ecological model certification process to ensure that planning models used on ecosystem restoration projects are sound and functional, which generally consists of evaluating tools relative to three categories: technical quality, system quality, and usability (EC 1105-2-412, PB 2013-02).

The technical quality of a model is assessed relative to its reliance on contemporary theory, consistency with design objectives, and degree of documentation and testing. As described in the conceptualization and quantification sections, the HRE barrier prioritization models are based on a general framework which has been extensively applied for barrier prioritization (McKay et al. 2016). The habitat quality models were developed from best-available information and based on general guidance on urban stream management (Wenger et al. 2009).

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[1] American Rivers © 2014. Additional information available online at http://www.americanriver.org/initiatives/dams/dam-removals-map/. Data were used from CT, DC, DE, MA, MD, ME, NH, NJ, NY, PA, RI, and VT (152 projects with dam height and cost data).
[2] Code available from authors upon request.

Ecological models must not only maintain an appropriate theoretical and technical basis but also be computationally accurate. System quality refers to the computational integrity of a model (or modeling system). For instance, is the tool appropriately programmed, has it been verified or stress-tested, and do outcomes behave in expected ways? The system quality of these models was evaluated in a variety of ways, including:

- Code adoption: Code was modified from a previous study (McKay et al. 2013) to minimize new computational errors.
- Code checking: All code was error-checked during and after development by the primary programmer (McKay) and inspected by team members throughout the process. Error checking considered consistent variable naming, investigated outputs from each line of code, and blocks of code (e.g., loops).
- Testing model outcomes: Model simulations were examined thoroughly as test cases for model functionality. For instance, if a barrier is completely impassable, all subsequent upstream reaches should have a 0 connectivity score and a 0 habitat value. These logical interpretations were examined as site-specific alternatives and were manually "turned on and off" in the model.

The usability of a model can influence the repeatable and transparent application of a tool. This type of evaluation typically examines the ease of use, availability of inputs, transparency, error potential, and education of the user. As such, defining the intended user(s) is a crucial component of assessing usability. This model was developed for targeted application by the USACE technical team in the HRE study, and, as such, there is currently no graphical user interface (GUI) for the model beyond the script itself. To this end, the current form of the model has maintained usability through two key mechanisms. First, the model is designed in a simple input-output workflow with all inputs stored in a single Excel file, which is structured such that a single primary data sheet is converted to a *.csv and imported directly. The model provides all results in a separate *.csv. Second, input data and files were checked extensively by the team to ensure the accuracy of data entry and manipulation in Excel.

Model Application. For a watershed-scale project, site-specific alternatives may be combined to develop unique basin-wide plans. Ideally, the solution space would be explored by analyzing every possible combination of alternatives and calculating costs and benefits. Each of these plans could then be carried forward to cost-effectiveness and incremental cost analyses. However, an exhaustive search of the entire solution space was numerically prohibitive with 49 proposed restoration sites (i.e., 49 sites provides 2^{49} possible plans or ~$5.6 * 10^{14}$ possible combinations). As such, a comprehensive search of the solution space was conducted with a maximum of 4 sites (231,526 plans). Sites were then down-selected if either of two criteria were met: (1) the site appeared in any cost-effective plans from the 0-4 site analysis or (2) the site was in the top third of cost-effective habitat patches (ignoring cumulative effects of multiple barriers). The solution space was then comprehensively searched for these 18 sites with all combinations of 5-18 actions (258,096). Finally, a plan was maintained which included actions at all 49 sites (1 plan) for reference of the maximum potential habitat gain. These 489,623 plans represent the potential combinations of actions explored for the EHB. Combinatorial plans were analyzed using built-in statistical functions in R. Benefits and costs (net over the future without project) were computed for all plans, and sites were screened based on this preliminary cost-effectiveness analysis (Figure 4).

Cost-effectiveness analysis identified 89 plans. This reduced set of plans was then manually subjected to incremental cost analysis following well-described methods (Robinson et al. 1995). Based on these analyses, 14 "best" plans were identified (Table 1). For reference, if all barriers in the study region were removed, 65.6 quality-weighted kilometers of habitat would be gained at a relative cost of 10.1M cost units (CUs). A variety of criteria could then be applied to recommend a plan (e.g., thresholds in habitat provision, cost, or incremental cost). For instance, incremental cost increases significantly beyond plan 466,439. This plan obtains 66% of the total potential habitat gain under all actions (i.e., 43.3 / 65.6 HUs) at 19% of the relative cost (i.e., 1.91M / 10.05M CUs).

