FINAL REPORT

Assessment of Existing Coastal Habitat Connectivity Data and Models for Feasibility and Use in the Long Island Sound

December 2024

Submitted to

Long Island Sound Study

NE IW PCC

Submitted by WSP USA Inc.

WSP

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This project has been funded wholly or in part by the United States Environmental Protection Agency under assistance agreement (LI-00A00688) to NEIWPCC in partnership with the Long Island Sound Study (LISS). The contents of this document do not necessarily reflect the views and policies of NEIWPCC, LISS, or the EPA, nor does NEIWPCC, LISS, or the EPA endorse trade names or recommend the use of commercial products mentioned in this document.

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1.0 INTRODUCTION

A goal of the Long Island Sound Study (LISS; Figure 1) is to increase connectivity among coastal habitats by restoring and/or protecting habitat patches that increase biodiversity and support migratory pathways (LISS 2023). When habitat patches are connected, fish and wildlife can freely move to meet their needs for feeding, breeding, resting, and/or migration. Connected habitats are also able to more effectively facilitate geneflow and genetic diversity, and ensure ecosystem resilience to stress by providing for species' recovery from disturbance (Basso et al. 2018). Habitat connectivity is one of five ecosystem targets developed for driving progress toward the LISS goal of "thriving habitats and abundant wildlife," as detailed in its Comprehensive Conservation and Management Plan (CCMP, LISS 2015). This ecosystem target is to "increase connectivity of coastal habitat by 2035 by restoring and/or protecting habitat patches that increase biodiversity and support migratory pathways." To achieve and track progress towards the habitat connectivity target, implementation action HW-4 is to "develop or apply habitat connectivity models to provide metrics for all restoration and protection projects." Appendix B of the CCMP (LISS 2015) describes how and why this target was chosen and how progress toward the target will be measured:

> "Research shows that improving habitat connectivity allows for genetic and ecological flow. Corridors provide fish and wildlife with greater ability to move for the purposes of feeding, breeding, and resting. Promoting restoration and protection projects, which increase aquatic and terrestrial connectivity, is an important component of ecosystem resilience, or the ability of an ecosystem and the fish and wildlife it supports to maintain function in the face of change. Connectivity gains can be both targeted and monitored by mapping restoration and protection projects in a GIS database and using decision support tools like the Stewardship Site Identification GIS Tool and Landscape Conservation Cooperative Connecticut River Pilot Landscape Design Tool which highlights the best areas of intact, resilient, and connected habitat and identifies corridors between these areas of high-quality patches. Using decision support tools like these will help to guide land protection decisions by highlighting areas on the landscape that have the greatest ecological value and identifying corridors between them. Efforts to refine these decision support tools are still underway as part of IA HW-4. Once these tools are complete, they will be used to establish a quantitative metric which will be used to estimate a baseline and set a more specific quantitative goal to be accomplished by 2035."

According to the five-year review of the CCMP (LISS 2020), LISS determined that it should capitalize on existing habitat connectivity tools and models rather than initiate new in-house efforts that would be more costly and challenging. Such models could also be incorporated into decision support tools to help guide land protection decisions.

2.0 METHODOLOGY

The research team conducted a review of existing habitat connectivity tools and models, including a limited number of practitioner interviews, to gain greater insight into habitat connectivity model development, application, and limitations. This review is the first step in understanding the options and approaches that the LISS could use to assess habitat connectivity improvements from its restoration and protection projects through the application of metrics. These metrics would be used for assessing habitat connectivity among priority coastal habitats and prioritizing habitat conservation actions.

The research team focused on addressing the following questions:

1. What existing habitat connectivity models and tools have been developed for the region, and can they be applied to address the stated habitat connectivity goals of LISS in a quantitative manner?
2. What are the key metrics to establish the importance and contribution of a restoration site to overall habitat connectivity?
3. Is there one approach or a combination of approaches available from existing connectivity models to meet LISS connectivity goals?

Section 3 focuses on addressing the first question with a literature review of regional connectivity models and other supporting tools.

Section 4 focuses on the metric development for tidal wetlands and for riverine migratory corridors to assess individual site contribution to local and regional habitat connectivity.

Lastly, Section 5 summarizes the findings and presents recommendations.

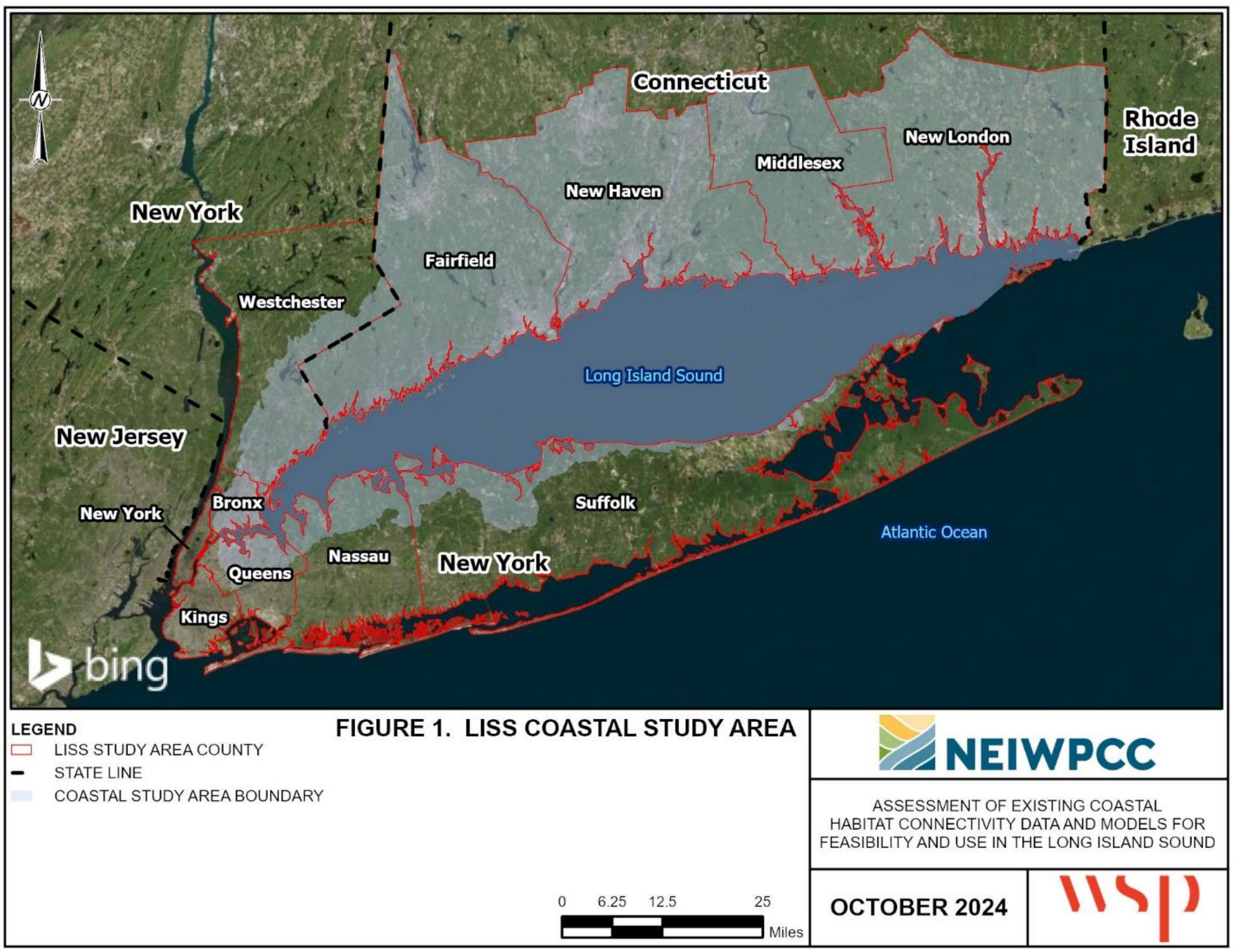


Figure 1. LISS Coastal Study Area

3.0 LITERATURE REVIEW AND INTERVIEWS

OVERVIEW OF LISS PRIORITY HABITATS

The LISS targets twelve types of coastal habitats for restoration to sustain nature and provide ecosystem services. Each coastal habitat type is described on the LISS webpage and an interactive ArcGIS story map provides examples. Table 1 lists the potential key plant and animal species that may be important to consider for habitat connectivity modeling and metric development in each priority habitat.

Table 1. LISS priority habitats and potential key species for habitat connectivity analysis (Sources: LISS 2003, Howard and Schlesinger 2012, NYSDEC 2015).

Priority Habitat	Potential Key Species	
Beaches and Dunes	Piping plover Least tern Black skimmer Other shorebirds	Northeastern beach tiger beetle Horseshoe crab American beachgrass (*Amophola brevicauda*) Seabeach amaranth (*Amaranthus pumilus*)
Cliffs and Bluffs	Peregrine falcon	Cliff swallow
Estuarine Embayments	Saltmarsh sparrow Diamondback terrapin Blue crab	Horseshoe crab American eel Winter flounder
Coastal Grasslands	Grasshopper sparrow Northern harrier American woodcock	Upland sandpiper Eastern box turtle
Coastal and Island Forests	Red-shouldered hawk Wood thrush	Migratory birds New England cottontail
Tidal Wetlands	Saltmarsh sparrow Seaside sparrow osprey American bittern Least bittern King rail Willet Great egret Snowy egret Little blue heron	Glossy ibis Diamond-backed terrapin Lesser sand-spurrey (*Spegularia canadensis*) Bulrush (*Scirpus cylindricus*) Bulrush (*Scirpus paludosus* var. *atlanticus*) Goldenclub (*Orontium aquaticum*) Mudwort (*Limosella subulata*) Arrowleaf (*Sagittaria subulate*)
Freshwater Wetlands	Spotted turtle Pickerel frog Southern leopard frog	Eastern spadefoot toad Blue-spotted salamander
Submerged Aquatic Vegetation Beds	Winter flounder Menhaden Bluefish Striped bass	American lobster Bay scallop Hard-shell clam Eelgrass (*Zostera marina*)
Shellfish Reefs	American lobster Various fish species	Eastern oyster Blue mussel
Intertidal Flats	Migratory shorebirds	Horseshoe crab Eastern oyster
Rocky Intertidal Zones	Striped bass	Eastern oyster
Riverine Migratory Corridors	Alewife (a.k.a. river herring) Blueback herring	American eel Atlantic sturgeon

MEASURING HABITAT CONNECTIVITY

Kindlmann and Burel (2008) define connectivity as the ease with which individuals of a species can move about the landscape, either due to habitat structure or through their behavioral response. Connectivity can be further defined based on landscape structure (structural connectivity) or based on the dispersal characteristics and habitat requirements of a species (functional connectivity) (Baguette and Van Dyck 2007). Structural connectivity is focused on the physical characteristics of the landscape and can be evaluated based on the size and spatial arrangement of suitable habitat patches and the number of suitable corridors connecting those patches. On the other hand, functional connectivity emphasizes ecological processes and species-specific movements like gene flow, and is based upon studies of animal behavior, resource selection, and species responses to landscape features.

Wade et al. (2015) describe six types of connectivity that can be modelled: one, structural connectivity, and five types of functional connectivity. The five distinct types of functional connectivity include:

1. Daily habitat connectivity, which describes movements that animals make between resource patches to find daily food, water, and shelter.
2. Seasonal migration connectivity, which describes movement to and from breeding areas, whether annually or seasonally.
3. Demographic movement connectivity, which describes animal movements that result in recruitment within a new population as a function of dispersal.
4. Genetic movement connectivity, which describes animal movement between populations and subpopulations that maintains genetic variability.
5. Range shift connectivity, which describes animal movement that allows species to move into new habitats in response to climate change or other disturbances.

Keeley et al. (2021) summarized 35 connectivity metrics, sorted along a spectrum from fully structural (i.e., derived from spatial datasets that do not include species information) to fully functional (i.e., based on continuous data of species-specific relationships with various ecosystem features). They created a decision tree for selecting the most appropriate connectivity metrics for a study using three factors: (1) the extent of human modification of the focal landscape, (2) the type of connectivity (structural, functional, or both) to be measured, and (3) which conservation objectives is to be assessed. Figure 2, from Keeley et al. (2021), depicts a decision tree for selecting metrics in a landscape such as Long Island, namely a “heavily modified ecoscape” (e.g., cities and farms).

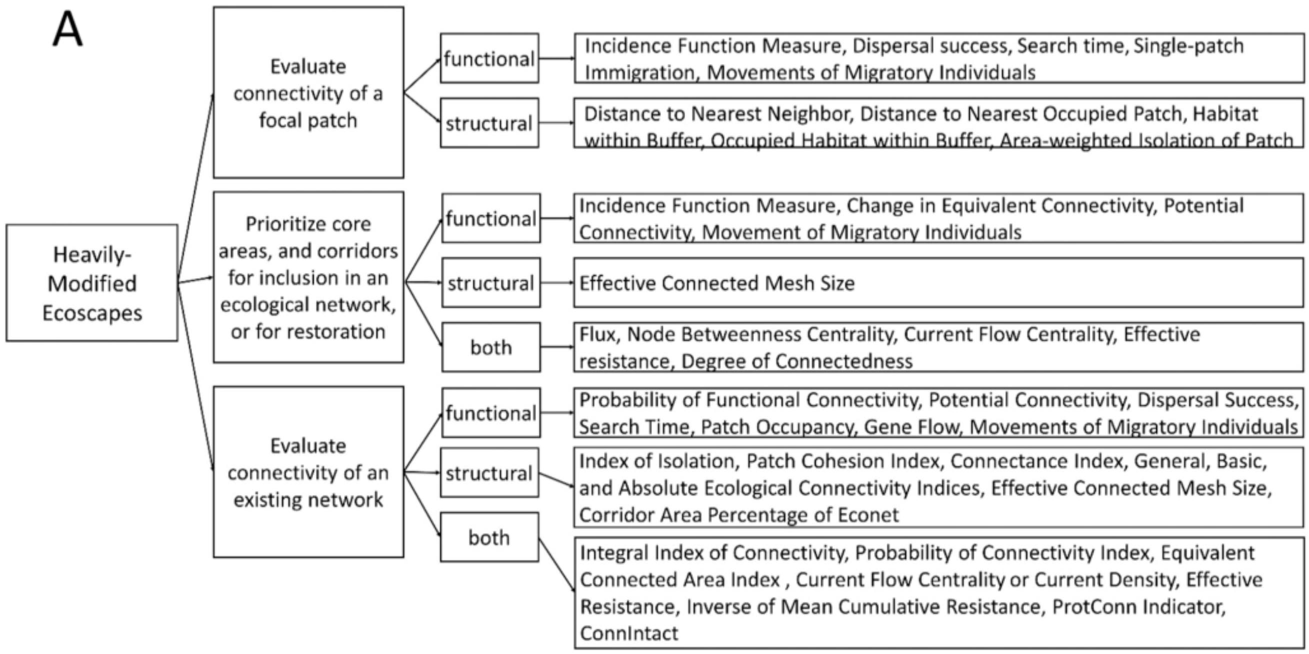


Figure 2. Decision tree for selecting connectivity metrics in a heavily modified ecoscape (Source: Keeley et al. 2021).

Keeley et al. (2021) conclude that, because an intact ecological network may support many species' movement, structural metrics that consider the human footprint should be used to assess of functional connectivity in developed regions like Long Island. Functional connectivity metrics may be preferred when conservation is focused on a particular species, or if there is abundant data on wildlife movement for a suite of species. While Wood et al. (2022) argue for the need to consider multispecies connectivity in conservation planning to ensure the persistence and resilience of species-rich communities, the lack of biological data is often a limiting factor for calculating functional connectivity metrics (Keeley et al. 2021).