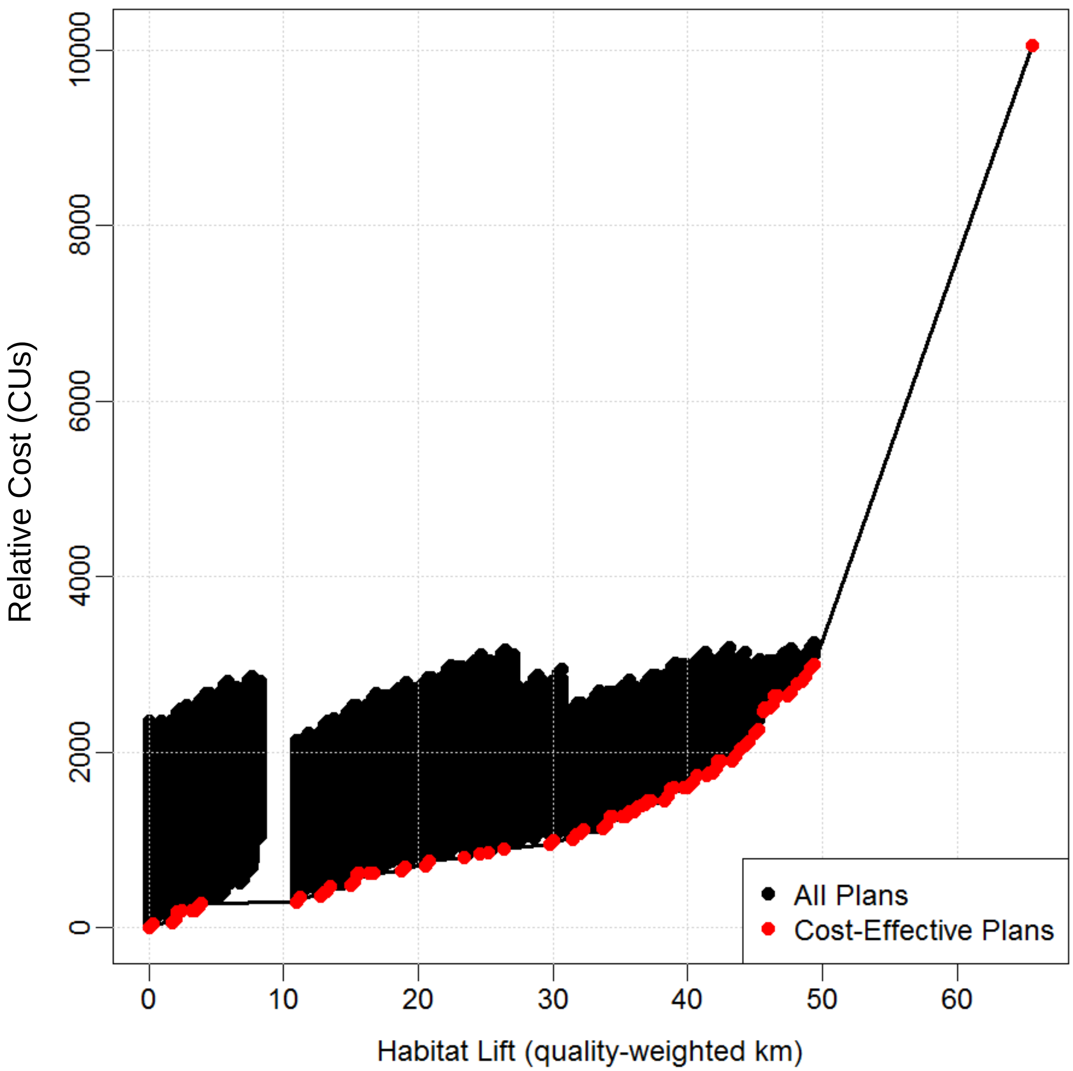

Figure 4. Cost-effectiveness analysis for alternative combinations of barrier removals.

Table 1. Recommended barrier removal plans over a range of costs as identified by the barrier prioritization ecological model, cost-effectiveness analysis, and incremental cost analysis.

Plan #	Habitat (HU)	Relative Cost (CU)	Incremental Cost / Unit (CU/HU)	Number of Sites	Sites Included
1	0.0	0	na	0	None (FWOP)
34	10.9	300,809	27,483	1	36
1,086	12.7	361,420	34,193	2	36, 51
262,521	31.5	1,010,922	34,581	7	2, 3, 9, 21, 36, 45, 51
298,004	33.7	1,133,631	54,653	8	2, 3, 9, 21, 36, 45, 51, 53
345,344	38.3	1,453,538	70,067	9	2, 3, 9, 21, 36, 45, 51, 53, 54
395,565	40.0	1,592,785	82,376	10	2, 3, 9, 21, 31, 36, 45, 51, 53, 54
437,994	41.9	1,766,087	93,425	11	2, 3, 9, 13, 21, 31, 36, 45, 51, 53, 54
466,439	43.3	1,905,334	98,839	12	2, 3, 9, 13, 21, 26, 31, 36, 45, 51, 53, 54
481,285	44.3	2,078,637	169,886	13	2, 3, 6, 9, 13, 21, 26, 31, 36, 45, 51, 53, 54
487,381	44.6	2,125,009	171,921	14	2, 3, 6, 9, 13, 18, 21, 26, 31, 36, 45, 51, 53, 54
489,192	48.7	2,859,961	175,846	15	2, 3, 6, 7, 9, 13, 18, 21, 26, 31, 36, 45, 51, 53, 54
489,553	49.4	2,999,208	205,663	16	2, 3, 4, 6, 7, 9, 13, 18, 21, 26, 31, 36, 45, 51, 53, 54
2	65.6	10,054,331	434,963	49	All

DISCUSSION: This technical note has presented an approach for prioritizing barrier removal within the Hudson-Raritan Estuary and demonstrated the application of this model in the Harlem River, East River, and Western Long Island Sound Planning Region. Although the model provides a rapid and defensible approach for articulating priorities, a few key assumptions and limitations are worth noting. First, this analysis relied heavily on a readily available geospatial data sets. The National Hydrography Dataset (NHD) has been previously identified as potentially inaccurate for small tributaries and headwater drainage (Fritz et al. 2013), and some EHB watersheds contained no mapped stream features (Appendix A). While the National Inventory of Dams provides a nationally available data layer, the NID is well-acknowledged to be incomplete and often does not include small dams or very old structures (e.g., mill dams), which are often ecologically significant and the target for restoration actions. Second, other important migratory barriers may exist in a watershed, such as culverted road crossings, exposed utility crossings, natural waterfalls, and other forms of barriers (e.g., water quality, temperature). Although the EHB study area is highly urbanized, we excluded culverts from the analysis to focus on larger scale restoration actions likely to be undertaken by the Corps, various issues and associated expense in developing and verifying a culvert inventory (no national inventory exists), and to minimize the size of the numerical data set (e.g., in the Great Lakes there are 38 times more culverts than dams, Januchowski-Hartley 2013). Third, the habitat quality assessment was based on three general proxies of stream health, and future analyses could be expanded to include species-specific habitat requirements (e.g., expected home ranges, critical habitat, or specific ecological zones of high integrity and function). Fourth, site-specific conditions in constrained urban environments can increase costs dramatically, and the estimates applied here should only be construed as a comparative estimate, not expected restoration cost.

As shown, barrier prioritization analyses can examine many potential combinations of restoration actions and produce a set of strategic improvement projects. However, the sequencing of removals can influence the efficacy of a given action. For instance, barrier improvement systematically pursuing a set of priorities over a 20 year horizon should not only focus on which actions, but also the order of those actions. For the case of anadromous fish, sequencing typically moves from downstream to upstream, although costs, feasible, and other factors can influence these choices (Oliver and Gendron 2016).