Six of twelve LISS priority habitats are estuarine ecosystems (estuarine embayments, tidal wetlands, submerged aquatic vegetation beds, shellfish reefs, intertidal flats, and rocky intertidal zones). Another priority habitat, riverine migratory corridors, includes rivers and streams that flow into estuarine waters. Although there are habitat connectivity models developed for riverine migratory corridors, habitat connectivity within aquatic habitats is among the most infrequent and ineffectively applied ecological criteria for marine conservation (Magris et al. 2014). This is because connectivity is difficult to measure in marine systems, although it is increasingly being studied using hydrodynamic models that simulate the movement of water and other elements, such as larvae, seeds, or sediment (White et al. 2019). Such models are often developed using ROMS (Regional Ocean Modeling System) approaches, which are typically four-dimensional models (three spatial dimensions and time). These models can be used to track how ocean currents, tides, and winds influence the dispersal of species or materials across different habitats, helping to identify key areas that facilitate connectivity between isolated patches. Recent work has focused on integrating connectivity into the planning and management of marine protected areas (Lausche et al. 2021). Also, because many marine species utilize different habitats throughout their life cycles and are vulnerable to threats from both terrestrial and marine environments, their management must include a focus on land-sea connectivity, as highlighted by Fang et al. (2017). The complexity and variability of this connectivity, influenced by both natural and human factors across multiple spatial and temporal scales, requires further theoretical research and practical application.

References to estuarine aquatic habitat connectivity models were not identified for the region and it is very likely that none have been prepared due the complexity of the model development, lack of appropriate data to support model development, and a lower priority placed on model development.

GIS DATASETS

Gathering relevant spatial data that characterize the landscape and its features is a critical step of habitat connectivity modeling. This may include land cover maps, topography, hydrological information, landscape fragmentation or barrier data (e.g., roads, dams, culverts, and human development), and other relevant datasets. Other habitat variables important for the target species or ecosystems may include vegetation types, habitat quality or biodiversity rankings, and other ecological factors. Datasets describing the ecological boundaries for focal species may also be useful, such as species distribution models, movement data (e.g., telemetry or GPS tracking), and home range or dispersal area of the target species.

Datasets from existing models describing habitat condition, connectivity, and suitability may provide valuable inputs in habitat connectivity modeling, or serve as useful stand-alone metrics. Such data are available from the New York Natural Heritage Program (2021); the Staying Connected Initiative data available on the USGS (2023) ScienceBase catalog; and the Nature's Network datasets developed by the USFWS (2023); and the TNC (2016) Resilient and Connected Landscapes project. These data can be obtained from government agencies, research institutions, or other reliable sources. Table 2 identifies many available datasets and describes how they may be applicable (relevant) to habitat connectivity in coastal areas of the Long Island Sound.

Table 2. **Relevant datasets to inform potential LISS habitat connectivity models.**

Theme	Dataset	Source	Web Address	Applicability to LISS
Land Cover	New York NLCD Land Cover, 2016	USGS	https://cugir.library.cornell.edu/catalog/cugir-009031	Identifies landscape features that influence movement (e.g., rivers, roads, or barriers)
Land Cover	Connecticut Land cover, 1985 – 2015 (various datasets)	Available at CT Geodata Portal (source agency not specified)	https://geodata.ct.gov/apps/CTECO::ct-land-cover-viewer/explore	Numerous datasets identify land cover change across time (e.g., LIS Land Cover Viewer)
Land Cover	C-CAP Regional Land Cover and Change	NOAA	https://coast.noaa.gov/digitalcoast/data/ccapregional.html	Identifies Long Island Sound Landcover and change 1985-2015 from the NOAA the Coastal Change Analysis Program
Human Footprint	Visible Infrared Imaging Radiometer Suite (VIIRS) Nighttime light data	NOAA	https://www.nesdis.noaa.gov/current-satellite-missions/currently-flying/joint-polar-satellite-system/visible-infrared-imaging	Identifies development density or level of urban development; see Zhai et al. (2016) "Land Use Change in Long Island Sound Watersheds Using Nighttime Light Data"
Human Footprint	Human Impact Index data	Wildlife Conservation Society (WCS)	https://wcshumanfootprint.org/	A widely used metric of human impacts that is a simple weighted sum of maps of population density, built infrastructure, and transportation networks
Topography	Elevation, Contours, LiDAR, and Aerials 2012-2023	CT DEEP	https://maps.cteco.uconn.edu/download/	Provides high resolution topographic data
Topography	Long Island Sound Bathymetric Contours	CT DEEP	https://geodata.ct.gov/datasets/CTDEEP::bathymetric-contours-in-meters-for-long-island-sound/explore	Provides high resolution bathymetric data
Built Environment	Connecticut bridge data	CTDOT	https://geodata.ct.gov/search?tags=structures	Identifies bridges for aquatic organism connectivity
Built Environment	Connecticut transportation datasets	Various CT state agencies	https://geodata.ct.gov/search?categories=transportation	Identify human infrastructure that affects habitat connectivity
Built Environment	Connecticut Built Environment datasets	UCONN	https://maps.cteco.uconn.edu/map-services/	Identify non-habitat area from impervious surface data
Built Environment	New York Roads	North Atlantic Landscape Conservation Cooperative	https://www.sciencebase.gov/catalog/item/57c49a9ae4b0f2f0cebc956b	Identify potential transportation features that affect habitat connectivity

Theme	Dataset	Source	Web Address	Applicability to LISS
Natural Features	Protected Areas Database	USGS	https://www.usgs.gov/programs/gap-analysis-project/science/pad-us-data-overview	America's official national inventory of U.S. terrestrial and marine protected area
Natural Features	NY State Freshwater Wetlands	NYSDEC	https://data.gis.ny.gov/maps/a57e144caedb4b1aaf510809013e4ac7/about	Identifies wetlands, which are a conservation priority because of the large number of associated species
Natural Features	New York Riparian Areas	North Atlantic Landscape Conservation Cooperative	https://www.sciencebase.gov/catalog/item/5812504be4b0b5a0c129ea20	Identifies habitats that are critical to wildlife and used by large numbers of species, not only for habitat but, as important corridors for dispersal and migration
Natural Features	New York Large Forest Blocks	North Atlantic Landscape Conservation Cooperative	https://www.sciencebase.gov/catalog/item/5818f6e5e4b0bb36a4c9074f	Identifies important habitats on the landscape that provide core habitats among which conservation actions may seek to restore or enhance connectivity
Natural Features	National Wetlands Inventory	USFWS	https://www.fws.gov/program/national-wetlands-inventory/data-download	Identifies wetlands, which are a conservation priority because of the large number of associated species
Natural Features	National Hydrography	USFWS	https://www.usgs.gov/national-hydrography/access-national-hydrography-products	Identifies streams for aquatic organism connectivity
Natural Features	FEMA Flood Maps	FEMA	https://msc.fema.gov/portal/advanceSearch	Floodplains and flood-prone areas typically retain natural vegetation and water resources, making them critical for maintaining ecological linkages across developed landscapes.
Species	New York Natural Heritage Data	NYNHP	https://www.nynhp.org/request-information/	Provides presence of rare or listed plants and animals or of significant natural communities
Species	Connecticut Natural Diversity Database	CT DEEP	https://ct-deep-gis-open-data-website-ctdeep.hub.arcgis.com/datasets/CTDEEP::natural-diversity-database/explore	Data includes known locations, both historic and extant, of state and federal listed species. Other CT NHP datasets include shellfish beds, eelgrass, cold water habitat sites, critical habitats, phragmites extent, and migratory waterfowl concentration areas

Theme	Dataset	Source	Web Address	Applicability to LISS
Species	Various Monitoring Data and Studies	LISS	https://longislandsoundstudy.net/research-monitoring/liss-research-grant-program/	Provides information on several key species and habitats, such as eelgrass and fishery studies
Modeled Data	Resilient and Connected Landscapes for Terrestrial Conservation	The Nature Conservancy	https://www.conservationgateway.org/ConservationByGeography/NorthAmerica/UnitedStates/edc/reportsdata/terrestrial/resilience/Pages/default.aspx	Integrates resilience, permeability, and diversity to develop a connected network of sites for various conservation strategies that will provide for species movement
Modeled Data	Nature's Network	North Atlantic Landscape Conservation Cooperative et al.	https://www.naturesnetwork.org/data-tools/download-tables/ Also available at: https://nalcc.databasin.org/galleries/8f4dfe780c444634a45ee4acc930a055/#expand=116000%2C116001%2C115998	Identifies the best opportunities for conserving intact habitat, supporting imperiled species, and connecting natural areas. Includes multiple datasets under four themes: Terrestrial and Connector Networks; Aquatic Core Networks, Habitat for Imperiled Species, and Connectivity for Marsh Mitigation
Modeled Data	Ecological Systems Model, New York State	North Atlantic Landscape Conservation Cooperative et al.	https://www.sciencebase.gov/catalog/item/57e2c7e6e4b09082500459ed	Represents the terrestrial and wetland ecological systems based on NatureServe's Ecological Systems Classifications, combined with human-modified land types such as roads and agriculture
Modeled Data	Index of Ecological Integrity, New York State	North Atlantic Landscape Conservation Cooperative et al.	https://www.sciencebase.gov/catalog/item/58062954e4b0824b2d1d3d2f	Ecological integrity is defined as the ability of an area (e.g., local site or landscape) to sustain important ecological functions over the long term
Modeled Data	Local Connectivity, New York State	North Atlantic Landscape Conservation Cooperative et al.	https://www.sciencebase.gov/catalog/item/58052fe6e4b0824b2d1c1e05	Estimates the degree of connectedness of a cell with its surroundings within a three km radius
Modeled Data	Significant Habitats, New York State	North Atlantic Landscape Conservation Cooperative et al.	https://www.sciencebase.gov/catalog/item/5808f91be4b0f497e78f3d8e	Highlights valuable habitats for Regional Species of Greatest Conservation Need based on an Ecological Systems Map and the Protected Areas Dataset

Theme	Dataset	Source	Web Address	Applicability to LISS
Modeled Data	Regional Flow Anthropogenic Resistance Categories	The Nature Conservancy	https://nalcc.databasin.org/datasets/b4a479ffc15a4674ae6b7d5a92cc33ff/	Shows basic patterns in current flow that reflect how the human modified landscape is spatially configured, allowing for the identification of where population movements and potential range shifts may become concentrated or where they are well dispersed, and it is possible to quantify the importance of an area by measuring how much flow passes through it, and how concentrated that flow is. The results can be used to identify important pinch points where movements are predicted to concentrate, or diffuse intact areas that allow for more random movements.
Modeled Data	Landscape Condition Assessment Model	NYNHP	https://www.nynhp.org/modeled-data/#LCA	Depicts the presumed impacts from a suite of anthropogenic stressors across the landscape and has been shown to be correlated with ecological conditions measured on the ground
Modeled Data	Sea Level Affecting Marshes Modeling	LISS	https://longislandsoundstudy.net/research-monitoring/slamm/	Provides one of many resources available to investigate how Long Island Sound's coastline may respond to sea-level rise, an important factor to consider for future habitat connectivity

HABITAT CONNECTIVITY MODELS AND TOOLS

Habitat connectivity models are valuable tools for assessing the interconnectedness of habitats, identifying potential barriers to species movement, and informing conservation and management strategies. Various modeling approaches, such as least-cost path analysis, graph theory, and circuit theory can be used to analyze connectivity. These methods help quantify connectivity, identify important corridors or stepping-stone habitats, and evaluate the effects of landscape changes or restoration actions on connectivity.

One of the oldest methods of predicting connectivity among habitat patches is least-cost path analysis (or permeability analysis), which is also the most commonly used analysis method (Ayram et al. 2015). The least-cost path is the route that offers the shortest cost-weighted distance between two habitat patches, which is considered the optimal route that an individual is most likely to take when moving across the landscape (Walker and Craighead 1997). More recently, habitat connectivity models based on graph theory and circuit theory have been developed. Graph-based models represent habitat patches as nodes and the connections or corridors between them as edges. These models analyze the structural properties of the habitat network to identify key areas for habitat connectivity. They consider factors such as patch size, shape, proximity, and edge effects, as well as the connectivity and redundancy of corridors. They can guide conservation actions by identifying important habitat patches for protection or restoration to facilitate movement of wildlife across the landscape. Circuit theory models simulate movement patterns of organisms based on electrical circuit theory principles. These models represent habitats as conductive elements and barriers as resistors, using resistance surfaces derived from spatial data, which assign resistance values to different landscape features based on their permeability to movement (see Wade et al. 2015). They consider the behavior of organisms as electrical current and use graph theory to evaluate connectivity. Circuit theory models can assess the flow of organisms through the landscape, identify pinch points, and evaluate the influence of different landscape features on connectivity. Both circuit theory and graph theory models require input data such as habitat maps, resistance surfaces, patch locations, and landscape connectivity data. These models can be implemented using specialized software or custom-developed algorithms.

While assessing connectivity in terrestrial landscapes has been extensively studied, the exploration of connectivity in riverine systems is recent. River networks differ from terrestrial systems, as the effects of river fragmentation on connectivity are significant and distinct from two-dimensional systems due to the existence of fewer possible pathways for water-mediated dispersal and recolonization (Fagan 2002). River systems often have fewer dispersal pathways, making them more susceptible to fragmentation, which can severely impact the dispersal and recolonization routes necessary for species survival. Additionally, aquatic environments are highly dynamic, and their connectivity is influenced by a range of physical, biological, and anthropogenic variables, in addition to the presence of barriers such as dams and culverts. Climate change also exacerbates the challenge of maintaining or restoring connectivity in aquatic ecosystems (Franklin et al. 2023). Recently, due to stressful summertime water temperatures in streams, there has been increased focus on addressing the challenge of defining, measuring, and conserving connectivity among thermally suitable habitats for species of conservation concern or economic importance. The functional value of waters with suitable temperatures depends on their connectivity to other thermally suitable habitats over time for allowing aquatic species to migrate or move to thermal refuges needed for survival during extreme temperature events. Thus, any reduction in thermal diversity across the riverscape can diminish connectivity.

Habitat connectivity models play a crucial role in assessing and understanding the migratory pathways of riverine species. Two key references that provide insights into habitat connectivity metrics and models for riverine migratory pathways are Fullerton et al. (2010) and JumanI et al. (2020). These papers provide insights into the methods, challenges, and opportunities associated with quantifying habitat connectivity and flow alteration in river systems. The Fullerton et al. (2010) study emphasizes the significance of studying migratory species capable of long-distance movements, such as diadromous fish species, to gain valuable insights into ecological connectivity. It summarizes research themes related to riverine hydrological connectivity and details the quantitative approaches used to evaluate connectivity in freshwater ecosystems. The JumanI et al. (2020) review presents a framework for visualizing the effects of different types of river infrastructure projects on fragmentation and flow alteration. It discusses various metrics available to quantify connectivity and flow alteration, along with their advantages, disadvantages, data requirements, and scales of application. It categorizes connectivity metrics into those that measure the structural, potential, or actual connectivity. Structural connectivity metrics are based on the physical attributes of the river network, such as the length of river segments or the location of barriers like dams. Potential connectivity metrics combine physical attributes with biological or ecological data, like the dispersal capabilities of species. Actual connectivity metrics are based on observed ecological data, such as species movement patterns. The review also provides decision-making trees to assist in selecting appropriate methods for assessing river fragmentation and flow alteration.

Modeling Habitat Connectivity

Because the multitude and complexity of methods, data needs and required expertise, modeling habitat connectivity can be challenging. Numerous online resources are available to assist. Conservation Corridor (2023) provides descriptions and a user guide to help determine which tool(s) to use (modified from Dutta et al. (2021)). The Conservation Corridor website also includes several useful FAQs. Numerous other resources exist that provide guidance about the tools, software programs, basics of connectivity modeling, how to select a modeling approach, and best practices for carrying out a connectivity modeling project. A list of six guidance documents, primary literature, and tools and software is provided below.

1. Resistance-surface-based wildlife conservation connectivity modeling: Summary of efforts in the United States and guide for practitioners (Wade et al. 2015). This guide provides an overview of resistance-surface-based connectivity modeling for terrestrial wildlife conservation through a review of the literature on connectivity modeling efforts in the U.S. It provides practitioners with guiding questions for constructing a robust, ecologically-sound, resistance-surface-based connectivity model. The authors state that "the methods for modeling connectivity in ocean (e.g., Treml et al. 2008) or riverine (e.g., Fagan 2002) environments may not lend themselves to resistance-surface-based approaches (but see Landguth et al. 2012)."
2. Pulling the Levers: A Guide to Modelling and Mapping Ecological Connectivity (Chernoff 2016) is a basic primer geared towards those with little or no experience in connectivity modeling. It provides easy-to-follow instruction and technical considerations of how to model and map connectivity. It follows a general blueprint or template for how to undertake connectivity projects, as laid out by organizations like the USFS (Wade et al. 2015). The guide covers project scoping, identifying data inputs, running the model, refining model outputs, and using model results.