Large-scale restoration projects often present the challenges of not only selecting an alternative at a given site but also selecting effective sites. Spatially explicit prioritization tools can inform watershed-scale decisions about the cumulative effects associated with multiple sites. However, cumulative effects analyses can often be complex to develop and execute due to dependencies between actions (e.g., the effect of an upstream wetland on downstream water quality). Here, a simple cumulative effects model is presented for fish passage improvement in the tributaries of the Hudson-Raritan Estuary. While this model does not address the complex dependencies between barrier removal and other forms of HRE restoration projects (e.g., coastal wetland restoration), the tool does provide a defensible framework for rapidly screening thousands of potential plans to a more manageable set of sites. These tools helped identify an effective and efficient portfolio of projects that achieve large amounts of ecological improvement at relatively low effort. From this analysis, 49 proposed sites were screened to a recommended plan addressing 12 sites (Plan 466,439, Figure 5), which provides 69% of the total potential habitat gain at 19% of the relative cost with only 24% of the potential sites.

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> McKay S.K., Reif M.K., Conyngham J.N., and Kohtio D.M. 2017. Barrier Prioritization in the Tributaries of the Hudson-Raritan Estuary. *EMRRP Technical Notes Collection*. ERDC TN-EMRRP-??. U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi. https://el.erdc.dren.mil/emrrp/emrrp.html

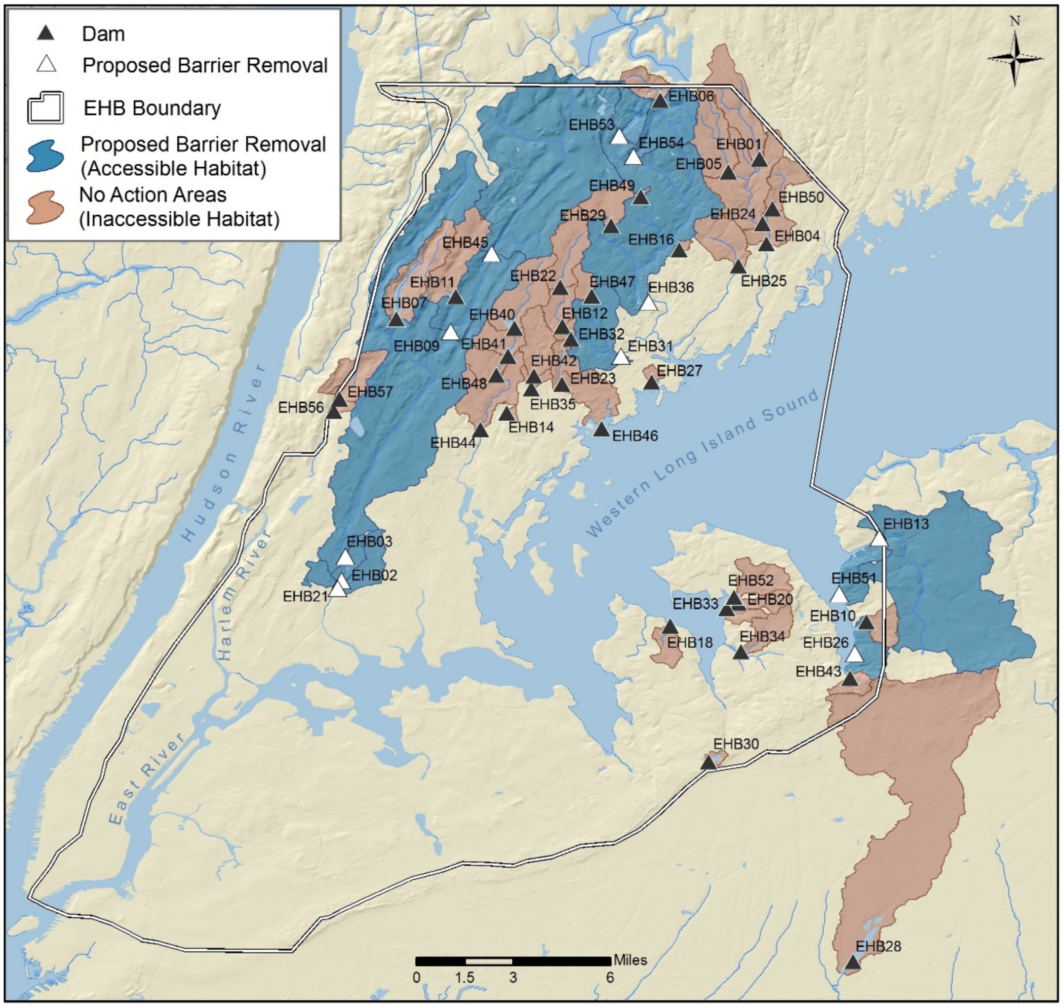

Figure 5. Example of barrier removal sites and accessible habitat (Plan 466,439).

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APPENDIX – EAST HARLEM / BRONX PLANNING UNIT DATA: (* denotes recommended plan)

Barrier Properties					Watershed Properties		303d Listing	Watershed Area in NLCD Land Use Code (km^2)				TNC-Secured Lands
Dam Name	BarrierID	Year Completed	Length (ft)	Height (ft)	Area (km^2)	Length (km)	Length (km)	LU 21	LU 22	LU 23	LU 24	Area (km^2)
Blind Brook Club Dam	EHB01	1959	130	32	5.938	5.803	5.141	1.627	0.729	1.068	0.521	0.112
Bronx River Dam (north) *	EHB02	1900	122	18	1.406	1.281	1.266	0.256	0.192	0.327	0.309	0.921
Bronx Zoo Dam (upper) *	EHB03	NA	NA	10	44.727	35.401	27.868	11.128	8.934	13.620	6.911	3.543
Brookside Lower Dam	EHB04	1985	150	10	2.196	1.972	1.089	0.649	0.533	0.715	0.209	0.036
Edgar Bronfman Lake Dam	EHB05	1962	150	8	4.806	5.813	5.813	2.138	0.536	0.216	0.110	0.000
Forest Lake Dam	EHB06	1996	220	12	1.986	1.555	0.000	0.474	0.536	0.066	0.000	0.008
Grassy Sprain Reservoir Dam	EHB07	1876	600	40	5.620	7.219	2.945	1.923	1.030	0.645	0.051	0.661
Hodgman Dam *	EHB09	1919	50	4	7.385	6.667	6.648	3.267	2.868	0.967	0.212	0.053
Clapham Dam	EHB10	1905	400	8	1.820	0.000	0.000	1.186	0.431	0.105	0.021	0.008
Crestwood Lake Dam	EHB11	1995	64	10	5.052	1.218	0.841	1.911	1.336	0.993	0.563	0.000
Dickerman Dam	EHB12	1895	135	10	2.000	2.203	2.203	0.639	0.883	0.279	0.004	0.289
Glen Cove Lower Dam *	EHB13	1912	250	12	33.906	7.121	7.121	13.982	6.134	3.861	0.798	0.164
Glenwood Lake Dam	EHB14	NA	NA	12	0.278	0.000	0.000	0.161	0.112	0.006	0.000	0.000
Hutchinson River Parkway Detention Dam	EHB16	NA	1025	13	0.249	0.000	0.000	0.162	0.053	0.000	0.000	0.000
Kings Point Dam	EHB18	1870	75	4	1.574	1.338	1.295	0.850	0.459	0.145	0.007	0.000
Baxter Estates Pond Dam	EHB20	1910	90	10	1.267	0.000	0.000	0.686	0.328	0.195	0.049	0.021
Bronx River Dam (south) *	EHB21	1883	80	6	3.854	0.420	0.420	0.114	0.262	1.314	2.126	0.142
Carpenter Pond Dam	EHB22	1925	156	16	4.246	2.987	2.987	2.518	1.263	0.329	0.028	0.054
Beechmont Lake Dam	EHB23	1904	250	21	1.535	1.508	0.000	0.983	0.384	0.064	0.016	0.000
Bowman Ave Dam	EHB24	1941	122	22	7.330	6.354	6.354	3.589	1.197	0.562	0.169	0.097
Durand Pond Dam	EHB25	1927	64	11	3.602	2.013	2.013	2.217	0.306	0.110	0.005	0.000
Goodwin Dam *	EHB26	NA	900	10	3.064	3.133	3.130	1.041	0.469	0.309	0.178	0.612
Hampshire Country Club Dam	EHB27	NA	NA	15	0.452	0.167	0.167	0.307	0.131	0.006	0.006	0.000
Hempstead Park Pond Dam	EHB28	1908	350	7	48.035	0.417	0.417	11.633	11.655	12.480	5.669	2.635
Lake Ridgeway Dam	EHB29	1926	NA	10	2.712	0.000	0.000	1.252	0.947	0.393	0.033	0.197
Lake Success Dam	EHB30	NA	108	4	0.456	0.000	0.000	0.172	0.099	0.015	0.004	0.000