3. New concepts, models, and assessments of climate-wise connectivity (Keeley et al. 2018) is a research paper that identifies thirteen approaches to modeling climate-wise connectivity, grouped by whether they focus on focal species or landscape structure. It provides guidance on selecting the best methods for a connectivity assessment depending on the objectives, available data, and landscape context. Table 2 in the paper lists the advantages and disadvantages of the thirteen approaches, including riparian corridors, carbon corridors, and environmental gradients. The authors state that, "when prioritizing areas for connectivity conservation, approaches include focusing on connecting areas of low climate velocity, refugia, climate analogs, or linking current to future suitable habitats. Riparian corridors should be considered in connectivity plans because of their importance as natural movement corridors, climate gradients, and refugia."

4. Landscape Connectivity Planning for Adaptation to Future Climate and Land-Use Change (Costanza and Terando 2019) reviews the latest advances in the literature on approaches for identifying (i.e., modeling) and promoting (i.e., maintaining and enhancing) habitat connectivity in the context of climate change and land-use change. They found that recent studies incorporated future climate change into connectivity planning more often than land-use change, but rarely considered the two drivers jointly. They argue that successful promotion of connectivity will depend on (1) the velocity of climate change, (2) the velocity of land-use change, and (3) the degree of existing landscape fragmentation. They present a conceptual framework to select an appropriate approach for modeling corridor networks given these three factors.

5. A review of ecological connectivity analysis in the Region of Resolution 40-3 (Arkilanian et al. 2020) explores the application of different methodologies and approaches used to assess connectivity in New England, which did not include New York but did include Connecticut. The authors critically evaluated various connectivity studies, examining their strengths and limitations. The paper provides an overview of the current state of knowledge regarding ecological connectivity analysis in the region, including recent advancements, areas for improvement, and the need for future research to advance our understanding of ecological connectivity.

6. General Landscape Connectivity Model (GLCM): a new way to map whole of landscape biodiversity functional connectivity for operational planning (Drielsma et al. 2022) presents a graph-theoretic approach to evaluating and mapping habitat networks to inform conservation priorities and plans. GLCM is built on two complementary metapopulation ecology-based measures: Neighborhood habitat area (*Ni*) and habitat link value (*Li*). *Ni* is a measure of the amount of connected habitat to each location considering its cross-scale connectivity to neighboring habitat. *Li* at any location is its contribution to the landscape connectivity of the study region by virtue of providing the 'least-cost' linkages between concentrations of habitat. Mapped *Li* provides insights into the pattern of a region's habitat network, highlighting functioning habitat corridors and stepping-stones, as well as candidate areas for conservation and restoration.

Table 3 summarizes habitat connectivity models. These models could be tailored to the specific needs and data availability in Long Island Sound. In addition to evaluating the connectivity benefits of LISS-funded restoration projects, connectivity models could be used to identify priority areas for conservation actions, assess effectiveness of existing corridors, and plan strategies to maintain or restore habitat connectivity.

Table 3. Summary of key habitat connectivity models.

Model Name	Description	Key Capabilities
Circuitscape (Shah and McRae 2008)	An open-source Python software package that uses electronic circuit theory to predict patterns of movement, gene flow, and genetic differentiation among populations.	• Can be run from a stand-alone interface or from ArcGIS. • Uses raster habitat maps as input and predicts connectivity and movement patterns between user-defined points on the landscape. • Includes the ability to connect climate analogs and climate gradients
Corridor Designer (Beier et al. 2007) (Majka et al. 2007)	An Arc Toolbox for creating habitat and corridor models with ArcGIS and an ArcMap extension for evaluating corridors. The ArcMap extension allows the user to evaluate and compare alternative corridor designs by calculating metrics such as: 1) Width and bottlenecks throughout a corridor, 2) Distances between habitat patches within a corridor, and 3) General statistics such as histograms of habitat suitability within a corridor	• Create habitat suitability maps, delineate habitat patches to map potential habitat linkages, and create corridor models.
Linkage Mapper (McRae and Kavanagh 2011)	A set of ArcGIS tools that use least-cost corridor analysis, circuit theory, and barrier analysis to map and prioritize wildlife habitat corridors. The primary and original tool in the Linkage Mapper toolbox is Linkage Pathways, which maps linkages among "core areas" of habitat and calculates the relative value of each grid cell in providing connectivity. This allows users to identify which pathways encounter more or fewer features that facilitate or impede movement between core areas. The Linkage Priority tool (Gallo and Green 2018) estimates and maps the relative priority of each linkage based on the weighted combination of ten considerations, including climate change.	• Uses resistance surfaces derived from land cover data to model the movement of organisms through the landscape. • Quantifies landscape connectivity by calculating metrics such as current flow, centrality, and betweenness. • Identifies important patches, corridors, and bottleneck areas for conservation prioritization.
Connectivity Analysis Toolkit (Carroll 2013)	A stand-alone software package that combines several connectivity analysis and linkage mapping methods in a single user interface, including least-cost path, circuit theory, and 'centrality' metrics	• Allows users to develop and compare three contrasting centrality metrics based on input data representing habitat suitability or permeability, to determine which areas, across the landscape, would be priorities for conservation measures that might facilitate connectivity. • Also allows application of these approaches to the more common question of mapping the best habitat linkages between a source and a target patch.

Table 3 (Continued). Habitat connectivity models.

Model Name	Description	Key Capabilities
Connecting Habitat Across New Jersey (CHANJ) New Jersey DFW (2019)	A web-based platform managed by NJDEP developed to make the landscape and roadways more permeable for terrestrial wildlife by identifying key areas and actions needed to achieve habitat connectivity across the state. The Interactive Mapping tool and Guidance Document can be used to help prioritize land protection, inform habitat restoration and management, and guide mitigation of road barrier effects on wildlife and their habitats.	• The CHANJ mapping of Cores and Corridors is based on a naturalness index approach (Spencer et al. 2010, Theobald et al. 2012) wherein areas are ranked based on their degree of human modification, following the assumption that species will have more success living in and dispersing through areas that are less modified by humans. This approach, compared to modeling several different focal species connectivity networks, is more analytically efficient and yields a single connectivity network that minimizes confusion and simplifies interpretation. The analysis also relies on land-use mapping data that is updated every 5 years.
TNC Resilient and Connected Landscapes Mapping Tool Anderson et al. (2016)	An online tool that defines resilient and connected lands across the continental U.S. by providing scores for climate change resilience, landscape connectedness, and landscape diversity for points and areas at a town-parcel scale.	• The project uses various data layers, including land cover, habitat condition, and ecological integrity, to identify areas that support important ecological processes and connectivity for species movement.
Marine Geospatial Ecology Tools (MGET) Roberts et al. (2010)	A stand-alone software package that combines several connectivity analysis and linkage mapping methods in a single user interface, including least-cost path, circuit theory, and 'centrality' metrics.	• Provides analysis to detect spatiotemporal patterns in environmental and ecological phenomena and build predictive species distribution models. • Allows modeling habitat connectivity by simulating hydrodynamic dispersal of larvae (e.g., Treml et al. 2008, Treml and Halpin 2012).

Examples and Key Resources

There are several habitat connectivity and resiliency models developed to prioritize conservation efforts in New York and Connecticut and support decision-making. Following are a few examples:

The Staying Connected Initiative, which focuses on maintaining habitat connectivity in the Northern Appalachian/Acadian region, including parts of New York and northwestern Connecticut. They use landscape-scale modeling techniques to identify and prioritize areas for conservation and strategic land protection to ensure connectivity for wildlife. Albrecht et al. (2020) described a preliminary connectivity assessment in the Mohawk Valley, which relied heavily on the resistance-surface based modeling approach described by Wade et al. (2015) and Zeller et al. (2012).

Scenic Hudson's Hudson Valley Conservation Strategy: Conservation in a Changing Climate (Mudd et al. (2017) describes a strategic framework to prioritize conservation actions. Landscape connectivity is one of four objectives, including conserving forest and wetland habitat cores, maintaining core-to-core corridors, and maintain local and regional connectivity. To implement the strategy, a systematic planning tool was developed that uses quantitative spatial data layers on habitat quality, landscape structure, and species occurrence to identify core habitats, corridors, and buffer zones that enhance connectivity for species movement. Specifically, the data layers quantified two conservation targets: (1) Habitat cores (identified as forest and wetland cover types), and (2) connective corridors (identified by a broad scale model that connected core areas); and two weighting factors to select the higher-quality land units: (1) local connectivity (estimated as the degree of connectedness of each 90-meter cell with its surroundings within a three-kilometer radius of that cell), and (2) regional flow (estimated by The Nature Conservancy's modeled regional flow patterns discussed above for the Resilient and Connected Landscapes project).

Previous habitat connectivity modeling in the Hudson Valley by Howard and Schlesinger (2013), named PATHWAYS, used a combination of species distribution and connectivity modeling using current and future climate regimes to prioritize connections among populations of 26 rare species. They modeled suitable habitat patches for each species and potential connections among those patches by finding the least-cost path for every patch-to-patch connection. These patches and paths were aggregated for each tax parcel.

The Town and Village of Red Hook and Village of Tivoli (Dutchess County, NY) performed a pilot project in 2014 that applied the results of a Cornell local habitat connectivity model. ESRI's ArcGIS Linkage Mapper tool was used to model least-cost corridors between regional forest patches of 200 acres or more in size. Conservation opportunities were then identified through stakeholder engagement and recommendations are described in Planning for Resilient, Connected Natural Areas and Habitats: A Conservation Framework. Linkages identified in the model were incorporated into the biodiversity criteria used to rank acquisition priorities in the Town of Red Hook's 2016 Community Preservation Plan Update.

The Nature Conservancy's Resilient and Connected Landscapes provides a framework for prioritizing conservation actions based on resilient and connected landscapes. The project used various data layers, including land cover, habitat condition, and ecological integrity, to identify areas that support important ecological processes and connectivity for species movement. Anderson et al. (2016) and Anderson et al. (2023) detail the resilient and connected network analysis, which was performed in pieces for twelve regional geographies to capture local ecological functions important to each region. One output is a "flow" map that shows the behavior of directional flows and highlights concentration areas and pinch-points. The results identify locally and regionally significant places where species range shifts are likely to be impeded by anthropogenic resistance, and that may warrant conservation.

The Resilient Land Mapping Tool allows users to explore the results of TNC's Resilient and Connected Network which provides basic analytic tools to understand the findings of the project. Users can upload a polygon of interest to get resilience scores for that area. As part of this effort, a metric was developed to measure local connectedness based on the presence of structures that impair connections between natural ecosystems within a landscape. Local connectedness is quantified by evaluating the configuration and density of human-created barriers such as major roads, development areas, energy infrastructure, and industrial land-uses. The metric measures permeability based on the level of similarity between adjacent cells and is a resistance-surface approach for understanding the level of access a species has to the habitats within its surrounding neighborhood. This metric was integrated with information on landscape diversity to develop resiliency scores; it serves to identify areas where connectivity improvements could significantly enhance ecological resilience (Figure 3).

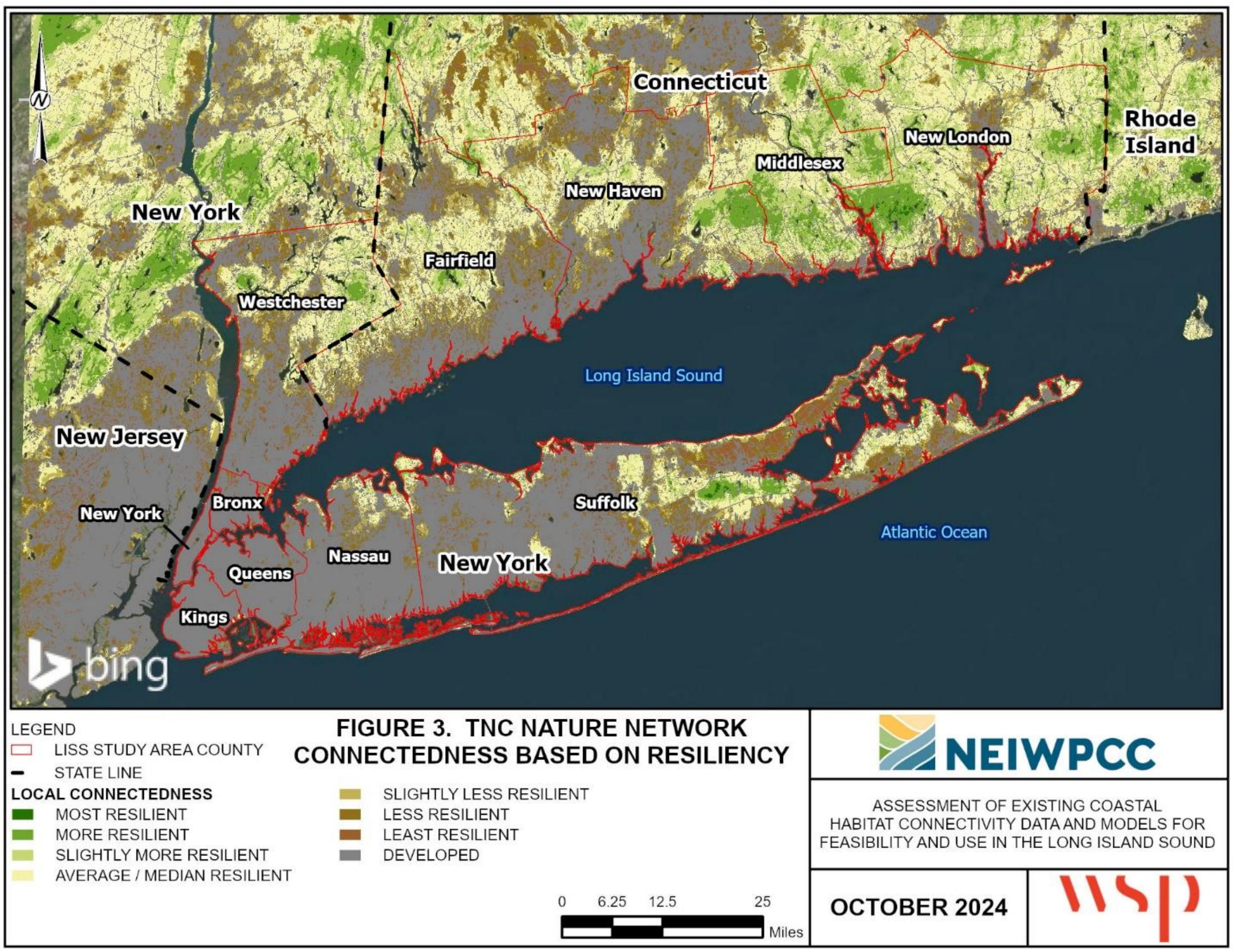


Figure 3. TNC Nature Network Connectedness Based on Resiliency

Several tools have been developed for biodiversity conservation in the northeastern United States by researchers at the University of Massachusetts Amherst. The Conservation Assessment and Prioritization System (CAPS; Compton et al. 2020) was developed in the early 2000s and the same researchers also completed the Critical Linkages project (McGarigal et al. 2012, 2013), which consisted of spatially explicit tools, (models, maps, and scenario-testing software) to assess how to mitigate the impacts of roads, railroads, and dams on the environment. These projects incorporate both a terrestrial connectedness and aquatic connectedness metric. This terrestrial connectedness metric uses a least-cost path algorithm to determine the area that can reach each focal cell, incorporating each cell's similarity to the focal cell. The aquatic connectedness includes the resistance from culverts, bridges and dams for organisms that are primarily aquatic. In 2015, the CAPS approach was applied to the 13-states in the North Atlantic region as part of the Designing Sustaining Landscapes (DSL) project, which combined CAPS with the Critical Linkages assessments, and risk of development and environmental change models, species-based models, and elements of The Nature Conservancy's Resilient Landscape analyses (see above), to provide data and analysis for use in conservation decision-making. The DSL project utilizes advanced landscape connectivity modeling techniques to assess the current state of habitat connectivity and predict how it may change under different land-use scenarios. A complete technical description of the DSL project and associated publications is available on the UMass Amherst website. Many of the associated datasets are also available for viewing and download in a gallery on the North Atlantic LCC Conservation Planning Atlas hosted by DataBasin. The broader framework is described by McGarigal et al. (2018a), with a focus on the most recent DSL project.

The DSL project provides much of the basis of the conservation planning tools that have been applied by the Nature's Network project. Nature's Network is a collaborative effort among thirteen states, the North Atlantic Landscape Conservation Cooperative, the U.S. Fish and Wildlife Service, the University of Massachusetts Amherst, and nongovernmental agencies to identify the best opportunities for conserving and connecting intact habitats and ecosystems and supporting imperiled species to help ensure the future of fish and wildlife across the Northeast region. Several data products from this project could be useful to the LISS for identifying priority areas for conservation, determining the effectiveness of conservation actions, and planning connectivity-enhancing strategies to maintain or restore habitat connectivity in Long Island Sound. Specifically, Nature's Network identifies the best opportunities to maintain regional connections among core habitat areas and connect tidal marshes to adjacent uplands. In addition to Nature's Network, the DSL models have been applied to the data and tools developed for the Connect the Connecticut project.

For aquatic habitats, the North Atlantic Aquatic Connectivity Collaborative (NAACC), through its Northeast Aquatic Connectivity Project, has contributed to the National Aquatic Barrier Inventory and Prioritization Tool to identify and prioritize barriers to aquatic connectivity in the northeastern U.S. The project provides a comprehensive database of barriers and recommendations for restoring aquatic connectivity. It assessed over 200,000 barriers in the 13-state region from Maine and Virginia for the potential benefit to anadromous fish if removed or mitigated. The project results, custom analysis tool, and full report allow users to explore in-stream barriers to aquatic connectivity and identify opportunities for aquatic connectivity restoration projects.

Cote et al. (2009) present the dendritic connectivity index, an approach to quantifying the longitudinal connectivity between upstream and downstream sections of a river network based on the probability of an organism being able to move freely between two random points of the network. This index is affected by the number, location, and permeability of barriers within the watershed. As impermeable barriers are added, the index declines from its maximum value of 100, indicating total connectivity, to as low as 0, indicating minimum connectivity. This approach could also be used to characterize watersheds, assess cumulative impacts of multiple barriers and determine priorities for restoration.

As noted previously, additional programs and tools that support connectivity modeling are available at Conservation Corridor (2023).

EXISTING REGIONAL CONNECTIVITY MODELS

This section provides a review of the regional connectivity models available in the LISS coastal study area. Table 4 provides a summary of connectivity models by priority habitat, or absence thereof.

Nature's Network

Data Sources—Elements of Nature's Network include the following datasets:

- *Terrestrial and Wetland Core Network:* This product consists of two components: core areas and connectors (Figure 4). Terrestrial and wetland core areas are intact, well-connected places that, if protected, will support a diversity of fish, wildlife, and plants, and the ecosystems they depend upon. Core areas are linked together by a network of connectors designed to enable the movement of animals and plants between core areas and across the landscape into the future. The terrestrial and wetland core areas and the core to core connectors were updated in 2020 to incorporate the updated index of ecological integrity and species models that were rerun using an improved version of the terrestrial habitat classification map (DeLuca et al. 2020).
- *Habitats for Imperiled Species*: This contains three datasets: Habitat Importance for Imperiled Species, Core Habitat for Imperiled Species, and Habitat Condition for Imperiled Species.
- *Aquatic Core Networks*: This includes three data layers: River and stream (lotic) core network, Lake and pond (lentic) core network, and Aquatic buffers.
- *Marsh Migration Zones*: This dataset depicts potential salt marsh migration zones at various sea level rise scenarios from 0-6 feet. Identification of suitable uplands adjacent to tidal wetlands is based on topography, habitat type, land-use, and development, and can be used for facilitating marsh migration through land protection and/or management.
- *Regional Flow*: This dataset, developed by The Nature Conservancy, identifies where population movements and potential range shifts may become concentrated or where they are well dispersed, and it is possible to quantify the importance of an area by measuring how much flow passes through it, and how concentrated that flow is. The results can be used to identify important pinch points where movements are predicted to concentrate, or diffuse intact areas that allow for more random movements.

Model—Natures Network focuses on integrating ecological and human-use datasets to inform conservation and land management decisions. It provides outputs such as conservation priority areas, connectivity networks, and habitat suitability maps. Some components of Nature's Network, such as the Terrestrial and Wetland Core Network, can be used for regional conservation planning by mapping critical corridors between habitats that facilitate the movement of species across the landscape. Other data products, such as Habitats for Imperiled Species and Marsh Migration Zones, can be used as inputs into other models.

Platform—In April 2024, the USFWS established a new and updated platform for the Natures Network as part of the Northeast Conservation Planning Atlas (Farnsworth, Renee, USFWS, personnel communication, April 26, 2024). The platform provides a web-based interactive mapping tool (Nature's Network Conservation Design, Northeast U.S. | Northeast Conservation Planning Atlas (arcgis.com)) that helps to identify conservation priorities from Maine to Virginia, including areas of degraded habitat that, if restored, would contribute to a network of connected, intact, and resilient sites. The tool is intended to supplement local-level planning tools by offering a broader, regional context. Users can manipulate metrics and variables to create a series of prioritization maps for a set of pre-defined "scenarios," reflecting different conservation goals or threats, and save and download results. The GIS data used to define both terrestrial cores and connectors, and aquatic cores and buffers, are currently available.

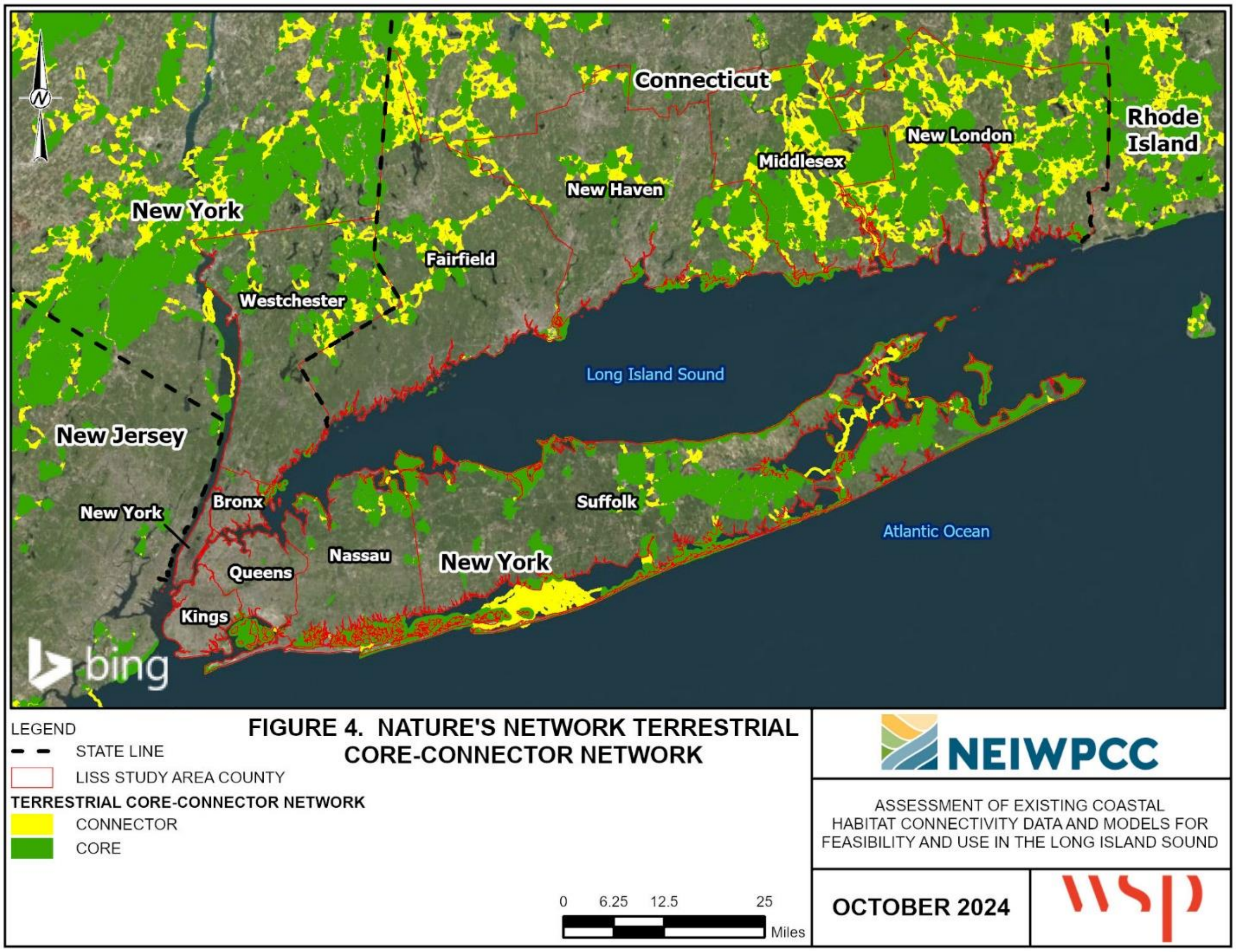


Figure 4. Nature's Network Terrestrial Core-Connector Network

Application to LISS Priority Habitats—Several data products available from the USFWS (2024), or the TNC (2016) Resilient and Connected Landscapes could be useful to LISS for identifying priority areas for conservation, determining the effectiveness of conservation actions, and planning connectivity-enhancing strategies to maintain or restore habitat connectivity in the Long Island Sound. Specifically, Nature's Network identifies opportunities to maintain regional connections among core habitat areas and connect tidal marshes to adjacent uplands. The model has output multiple datasets under four themes applicable to LISS: Terrestrial and Connector Networks; Aquatic Core Networks, Habitat for Imperiled Species, and Connectivity for Marsh Mitigation.

ecoConnect: Regional Ecosystem-based Connectivity

Data Sources—The ecoConnect project is the latest ecosystem-based model of regional connectivity developed by the Landscape Ecology Lab at the University of Massachusetts. Like Nature's Network, it is based on data from the DSL project but uses more detailed landcover maps and is not based on focal species. EcoConnect integrates structural and functional connectivity into a resistance-based metric using a graph theory approach. The model assesses the resistance of the matrix (habitat surrounding core areas) in a structural sense by identifying natural corridors and linear barriers (e.g., roads, railways, and canals) and using NAACC data to identify bridges and culverts that provide potential passage for terrestrial wildlife. It then uses random low-cost paths to relate the resistance to the degree of human impact, or the naturalness of the matrix. These paths follow low-resistance routes, but explore multiple sub-optimal alternatives based on landscape resistance, derived from 24 natural and anthropogenic variables, such as wetness, slope, percent impervious, and traffic rates (Compton et al. 2023). Keeley et al. (2021) contend that "naturalness-based connectivity [such as this] is a powerful conservation strategy for planning and assessing connectivity as an adaptation to climate change." An key input to ecoConnect are ecological integrity datasets, which provide various measures of ecosystem intactness and resiliency. These data are also combined into a composite Index of Ecological Integrity (IEI; McGarigal et al. 2018b) (Figure 5).

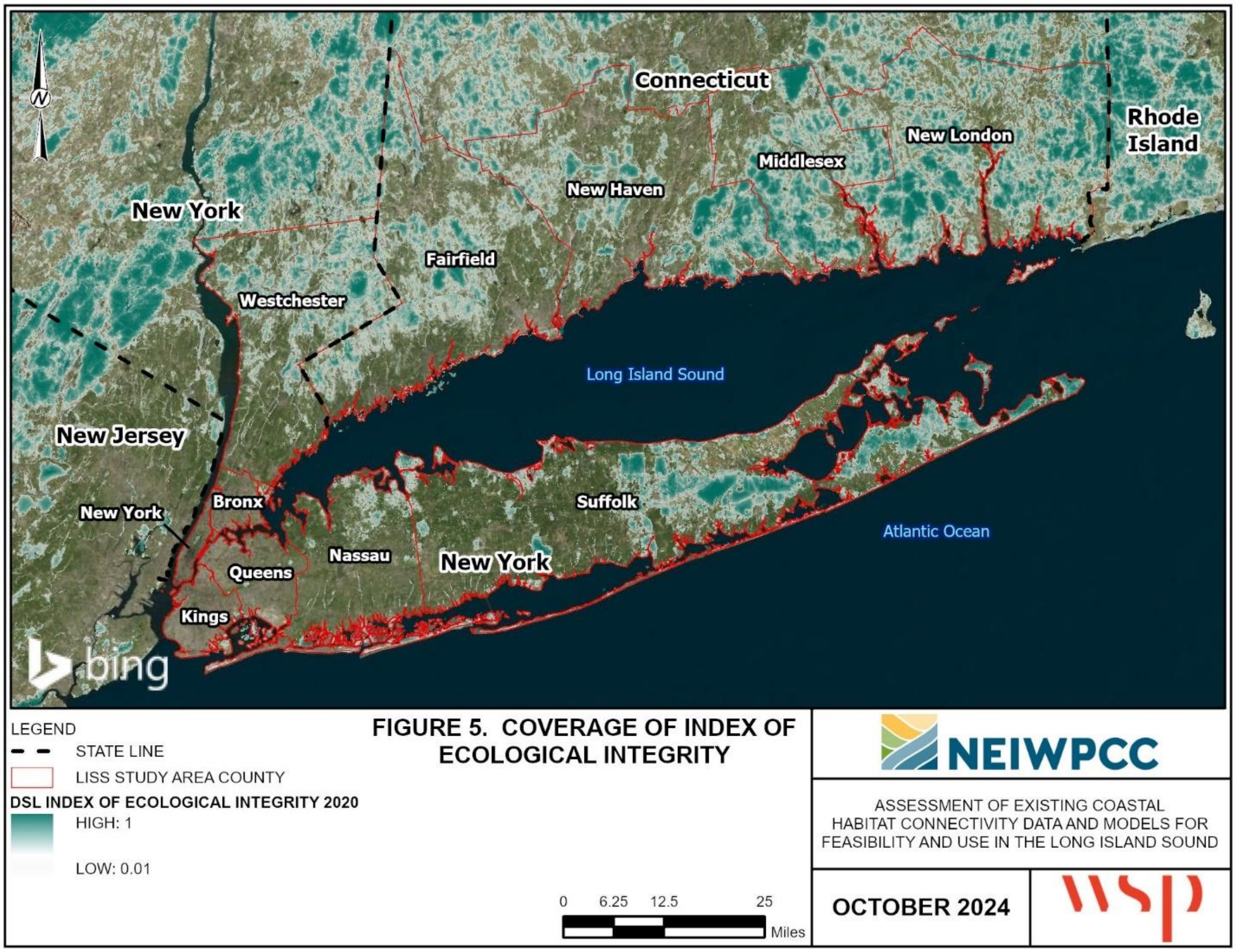


Figure 5. Coverage of Index of Ecological Integrity

Ecological integrity is defined as the ability of an area (e.g., local site or landscape) to support and maintain a community of organisms that has species composition, diversity, and functional organization comparable to those of natural habitats. These datasets are available by ecosystem (e.g., for estuarine intertidal ecosystems) and for various geographic extents (Northeast region, state, ecoregion, and HUC6 watersheds). important ecological functions over the long term. Projected future Index of Ecological Integrity for 2030 and 2080 are also being developed based on models of land development, climate change, and forest change. Measuring ecological integrity is a naturalness modeling approach, which Krosby et al. (2015) concluded to be an effective proxy for more resource-intensive focal species-based approaches, particularly for large and wide-ranging animals, though it may not fully represent the needs of smaller, less mobile species.

Platform—The ecoConnect model, is developed and maintained by a team from the Department of Environmental Conservation at the University of Massachusetts Amherst. The ecoConnect models are still under development and a temporary web viewer provides model results for four ecosystems across northeastern U.S.: (1) forests, in general; (2) large river floodplain forests; (3) nonforested wetlands; and (4) ridgetop systems. With committed funding from the USGS Northeast Climate Adaptation Science Center, this viewer will be replaced with a full-featured site in the Summer 2024 that will include additional regional connectivity model outputs and a site scoring tool.

ecoConnect is run on ecological systems based on The Nature Conservancy's Terrestrial Habitat Map for the Northeastern U.S. (Ferree and Anderson 2013), which includes tidal salt marsh, although that model may not be completed. The team lead, Brad Compton, has indicated that: "we didn't run ecoConnect for tidal wetlands because our dataset has minimal representation of the ocean… [and] since so much connectivity among coastal wetlands is marine, we didn't feel like we could do them justice." The ecoConnect team expects to continue enhancing the model by expanding the range of ecosystems and geographical areas covered and incorporating more detailed ecological data as it becomes available. They are also able to do custom runs for other sets of ecological systems.