Barrier Properties					Watershed Properties		303d Listing	Watershed Area in NLCD Land Use Code (km^2)				TNC-Secured Lands
Dam Name	BarrierID	Year Completed	Length (ft)	Height (ft)	Area (km^2)	Length (km)	Length (km)	LU 21	LU 22	LU 23	LU 24	Area (km^2)
Larchmont Dam *	EHB31	1925	210	10	6.275	4.505	2.348	4.092	1.348	0.216	0.018	0.129
Larchmont Water Company Dam #2	EHB32	1935	1000	31	0.659	0.828	0.828	0.215	0.181	0.102	0.000	0.013
Leeds Pond Dam	EHB33	1908	390	10	1.036	1.119	1.119	0.171	0.375	0.325	0.151	0.010
Little Leeds Pond Dam	EHB34	1910	125	8	2.395	0.825	0.825	0.986	0.856	0.398	0.103	0.000
Mahstedt Reservoir Dam	EHB35	1885	7000	15	0.590	0.000	0.000	0.239	0.334	0.005	0.000	0.023
Mamaroneck Reservoir Dam *	EHB36	1928	185	19	24.417	21.142	10.682	9.457	4.825	4.072	1.054	3.450
New Rochelle Reservoir #1 Dam	EHB40	1894	680	30	4.939	3.759	0.690	2.082	1.835	0.489	0.119	0.466
New Rochelle Reservoir #3 Dam	EHB41	1908	450	30	2.201	1.505	0.000	0.512	0.868	0.389	0.102	0.432
Paine Lake Dam	EHB42	1890	250	13	3.272	0.000	0.000	1.874	1.046	0.277	0.069	0.000
Paper Mill Pond Dam	EHB43	1914	325	10	1.206	0.206	0.000	0.519	0.369	0.098	0.016	0.081
Pelham Lake Dam	EHB44	1890	590	14	4.831	3.467	3.467	1.444	2.219	0.759	0.130	0.448
Popham Road Dam *	EHB45	NA	90	8	35.440	16.986	14.495	14.151	7.596	5.709	2.649	1.594
Premium Mill Pond Dam	EHB46	NA	400	11	3.718	3.307	3.301	1.611	1.073	0.606	0.288	0.215
Quaker Ridge Golf Club Dam	EHB47	1966	300	6	1.088	0.000	0.000	0.658	0.345	0.049	0.001	0.070
Reservoir #2 Dam	EHB48	1892	550	25	1.931	1.004	0.066	0.935	0.625	0.186	0.024	0.257
Ridgeway Country Dam	EHB49	NA	100	0	0.159	0.000	0.000	0.099	0.004	0.014	0.000	0.000
Rye Brook Estates Dam	EHB50	NA	150	14	2.372	1.660	0.393	1.217	0.828	0.207	0.011	0.092
Scudders Pond Dam *	EHB51	1900	675	5	3.055	4.883	2.842	1.350	0.690	0.460	0.230	0.079
Shore Road Dam	EHB52	1913	245	6	2.831	0.000	0.000	1.466	0.461	0.592	0.061	0.041
Silver Lake Dam *	EHB53	1815	225	9	2.779	3.309	1.894	0.542	0.233	0.295	0.018	1.251
Spring Lake Dam *	EHB54	1895	250	20	5.279	8.662	2.469	2.590	0.459	0.373	0.024	0.040
Tibbetts Park Dam #1	EHB56	1925	150	8	0.571	0.000	0.000	0.154	0.130	0.111	0.018	0.220
Tibbetts Park Dam #2	EHB57	1925	100	17	3.353	1.576	0.003	1.217	0.838	0.857	0.126	0.478