The data from ecoConnect, and the DSL project in general, are made accessible to the public, offering detailed documentation for each dataset, which includes ecological integrity metrics, regional ecosystem-based connectivity, urban growth impact metrics, and focal species models. The project outputs are available for download in formats suitable for GIS software and data packages are available by state for convenience. Updates to the data are frequent, with the most recent major update in 2020 enhancing various data products, including the introduction of new species models and improvements in landcover data.

Application to LISS Priority Habitats—The ecoConnect model could be used to assess the level of connectivity among existing conservation lands, and to target additional land to conserve habitat connectivity. It could also be used to assess potential locations for road crossing structures for wildlife and identify locations where bridges and culverts may already provide connectivity under high-traffic roads. The ecoConnect model results are currently available for only four ecosystems: forests (including forested wetlands), non-forested wetlands, ridgetop systems, and large river floodplain forests. Values range from 0 (no contribution to connectivity) to 100 (highest contribution) for each ecosystem. Currently, LISS could conceivably employ two of these available models, for both forests and non-forested wetlands (Figures 6 and 7, respectively).

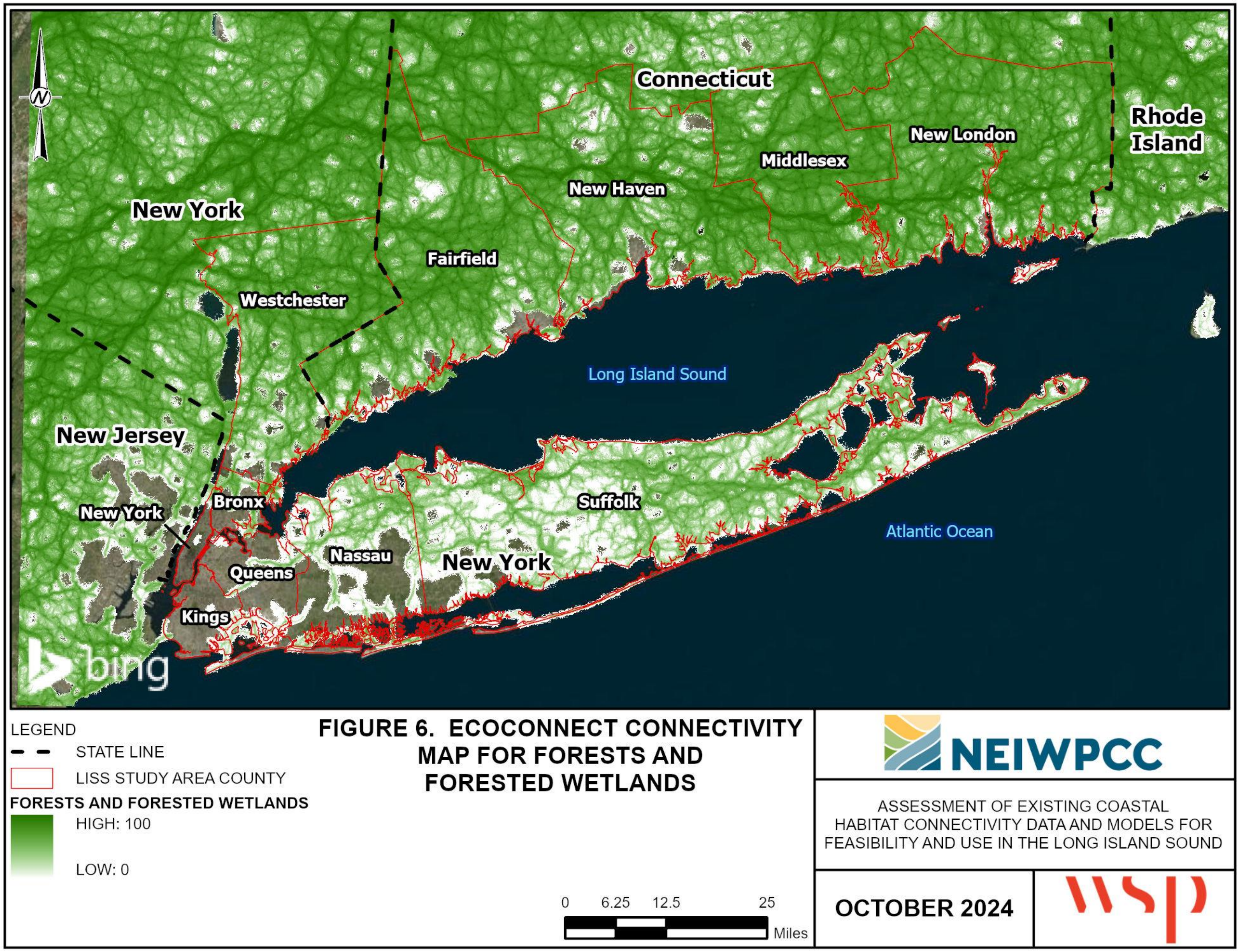


Figure 6. ecoConnect Connectivity Map for Forests and Forested Wetlands

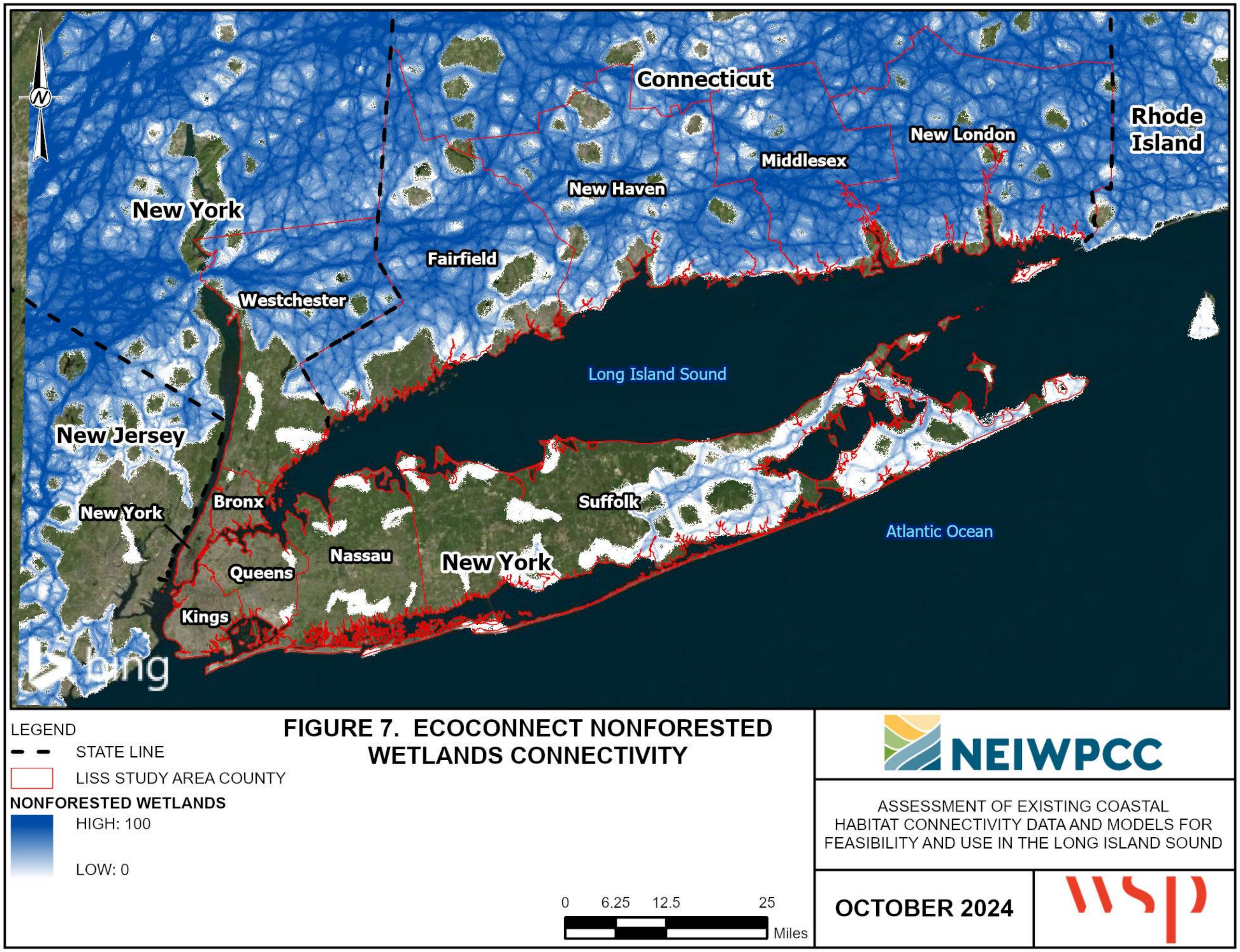


Figure 7. ecoConnect Nonforested Wetlands Connectivity

The ecoConnect model outputs are primarily valuable for visual rather than quantitative purposes. However, LISS could summarize means or sums of ecoConnect models for its parcels as a relative basis to evaluate habitat connectivity. The model does not evaluate individual sites at a finer scale than 2 km and would thus not be applicable to evaluating local, fine-scale habitat connectivity.

Connecting Habitat Across New Jersey (CHANJ)

Data Sources—CHANJ is a web-based platform created by the New Jersey Department of Environmental Protection (NJDEP) to identify and prioritize habitats for conservation and connectivity. CHANJ utilizes various datasets including land cover, land-use, and habitat suitability models.

Model—The CHANJ mapping of Cores and Corridors is based on a naturalness index approach (Spencer et al. 2010, Theobald et al. 2012) wherein areas are ranked based on their degree of human modification, following the assumption that species will have more success living in and dispersing through areas that are less modified by humans. The approach, compared to modeling several different focal species connectivity networks, is more analytically efficient, and yields a single connectivity network that minimizes confusion and simplifies interpretation. It provides outputs such as habitat suitability maps, connectivity corridors, and conservation opportunity areas that can be used to make the landscape and roadways more permeable for terrestrial wildlife by identifying key areas and actions needed to achieve habitat connectivity across the state.

Platform—The CHANJ data and tools are accessible via the NJDEP website and the NJDEP Open Data portal. Users can download GIS layers directly or integrate them into existing mapping software via feature services, which facilitates easy application in conservation planning and land management decision-making. The CHANJ platform undergoes regular updates, as it relies on land-use mapping data that is updated every 5 years.

Application to LISS Priority Habitats—The CHANJ model is not directly applicable to the LISS coastal study area but provides insight into a statewide mapping effort of core terrestrial wildlife habitats and the corridors connecting them, for comparative analysis with similar habitat types found within the Long Island Sound area. By employing GIS to overlay the CHANJ connectivity data with LISS-specific landscape features, decision-makers can identify potential areas for habitat conservation and connectivity enhancement. Moreover, the use of remote sensing data to periodically update land cover changes would provide LISS with the ability to monitor and adapt their conservation strategies effectively. The Interactive Mapping tool and Guidance Document (NJDEP 2019) could be reviewed by LISS to understand the types of data used to help prioritize land protection in similar urban landscapes, learn about habitat restoration and management, and guide mitigation of road barrier effects on wildlife and their habitats.

North Atlantic Aquatic Connectivity Collaborative (NAACC)

Data Sources—NAACC is a collaborative effort led by the U.S. Fish and Wildlife Service and other partners, focused on assessing and improving aquatic connectivity in the North Atlantic region. The NAACC database stores data from assessments of road-stream crossings that evaluate the impact of roads, bridges, and culverts on aquatic connectivity, particularly for fish and other aquatic organisms (NAACC 2024a). NAACC utilizes various datasets including stream networks, barrier inventories, and fish species distributions. The data is primarily sourced from state agencies, academic institutions, and non-profit organizations. Anyone can survey crossings using NAACC protocols but they must belong to an organized regional group headed by a designated survey coordinator.

Model—The collected data is stored in an online database that houses information on road-stream crossing assessments. Each road-stream crossing has an aquatic barrier score based either on the passability score, derived from field measurements of the crossing structure, or on the predictions from a statistical GIS-based model, where dams and road-stream crossing are assigned values that range from 0 (no barrier) to 1 (complete barrier). For any given barrier, metrics involving three different watershed scales are used in the analysis. The contributing watershed, or total upstream watershed, is defined by the total upstream drainage area above the target barrier. The local watersheds of the upstream and downstream river network are bounded by the watershed of the next upstream and downstream barrier. A total of 38 criteria are calculated for all barriers, such as length of connected network, species present downstream, and land cover characteristics, and then is used to calculate a passability score and rank prioritization at the regional scale. While the NAACC's data model primarily focuses on non-tidal crossings, the principles and protocols can be adapted for assessing tidal crossings as well. Becker et al. (2018) developed the information necessary to create guidelines and rapid assessment tools for assessing tidal crossings and NAACC (2021) developed an Aquatic Passability Scoring Systems for Tidal Stream Crossings.

Platform—The NAACC provides online tools for prioritizing upgrades to culverts, bridges, or other aquatic barriers based on their benefits to aquatic organisms. Users can search, view, map, and download the data to analyze the impact of road crossings on aquatic connectivity. The platform is periodically updated to incorporate new data and improve modeling techniques.

Application to LISS Priority Habitats—The metrics for evaluating habitat connectivity of riverine migratory corridors are calculated based on barrier severity, permeability for target species, and the impact on upstream habitat accessibility. LISS could access this data on barriers and streams using the Aquatic Barrier Inventory and Prioritization Tool, which allows for the calculation of numerous metrics that describe the quality and status of their functional networks. This online tool houses GIS data and metrics on hundreds of riverine barriers in the region, which can be customized to meet unique needs. For example, LISS could prioritize potential projects or evaluate the effectiveness of barrier removal based on the barrier severity, miles gained, and the percent of upstream network in unaltered stream channels. The NAACC includes a map viewer to help visualize patterns of aquatic connectivity to pinpoint critical barriers that need attention. Furthermore, its GIS tools can assist in scenario planning, where different conservation actions are modeled to predict their impacts on aquatic connectivity, helping to prioritize interventions.

POTENTIAL METRICS FOR EVALUATING CONNECTIVITY OF LISS PRIORITY HABITATS

Table 4. Potential connectivity models applicable to LISS priority habitats.

Priority Habitat	Potential Connectivity Models and Metrics
Beaches and Dunes	No applicable models or metrics identified. Coastal dunes are one of the patchiest landscapes on earth, fragmented by regular disturbance (Malavasi et al. 2018). A simple metric such as patch size is a good indicator of dune habitat fragmentation (Marzialetti et al. 2024). For beaches, models using a graph theory approach, like that used by Pearson et al. (2020) to map sediment transport pathways along coastlines, could be employed to model habitat connectivity. Also, repeated high-resolution mapping of beach/dune topography and vegetation could be input into models that predict future changes due to development or natural events like storms. Because wrack provides a critical food source on sandy beaches, models have been developed elsewhere that predict spatial patterns of cover and composition based on the proximity of local donor habitats such as eelgrass beds (e.g., Liebowitz et al. 2016) These models could be adapted to Long Island Sound by incorporating local data and factors influencing wrack deposition.
Cliffs and Bluffs	No applicable models or metrics identified. Similar to beaches and dunes, metrics using patch size can provide an indicator of habitat fragmentation (Marzialetti et al. 2024), and simple metrics based on distance measures to nearby natural habitats, proximity to corridors and similar habitats that could facilitate flows of species, genetic material, and ecosystem services.
Estuarine Embayments	Because estuaries that provide requisite interactions among species require a mixture of fresh and salt water, hydrodynamic models could be used to assess tidal flow and water quality. Models are available to measure an embayment's connectivity relative to natural levels of tidal and riverine flow (e.g., ADvanced CIRCulation [ADCIRC] and DELFT3D).
Coastal Grasslands	The TNC (2016) Resilient and Connected Landscapes data could be used to quantify a site's connectivity to other natural areas and the capacity to support biodiversity in response to changing conditions. ecoConnect would provide used to provide metrics of regional connectivity in grassland patches. Circuitscape could be used to calculate current flow and effective resistance. Finally, Linkage Mapper could be used to determine if the grassland is within a wildlife corridor and if so, determine the relative priority of the corridor.
Coastal and Island Forests	Metrics such as the fraction of a habitat's perimeter adjacent to developed land and measures of habitat fragmentation can used to assess connectivity among forest patches. For example, the LISS habitat assessment framework (Basso et al. 2018) included metrics for forest edge connectivity and fragmentation based on proximity to development, calculated using the University of Connecticut CLEAR (2007) Landscape Fragmentation Tool. Updates to baseline data would be required.
Tidal Wetlands	McGarigal et al. (2017) have developed a tidal restriction severity metric as an element of its composite Index of Ecological Integrity measure. This metric predicts the restriction severity of a road and railroad crossings (including tide gates associated with transportation infrastructure) by estimating the salt marsh "loss" ratio above each crossing. The ratio represents the proportion of the upstream area that is modeled as potential salt marsh based on tide range and elevation but is not mapped as existing salt marsh by the NWI. Crossings and affected salt marsh areas are given a score ranging from 0 (no effect from downstream tidal restrictions) to 1 (severe effect).

	The ability of a tidal wetland site to adapt to sea level rise by migrating landward depends on the adjacent, connected ecosystems, through which tidal marshes can migrate inland. The tidal wetland connectedness under projected sea level rise scenarios could use the Marsh Migration Zones data from Nature's Network, derived from the NOAA's Coastal Change Analysis Program, could be used to prioritize conservation and management actions aimed at encouraging a healthy extent of tidal marsh habitat into the future. A marsh resilience score could also be obtained from the marsh resilience to sea level rise metric (Raposa et al. 2016).
Freshwater Wetlands	ecoConnect would provide useful metrics of regional connectivity among freshwater wetlands.
Submerged Aquatic Vegetation Beds	Pastor et al. (2022) describes a framework for eelgrass connectivity, which includes combining hydrodynamic models and network analysis (graph theory) to identify key eelgrass populations and assess their connectivity. By analyzing biophysical pathways through which eelgrass seeds and shoots disperse, the model identifies which eelgrass patches are most crucial for maintaining overall network connectivity,
Shellfish Reefs	Shellfish reefs depend on connectivity through larval transport. Powers et al. (2023) modeled the trajectories of particles parameterized to mimic oyster larvae using the ADCIRC to evaluate potential connectivity within and among embayments in Louisiana and Alabama. Similarly, Ani et al. (2024) used OceanParcels, a particle tracking simulator, with output from a hydrodynamic-biogeochemical model to simulate the dispersal and settlement of coral larvae on the Great Barrier Reef. Milroy et al. (2020) used a coupled ocean-atmosphere-wave-sediment-transport (COAWST) model to calculate habitat suitability indices for oyster larvae and predict the likelihood of direct connectivity of spawning locations. The larval transport model simulations provide outputs that include connectivity matrices to describe the proportions of larvae that are released and settled among the multiple reefs. However, more work is needed to build datasets for model validation and improve understanding of larval transport (Le Peyre et al. 2021).
Intertidal Flats	No applicable models or metrics identified. Similar to estuarine embayments, hydrodynamic models could be used to assess tidal flow, nutrient and water quality interactions, and combine with network analysis to assess connectivity to similar habitat.
Rocky Intertidal Zones	No applicable models or metrics identified. Similar to estuarine embayments, hydrodynamic models could be used to assess tidal flow, rack deposition and water quality interactions, and combine with network analyses to assess connectivity to similar habitat.
Riverine Migratory Corridors	The National Aquatic Barrier Inventory and Prioritization Tool could be used to identify and prioritize barriers to aquatic connectivity (see previous section). The Aquatic Core Networks connectivity model from Nature's Network could also be used (see next section).

INSIGHTS FROM EXPERT INTERVIEWS

Interviews with key practitioners of connectivity modeling provided insight into the challenges and considerations for developing connectivity models tailored to the Long Island Sound. These discussions revolved around the applicability and limitations of existing models. Following is a summary of the key takeaways from these interviews.

Brad Compton, Research Associate, and Scott Jackson, Extension Professor, at the University of Massachusetts Amherst, answered questions posed by the project team about the CAPS and ecoConnect models. These models are primarily designed for terrestrial ecosystems and do not directly address marine or coastal habitats. Compton (2024) indicated that neither the ecoConnect nor the CAPS models, in their current forms, are fully equipped to address the specific connectivity modeling needs for LISS. The existing models do not evaluate individual sites at a finer scale than 2-kilometer, which may not be sufficient for the detailed assessment required for LISS. Nevertheless, the geodatabase accessible through DSL programs could be a valuable data source, and the UMass Amherst researchers could provide support to LISS if they desire to develop custom connectivity models. When asked about applying existing connectivity models to the LISS 12 coastal habitats, Compton (2024) suggested that the development of habitat-specific metrics to evaluate the connectivity would need to be developed independently. However, he cautioned that models designed to assess connectivity within specific, discrete habitat types may miss important linkages that occur between different habitat types, potentially overlooking important areas where species move across these transitions. For habitats like bluffs or submerged aquatic vegetation beds, which may exist along a natural transition between different ecological zones (e.g., from upland to wetland, or from shallow to deep water), it is important to consider how these habitats interact and connect across this gradient. He also pointed to the DSL project website for documentation and data sorted by state, which could be beneficial for LISS model development.

Through an interview with Gretchen Fowles, GIS specialist and biologist with the New Jersey Department of Environmental Protection (NJDEP) and project lead for NJDEP CHANJ project, several insights for were learned relative to connectivity model development and management. The key takeaways are:

- Data Ownership and Updates: The NJDEP controls all data used in the CHANJ model. While data layers are available for public download and viewing, they are not regularly updated; updates occur alongside revisions to the State's Land Use/Land Cover (LU/LC) data, which typically happens every five years.
- Model Setup and Stakeholder Engagement: The CHANJ model was developed with input from a large working group formed in 2012, consisting of numerous agencies and stakeholders.

This collaboration was crucial in achieving early buy-in and informing the model's user interface.

- Integration with Decision-Making: The CHANJ project has been integrated into various decision-making processes, such as land acquisition prioritization, conservation planning, and road mitigation projects.
- Use of Open Access Tools: Tools like Core Mapper and Linkage Mapper were highly effective and user-friendly, with customizable inputs that could adapt to different ecosystems. There were no significant software compatibility issues.
- Technical Challenges: The model's extensive processing requirements necessitated upgrading computing power, and there was a need to balance complexity with user accessibility.
- Lessons for LISS: Simplifying the model while ensuring robustness in predictions, particularly for sensitive species, was highlighted as a critical lesson. Riparian areas were emphasized as key inputs in NJ, which might inform similar efforts in LISS.

Analie Barnett and Arlene Olivero from the TNC Center for Resilient Conservation Science (CRSC) were interviewed regarding the Resilient and Connected Landscapes Mapping Tool. They noted that the platform was updated in September 2024 and now provides access to terrestrial, freshwater (riverine) and marine (offshore) resilient connectivity mapping. Similar to Mr. Compton, they noted that the regional level of the connectivity models required the individual data points to be scaled up in size (120 m^2) which is not conducive to evaluating individual sites. However, for the marsh migration dataset, the analysis is based on lower resolution with a resistance kernel size of 10 m^2. TNC maintains the website and the dataset and will update the land-use data on an approximately 10-year cycle. Based on preliminary testing, land-use changes over a shorter term have not shown to be significant enough to alter the outcomes of the models.

4.0 CONCEPTUAL PILOT CONNECTIVITY METRICS FOR TIDAL MARSH AND RIVERINE MIGRATORY CORRIDORS

Since this project serves as a first look into the available GIS resources and habitat connectivity models available to LISS, the scope was limited to develop draft metrics for the two habitat types that represent the majority of completed restoration and protection projects in Connecticut and New York. Table 5 summarizes the habitat connectivity models considered in the preceding sections and their applicability to tidal marsh and riverine migratory corridors. This section focuses on the development of draft metrics for the analysis of connectivity of two habitat types, tidal marsh and riverine migratory corridors, and the GIS data used to support the analysis. Important considerations for the development of the draft metrics were:

1) Availability of existing connectivity model data and its suitability to support connectivity analysis for tidal marsh and riverine migratory corridors;
2) Suitability of the project site data for tidal marsh and riverine migratory corridors provided by New York State Department of Environmental Conservation (NYSDEC) and Connecticut Department of Energy and Environmental Protection (CT DEEP); and,
3) How to demonstrate that LISS-supported projects are improving or maintaining habitat connectivity within the Long Island Sound watershed.

Table 5. Application of habitat connectivity models to Tidal Marsh and Riverine Migratory Corridors.

Model Name	Suitability for Tidal Marsh Connectivity Assessment	Suitability for Riverine Migratory Corridor Connectivity Assessment	Suitability For Use With CT Data	Suitability For Use With NY Data	Publicly Available
TNC Resilient and Connected Landscapes Mapping Tool	Yes, provides useful metrics to identify marsh migration corridors, as well as parcels critical to sediment transport.	No, not applicable	Yes	Yes	Yes
Nature's Network	Yes, provides useful connectivity metrics	Yes, provides useful connectivity metrics	Yes	Yes	Yes
North Atlantic Aquatic Connectivity Collaborative	No, not applicable	Yes, provides useful connectivity metrics	Yes	Yes	Yes
Circuitscape	Yes, although custom modeling required	No, not applicable	Yes	Yes	Yes
Corridor Designer	Yes, although custom modeling required	No, not applicable	Yes	Yes	Yes
Linkage Mapper	Yes, although custom modeling required	No, not applicable	Yes	Yes	Yes
Connecting Habitat Across New Jersey (CHANJ)	No, not applicable	No, not applicable	No	No	No
Marine Geospatial Ecology Tools (MGET)	No, not applicable	No, not applicable	No	No	Yes

AVAILABLE CONNECTIVITY MODELS AND DATA

After a review of the existing connectivity models for the region, the project team selected datasets from the Terrestrial and Wetland Core-Connector Network and the Aquatic Core Network from the Nature's Network project. These two datasets define habitat cores and core connectors for terrestrial habitats, including tidal wetlands, and aquatic habitats (lentic and lotic habitats) within the LISS Study area. The datasets are derived from a complex analysis of spatial and nonspatial inputs covering approximately 25 abiotic and biotic variables provided by a Landscape Change, Assessment and

Design (LCAD) model, representative species-specific land capability models, and ecological integrity models (McGarigal et al. 2018b). The development and integration of the models and applications are robust and well-documented (see The Designing Sustainable Landscapes (DSL) Project). As noted, the terrestrial and aquatic core and core connectors were recently updated in 2020. The datasets appear to be the only habitat connectivity data for the LISS Study Area.

LISS PROJECT DATA

The project team conducted a review of the project data provided by NYSDEC and CT DEEP.

The data provided by NYSDEC was in the form of an Excel file listing 286 projects and providing the following information: project name, site coordinates, project description, habitat description, habitat type, acreage, length (miles/feet), and restoration technique. The restoration techniques include a range of 16 actions with 12 habitat types.

The number of projects by habitat type in New York is provided in Table 6. The habitat descriptions did not exactly align with the 12 Priority Habitats, and some sites include more than one habitat type, so the project was included within the predominant habitat type as inferred by the descriptive site information. The two preservation sites listed under Other did not report the habitat types within the site.

Habitat Types	No. of Sites	Acres	Miles
Agriculture/Ranch Land	35	872.8	
Beach	5	11.3	
Estuarine Shoreline	4	11.7	
Estuarine Water Column	2	86	
Field/Meadow	18	268.4	
Forest/Woodland	136	1297.7	
Forested Wetland	17	428.0	
Freshwater Marsh	7	13.4	
Grassland	4	43.0	
In-Stream	3	80.725	2.5
Lake/Pond	5	19	0.3
Other - Preservation	2	2.9	
Riparian	5	19.0	
Salt Marsh	39		
Submerged Aquatic Vegetation	4	4.35	
Total	286	3158.193	

Table 6. The number of projects by habitat types in the New York portion of Long Island Sound.

New York project sites within salt or tidal marsh habitats total 39 and involve eight types of restoration techniques, or actions. The frequency of restoration techniques for these projects is provided in Table 7. In addition, 3 riverine migratory corridor projects were also included in the dataset.

The data provided by CT DEEP was in three separate shapefiles containing attribute data for project sites, separated based on site protection, habitat restoration (i.e., restoration, rehabilitation, enhancement), and riverine migratory corridors. Each dataset provided similar information for each project site, including project name, town, project type, project notes, habitat type, acreage, length (miles/feet) completion date, restoration technique and status. Within the dataset are notes indicating some projects were listed for planning purposes, and others which did not have completion dates or other missing information. Discounting planned projects, the three datasets include a total of approximately 587 projects between them. Table 8 provides an estimate of the completed and in-progress habitat restoration and preservation sites as of December 2023 organized by habitat type.

Restoration Technique	No. of Sites
Berm/Dike Removal	1
Bulkhead Removal	1
Debris Removal	3
Easements	2
Fill Removal	6
Invasive Plant Control	4
Land Acquisition	16
Planting	6
Total	39

Table 7. Restoration and protection techniques used within tidal marsh habitats in the New York portion of Long Island Sound.

Approximately 229 sites are associated with tidal marsh restoration, enhancement, and preservation activities, and over 270 projects include a tidal marsh component. The frequency of restoration techniques for these projects is provided in Table 8. The project team reviewed the list of projects and selected a total of 273 projects that included an action that restored or protected tidal marsh habitat. Projects that were listed as planned or had no completion dates were not included. Table 9 summarizes the number of sites by restoration technique.

The dataset for riverine migratory corridor projects includes over 188 project sites. The datasets also include a few projects dating back to the late 1980s.

The available project data provides critical information for use in developing metrics to analyze an individual project site's role in maintaining or improving local and regional habitat connectivity. The following key site attributes are generally available from the NYSDEC and CT DEEP datasets for tidal marsh sites:

Habitat Type	No. of Restored Sites	Acres	No. of Protected Sites	Acres
Beaches & Dunes	19	86.17		
Coastal Forest	7	299.03	66	4791.71
Coastal Grassland	5	33.92	3	110.41
Estuarine	11	141.38		
Freshwater wetland	2	5.72	1	3.5
Tidal Marsh	207	2616.78	20	145.59
Tidal Marsh w/ Bluffs			2	19.19
Instream (Invasive Removal)	13	6.59		
Shellfish reef	1	0.28		
Uplands	1	11.48	2	114.34
Other (blank entries)			38	1831.04
Totals	267	3201.36	132	7015.78

Table 8. The number of projects by habitat type in the Connecticut portion of Long Island Sound.

- **Landscape position** – a project located within or outside of habitat cores and core connectors will increase or decrease an individual site's importance for improving habitat connectivity.
- **Habitat Size/Length** – in general, larger scale projects will have a larger influence on connectivity versus smaller sites with a more limited area of influence.
- **Management Action** – the onsite action(s) taken to alter site conditions and restore or improve habitat or alter the site's trajectory.

Restoration Technique	No. of Sites
Tidal Wetland Restoration	5
Fill Removal	12
Tidal Flow Restoration	236
Invasive Plant Control	5
Land Acquisition	15
Total	273

Table 9. Restoration and protection techniques used within habitats in the Connecticut portion of Long Island Sound.

An additional factor, **habitat quality**, is not included in the project site datasets. In general, a habitat that is of higher ecological value would have the potential for greater contribution to biodiversity protection and support, ecosystem functions and resiliency, and a greater influence on habitat connectivity. As addressed below, the project team assumed that the proposed management actions at each site achieved project goals and support fully functional tidal marshes or aquatic habitats, and reviewed other model datasets that could potentially serve as a surrogate for this site attribute.

While the content of the data provided by NYSDEC is adequate, the absence of shapefiles to define specific site locations and dimensions required a modified analysis using the point data for each site location. The inclusion of this New York dataset analysis is for preliminary assessment purposes only. The metric results in the following sections are discussed separately for each state.

DRAFT PILOT METRIC FOR CONNETICUT TIDAL WETLANDS

Consistent with LISS preference for the use of existing habitat connectivity tools and models, the project team utilized the Terrestrial and Wetland Core-Connector Network connectivity dataset from Nature's Network, combined with available project site data to develop the key factors to include in the draft metric. The draft metric was developed using a similar approach as a wetland functional assessment, by scoring site attributes and weighting factors to derive an individual site score. The goal of the metric is to assess each tidal wetland site's importance and relative contribution to habitat connectivity among similar tidal marsh sites. The site attributes evaluated include:

- Landscape position of site relative to model defined primary habitat connectivity cores and connectors.
- Habitat patch size (acreage)
- Habitat quality
- Presence of tidal restrictions
- Actions taken at the site to maintain or improve habitat (preservation, enhancement, rehabilitation, reestablishment).

Associated with each of these elements is a range of possible scores and assumptions for scoring to reflect a site's relative importance and contribution to habitat connectivity. The attribute scores for the sites are based on a scale of 0 to 1, and the attribute scores are summed to provide a total attribute score for the site. The attribute score is then adjusted by multiplying the attribute score by the specific Action to get a weighted score for the site. The Action score is used as a weight to adjust the cumulative site attribute score to reflective the degree of habitat improvement achieved. The data sources and assumptions used in attribute scoring is described below.

- **Landscape Position:** This site attribute utilizes the terrestrial connectivity model output to define the site's location relative to the primary habitat cores and connectors within the terrestrial landscape (Figure 8). The location of a project site in relation to these features has a direct relation to the project site's importance for maintaining or improving existing habitat connectivity. A site within a core is assumed to contribute more to maintaining habitat connectivity and protecting biodiversity than locations outside of a core. A site within any defined corridor carries a higher importance and score than a site outside either location.

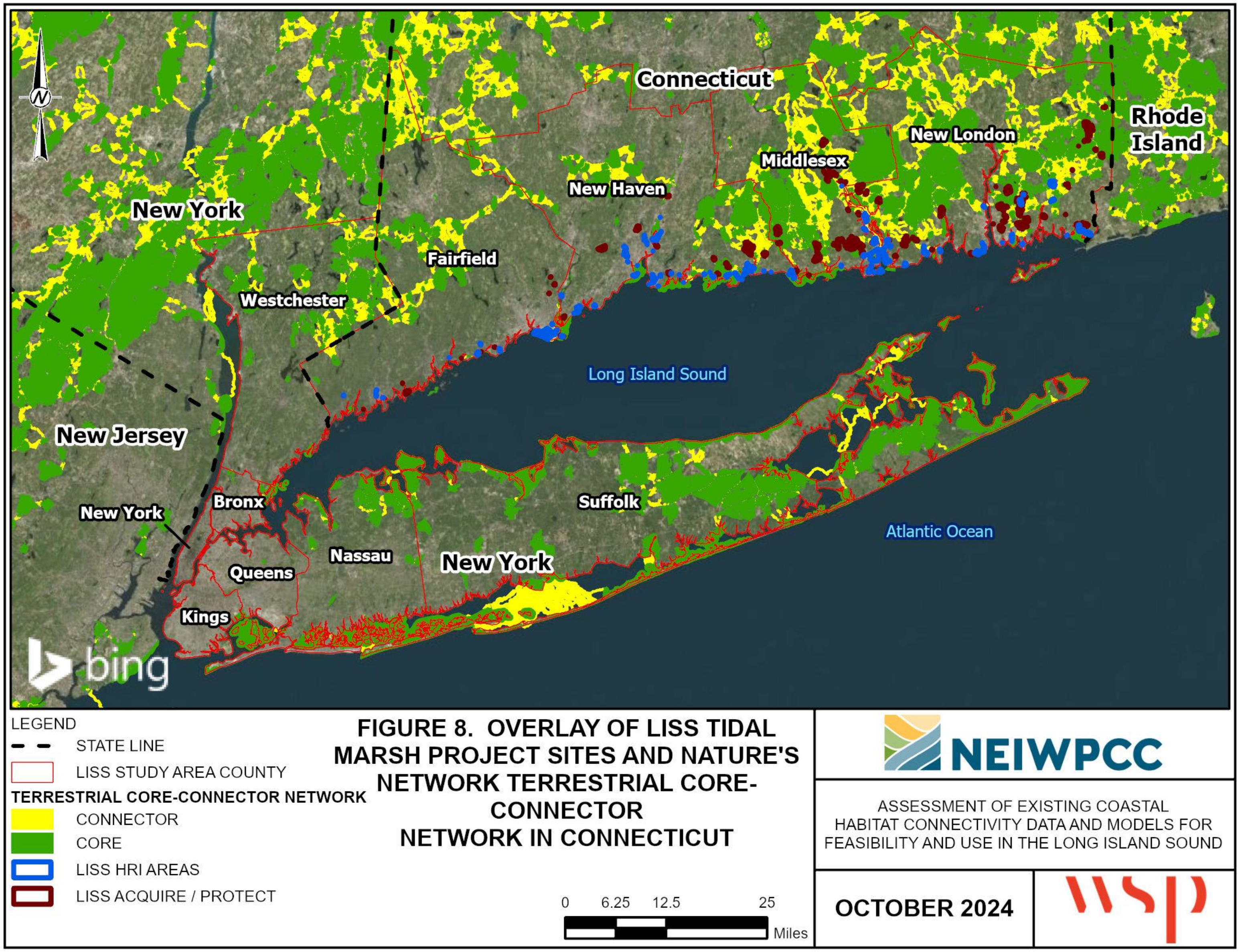
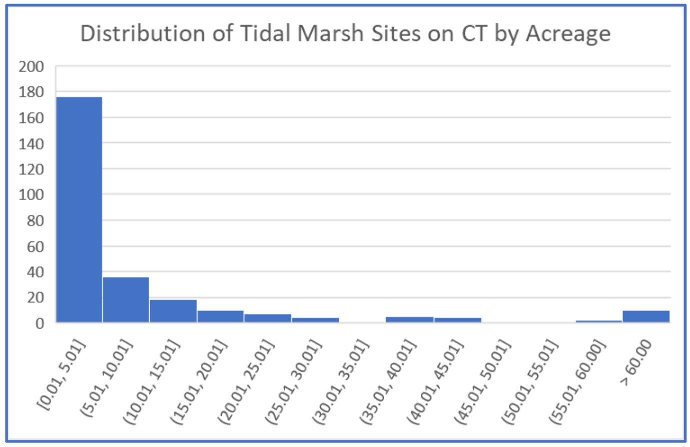


Figure 8. Overlay of LISS Tidal Marsh Project Sites in Connecticut and Nature's Network Terrestrial Core-Connector Network

- **Habitat Patch Size:** The size of an individual site directly influences that site's relative importance to ecosystem functions on a broader scale, including habitat connectivity. For this attribute the project team established four habitat patch size ranges and assigned a score for each class. The largest patch size is >10 acres with an attribute score of 1.0, and the lowest attribute score of 0.2 was assigned to patches less than 1 acre in size. Of the 273 tidal marsh sites, 176 of them are 5 acres or less in size, and 105 are less than 1.0 acre in size.



- **Habitat Quality:** The quality of the tidal marsh habitat has a direct bearing on the potential utilization of a site by native plants and wildlife and its capacity to support these species. In the absence of site-specific data or other available sources of habitat quality, the project team utilized data for the Index of Ecological Integrity (IEI) metric developed by DSL (McGarigal et al. 2018). The IEI is a composite index derived from 21 landscape metrics applied to 30-meter square cells to measure both relative intactness (i.e., freedom from adverse human modifications and disturbance) and resiliency to environmental change (i.e., capacity to recover from or adapt to changing environmental conditions driven by human land-use and climate change). The index is scaled 0-1 by ecological system and geographic area, with 1.0 representing large, undisturbed natural areas and 0.0 representing highly disturbed, modified areas. For each site, an average of all IEI values within the site is calculated and applied for scoring.

- **Tidal Restrictions:** The free and unimpeded flow of tides within tidal wetland sites is a key component of habitat connectivity within these systems. The potential presence of tidal restrictions from undersized culverts, tide gates, berms, dams, and other sources reduces tidal exchange that may affect nutrient cycling and exchange, change native plant and wildlife species composition, increase the abundance or distribution of invasive plant species, and contribute to the loss of tidal marsh habitat. The project team incorporated the Tidal Restriction stressor metric developed by DSL. The metric estimates the effect of potential tidal restrictions on upstream wetland systems, including intertidal systems such as salt marshes. The metric values range from 0 (no effect) to 1 (severe effect), and as a stressor, the value is subtracted from the cumulative attribute scores to reflect the negative effect on habitat connectivity. While this data may be useful, its source data has not been recently updated and so may not reflect current site conditions. In addition, only two sites within the CT DEEP site database had tidal restriction scores. This information was retained and used as part of the exercise for evaluating the draft metric.

- **Action Type:** The action applied at each tidal marsh site to improve or protect tidal wetland habitat and connectivity ranges from preservation to reestablishment, each with a specific score to reflect a degree of improvement to habitat connectivity that was obtained. Preservation of a site is assumed to provide the least change in site conditions but has value as site preservation is assumed to protect the tidal marsh from future loss and increases the opportunity for future management actions. Reestablishment is assumed to result in the greatest benefit to habitat connectivity by restoring fully functional tidal marsh habitat. Both enhancement and rehabilitation improve tidal marsh habitat and connectivity to a lesser degree. For each site the Action Type is sourced from the project site data. The Action Type score is used as a weighting factor to modify the cumulative site attribute score so that the degree of site improvement is reflected in the site score.

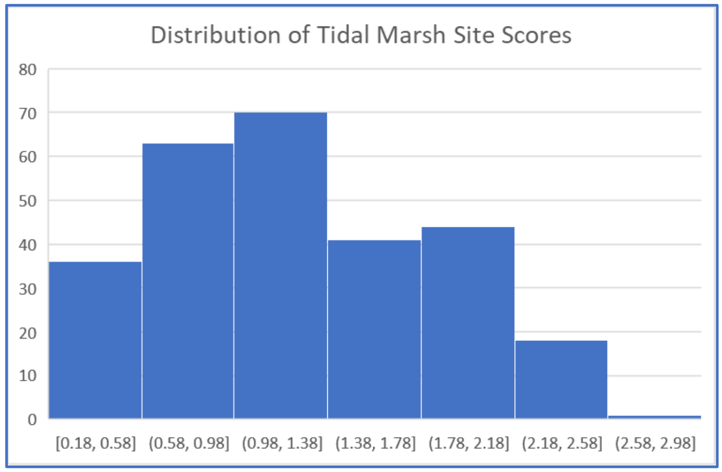
The final site score is calculated using the equation below:

(Landscape Position + Habitat Patch Acreage + Habitat Quality (IEI)-Tidal Restriction)*Action Type

Draft Tidal Marsh Metric

Tidal Wetlands Connectivity Metric Table							
SITE ATTRIBUTES	Landscape Position				Scoring Ranges		
Site Location	Core	Connector	Remote		High/Low Scores		Mid-Point Scores
Measure	Y/N	Y/N	Y/N		High	Low	Avg
Score (Y)	1.0	0.7	0.4		1.0	0.4	0.7
Habitat Patch Characteristics	Tidal Marsh Habitat Patch Size (acres)						
Measure	< 1	>1 to 5	> 5	>10			
Score	0.2	0.5	0.7	1.0	1.0	0.2	0.6
	Index of Ecological Integrity						
Measure	IEI score averaged across tidal marsh area within site						
Score	0.0 - 1.0				1.0	0.0	0.5
	Tidal Restriction						
Measure	Tidal restriction score averaged across tidal marsh area within site						
Score	0.0 - 1.0 (severe effect)				0.0	-1.0	-0.5
					3.0	-0.4	1.3
Action Type	Preservation	Enhancement	Rehabilitation	Reestablishment / Restoration			
Measure	Y/N	Y/N	Y/N	Y/N			
Score	0.2	0.5	0.7	1.0	1	0.2	0.6
					3	**-0.08**	**0.8**

As shown in the draft tidal marsh metric, the potential scores that can be obtained range from 3.0 to -0.08, with a mid-point value of 0.8. The draft metric was applied all 273 tidal marsh sites summarized below. The mean score was 1.26 with a standard deviation of 0.58. The lowest score was 0.18 and the highest was 2.62. In general, the 36 sites with a score under 0.58 have an IEI score of 0, were less than 1 acre in size, and all 15 preservation sites fall into this group. Acknowledging that further refinement of the metric and data is necessary, a subset of sites within this lower tier of the scores would be expected to contribute marginally to habitat connectivity as individual sites.



The draft metric includes several assumptions regarding the data sources including:

1. The values used in scoring some attributes is based on best professional judgement and input from the Technical Advisory Committee (TAC).
2. The habitat connectivity model results are representative of current conditions.
3. The project site data is accurate and representative of current site conditions.
4. The project site Actions achieved project goals and the project site improvements have been maintained and the site has not degraded over time.

There are a several open items to resolve with the draft metric related to attributes and scoring. These include:

1. For assessing site habitat quality, the Index of Ecological Integrity is representative of site conditions as assessed in 2016 and may not be representative of current conditions. The project team did not locate an alternative data source to use. A site-specific evaluation to derive an attribute score would provide the most accurate data for use in this metric.
2. The use of the tidal restriction metric score developed by DSL was selected by the project team since it was a readily available estimate of tidal restriction. This data is also dated and is not necessarily reflective of current site conditions. If further project data review reveals that site restoration actions removed the tidal restriction, then the few sites affected by the scoring can be updated.
3. Multiple sites include habitats other than tidal marsh, so in some cases the site acreage overestimates the acreage of tidal marsh and may require adjustment. The adjustments could be made utilizing existing data sources such as NWI mapping, a comparison LIDAR topographic data and tidal datum, or a site-specific evaluation to update the database.

4. Several tidal wetland sites are small portions of a larger, contiguous tidal marsh sites. If restoration actions are similar and occurred within a narrow period, grouping these individual sites into one collective acreage would improve the overall score.

DRAFT PILOT METRIC FOR CONNECTICUT RIVERINE MIGRATORY CORRIDORS

Riverine migratory corridors in Long Island Sound are critical pathways for fish species like alewife (*Alosa pseudoharengus*) and American eel (*Anguilla rostrata*). These corridors allow fish to access their historic spawning grounds, ensuring the continuation of their life cycle and contributing to the overall health of the LISS ecosystems. Thus, connectivity is a primary factor for riverine migrator corridor conservation and projects aimed at removing instream barriers are essential for providing access to spawning, rearing, and refuge habitats for migratory fish species. Good water quality, natural levels of riverine flow, and cool water temperature are also important.

The CT DEEP dataset contains approximately 135 completed projects and 53 projects that were identified but not advanced for various reasons. The 135 completed projects represent over 472 miles of reconnected streams which, in many cases, do not always include tributaries. In a few instances the linear length of stream channel was calculated based on mapped channel lengths which do not follow the centerline of the stream channels and so likely undercount the linear feet of reconnected stream channels.

The draft metric for riverine migratory corridors follows a similar approach as used in the tidal marsh metric. The project team utilized the Aquatic Core Network connectivity model from the Nature's Network and project site data to develop the key factors to include in the draft metric (Figure 9). The aquatic core networks represent intact, well-connected stream reaches, lakes, and ponds that support a broad diversity of aquatic species and the ecosystems on which they depend.

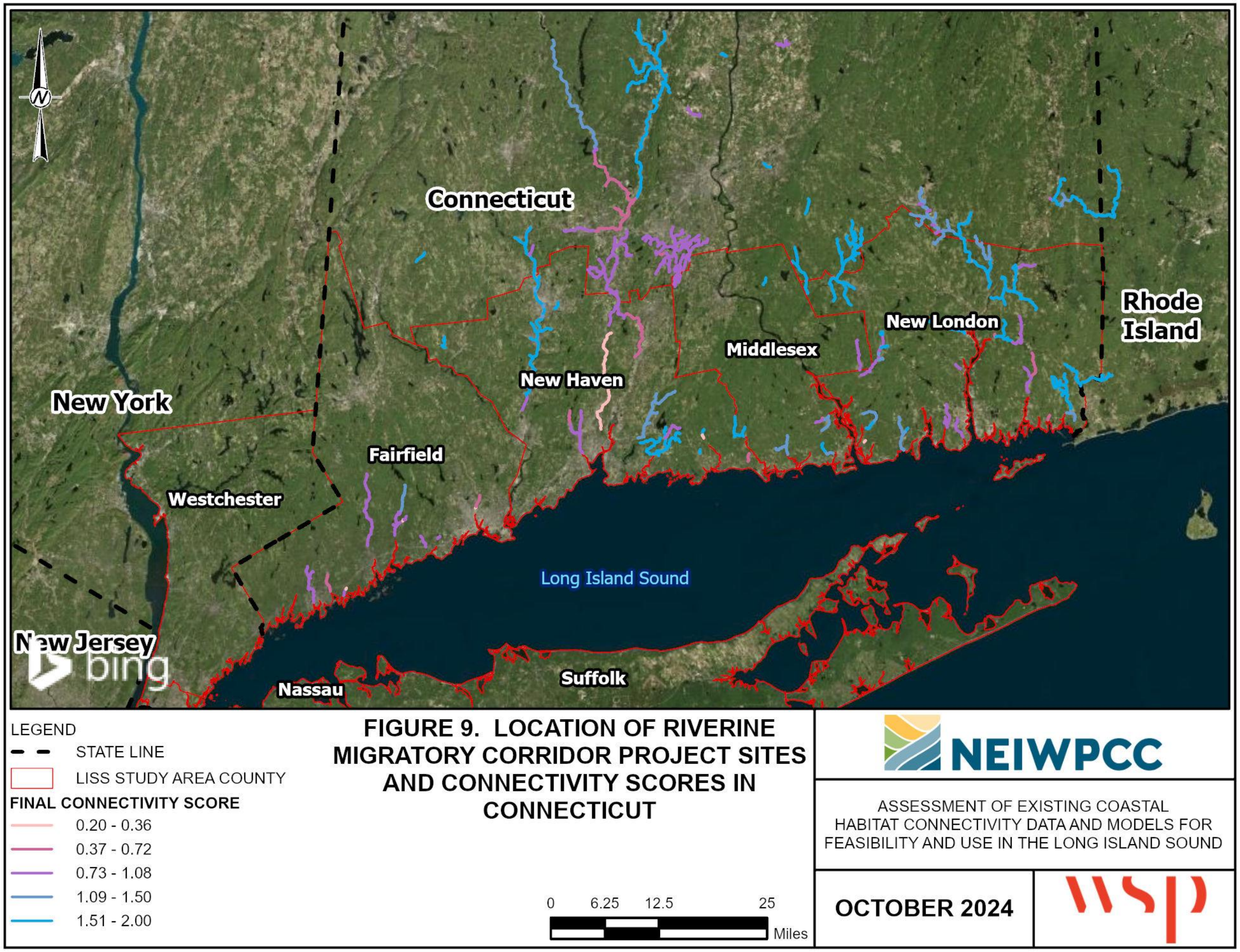
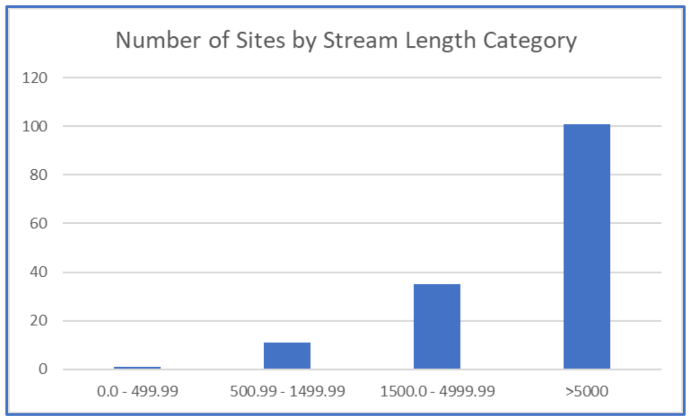


Figure 9. Location of Riverine Migratory Corridor Project Sites in Connecticut and Connectivity Scores

The draft metric utilizes a qualitative scoring of site attributes and a weighting factor based on the type of restoration action to derive an individual site score. The goal of the metric is to assess each riverine migratory corridor project site's importance and relative contribution to aquatic connectivity. The site attributes are described below.

- **Site Location:** This site attribute utilizes the project site's location relative to the priority aquatic core networks. The location of a project site in relation to an aquatic core has a direct relation to the projects potential to improve or maintain high quality aquatic habitats. A site within a core is assumed to contribute more to maintaining aquatic connectivity and protecting biodiversity than locations outside of a core. A second tier are sites that are connected to or are a tributary of an aquatic core and has the potential to contribute to the improvement or maintenance of the aquatic core. The third tier are site locations that are not tributary to or connected with aquatic cores.
- **Linear Stream Length:** The length of riverine corridor reconnected was used to assess the potential contribution and influences on aquatic connectivity. For this attribute the project team established four classes of stream length (feet) and assigned a score for each class. The stream projects affecting more than 5,000 linear feet of stream received an attribute score of 1.0, and the lowest attribute score of 0.2 was assigned to stream lengths under 500 linear feet. Of the 135 project sites, 90 project sites exceed 5,000 linear feet of aquatic connectivity improvement, and only one project site was less than 500 linear feet in length.

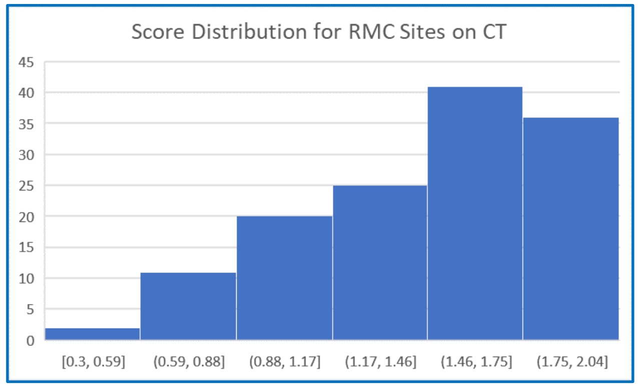


- **Action Type:** The Action applied at each riverine migratory corridor will range from maintenance or improvement to existing connectivity (e.g., fish/eel passage structures) to reestablishment of aquatic connectivity through the removal of barriers such as dams or culverts. Each Action has a specific score to reflect a degree of potential improvement to aquatic connectivity that can be achieved. Reestablishment is assumed to result in the greatest benefit to aquatic connectivity for migratory species as well as other aquatic organisms. Rehabilitation provides new aquatic connectivity for target migratory fish and eels using specialized devices. The Action Type score is used as a weighting factor to modify the cumulative site attribute score so that the degree of potential aquatic connectivity improvement is reflected in the final site score.

The final site score is calculated using the equation below:

(Site Location + Linear Stream Length)*Action Type

As shown in the draft riverine migratory corridors metric below, the potential scores range of 2.0 to 0.14, with a mid-point value of 0.9. The draft metric was applied to all 135 riverine migratory corridor sites. The mean score was 1.43 with a standard deviation of 0.43. The lowest score was 0.3 and the highest was 2.0. The majority of the sites obtained scores exceeding the mid-point. The two lowest scores are associated with maintenance type Actions. Acknowledging that further refinement is necessary, the majority of the projects have improved aquatic connectivity.

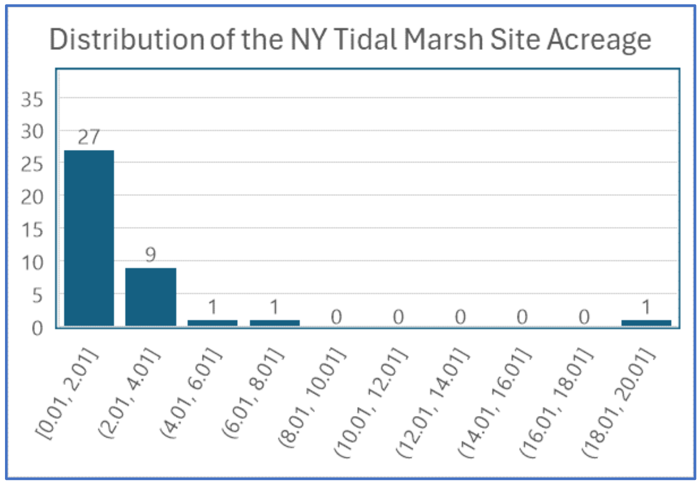


Draft Riverine Migratory Corridor Metric

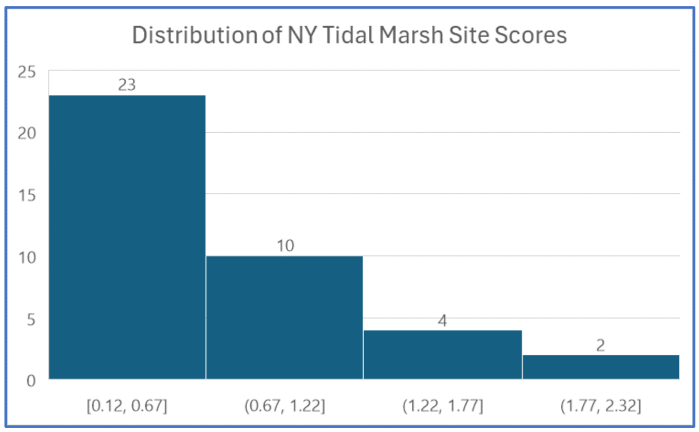
Riverine Migratory Corridor Metric Table							
	Metric Factors						
Site Attributes							
Site Location	High Priority Core Network	Direct Tributary To HP Core	Not Connected to HP Core		Potential High/Low Scores		Mid-Point Scores
Measure	Y/N	Y/N	Y/N		High	Low	Avg
Score (Y)	1.0	0.7	0.4		1.0	0.4	0.7
Linear Stream Length	<500 linear ft	>500 lf, <1,500 lf	>1500 lf, <5,000 lf	>5,000 ln ft			
Measure	Y/N	Y/N	Y/N	Y/N			
Score (Y)	0.3	0.5	0.8	1.0	1.0	0.3	0.7
					Cumulative Attribute Score		
	Passage Improvement				2.0	0.7	1.4
	Maintenance	Rehabilitation	Reestablishment	Reestablishment			
Action Type	Eel Pass	Fishway/ Fish Ladder	Culvert Replacement	Dam Removal			
Measure	Y/N	Y/N	Y/N	Y/N	Weighting Factor		
Score	0.2	0.6	1.0	1.0	1.0	0.2	0.7
					Final Score		
Degree of connectivity improvement					**2**	**0.14**	**0.9**
>1	allow for passage of all aquatic organisms						
0.6	allows for passage of migratory fish and eels						
0.2	allows for passage of eels only, or maintains an exisiting structure						

DRAFT PILOT METRIC FOR NEW YORK TIDAL WETLANDS

The draft metric for tidal wetland was applied for New York using the same approach as described above for Connecticut. The Nature's Network terrestrial core-connector dataset was used to define the site's landscape position (Figure 10).



For the New York tidal marsh sites, the project team established four habitat patch size ranges and assigned a score for each class. The largest patch size is >10 acres with an attribute score of 1.0, and the lowest attribute score of 0.2 was assigned to patches less than 1 acre in size. Of the 39 tidal marsh sites, the majority of the sites are under 2 acres in size, with only two sites exceeding 5 acres or more in size.



As noted above, the draft tidal marsh metric has a potential score range of 3.0 to -0.08, with a mid-point value of 0.8. The draft metric was applied to 39 tidal marsh sites in New York and the score distribution is summarized in the chart. The mean score was 0.68 with a standard deviation of 0.52. The lowest score was 0.12 and the highest was 2.15. The scoring is based on the use of a single point location and not a site polygon which likely resulted in lower potential scores for some sites. Both the IEI score and the Core/Connector score are influenced by the size and proximity of the site, and without site polygons, it is likely that site scores were undercounted. Twenty of the sites had an IEI score of 0, which could be due to the limitation of sampling one IEI grid cell corresponding to the point location.

As shown in the draft tidal marsh metric, the potential scores that can be obtained range from 3.0 to -0.08, with a mid-point value of 0.8. The draft metric was applied all 273 tidal marsh sites summarized below. The mean score was 1.26 with a standard deviation of 0.58. The lowest score was 0.18 and the highest was 2.62. In general, the 36 sites with a score under 0.58 have an IEI score of 0, were less than 1 acre in size, and all 15 preservation sites fall into this group. The 12 lowest scoring sites were all preservation sites and within the Remote category for Core/Connector. These two scoring factors appear to be the primary factors influencing the lower scores. Acknowledging that further refinement of the metric and data is necessary, a subset of sites within this lower tier of the scores would be expected to contribute marginally to habitat connectivity as individual sites.

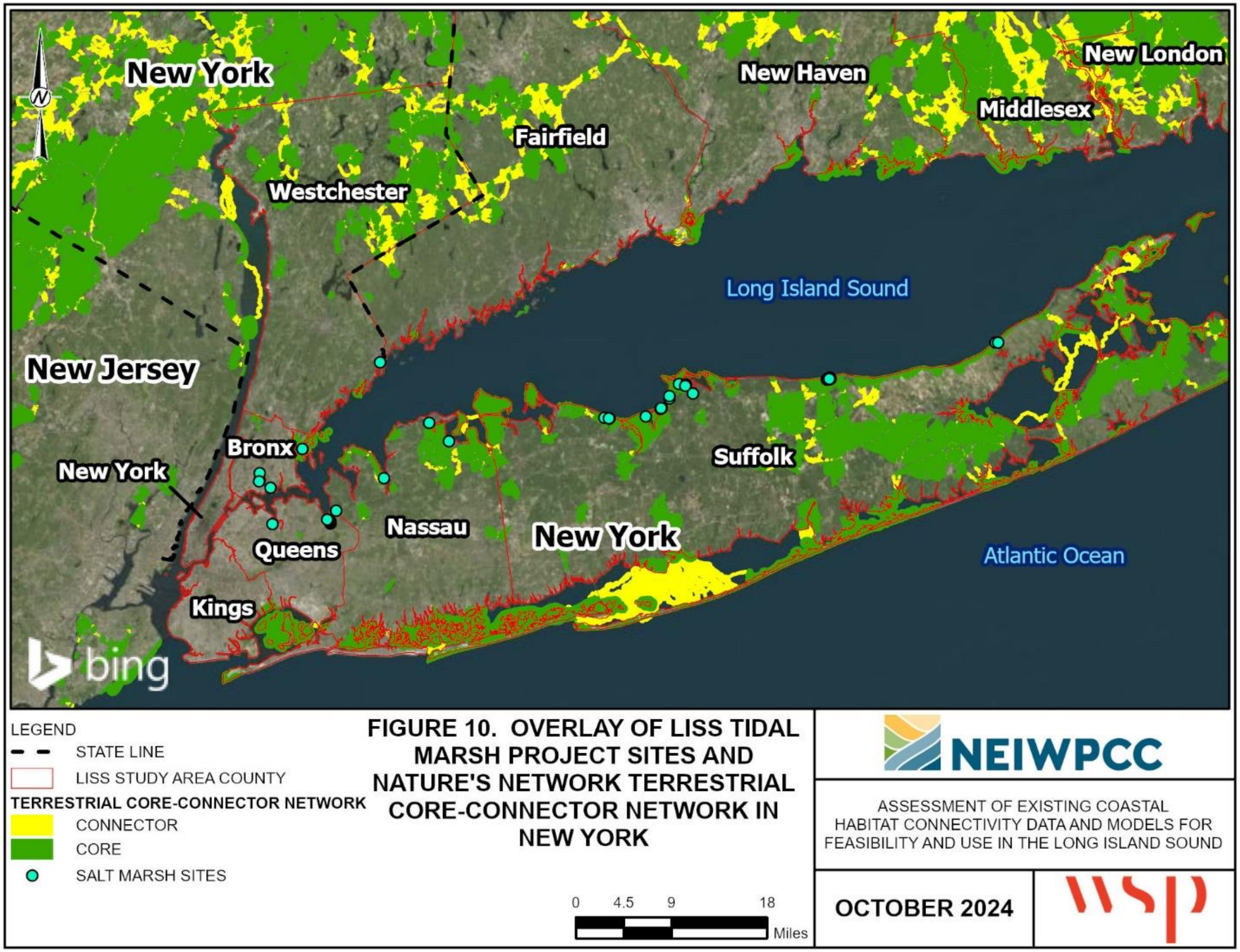


Figure 10. Overlay of LISS Tidal Marsh Project Sites in New York and Nature's Network Terrestrial Core-Connector Network

DRAFT PILOT METRIC FOR NEW YORK RIVERINE MIGRATORY CORRIDORS

The project team utilized the Aquatic Core Network connectivity model from the Nature's Network to assess connectivity of riverine migratory corridors (Figure 11), together with other factors as described above for Connecticut.

The draft metric was applied the 3 riverine migratory corridor sites that are associated with aquatic connectivity improvements through the installation of fish passage devices. One project exceeded 5,000 linear feet (ln ft) of aquatic connectivity improvement (7,920 ln ft), and the remaining two were 4,224 ln ft and 1,056 ln ft in length. Each site was assessed as a Rehabilitation Action and none of the sites were associated with a Habitat Core or a Tributary to Core.

The site scores were 0.84, 0.72, 0.54 and align with the project lengths. Acknowledging further refinement is necessary, the scores indicate that the projects have improved aquatic connectivity.

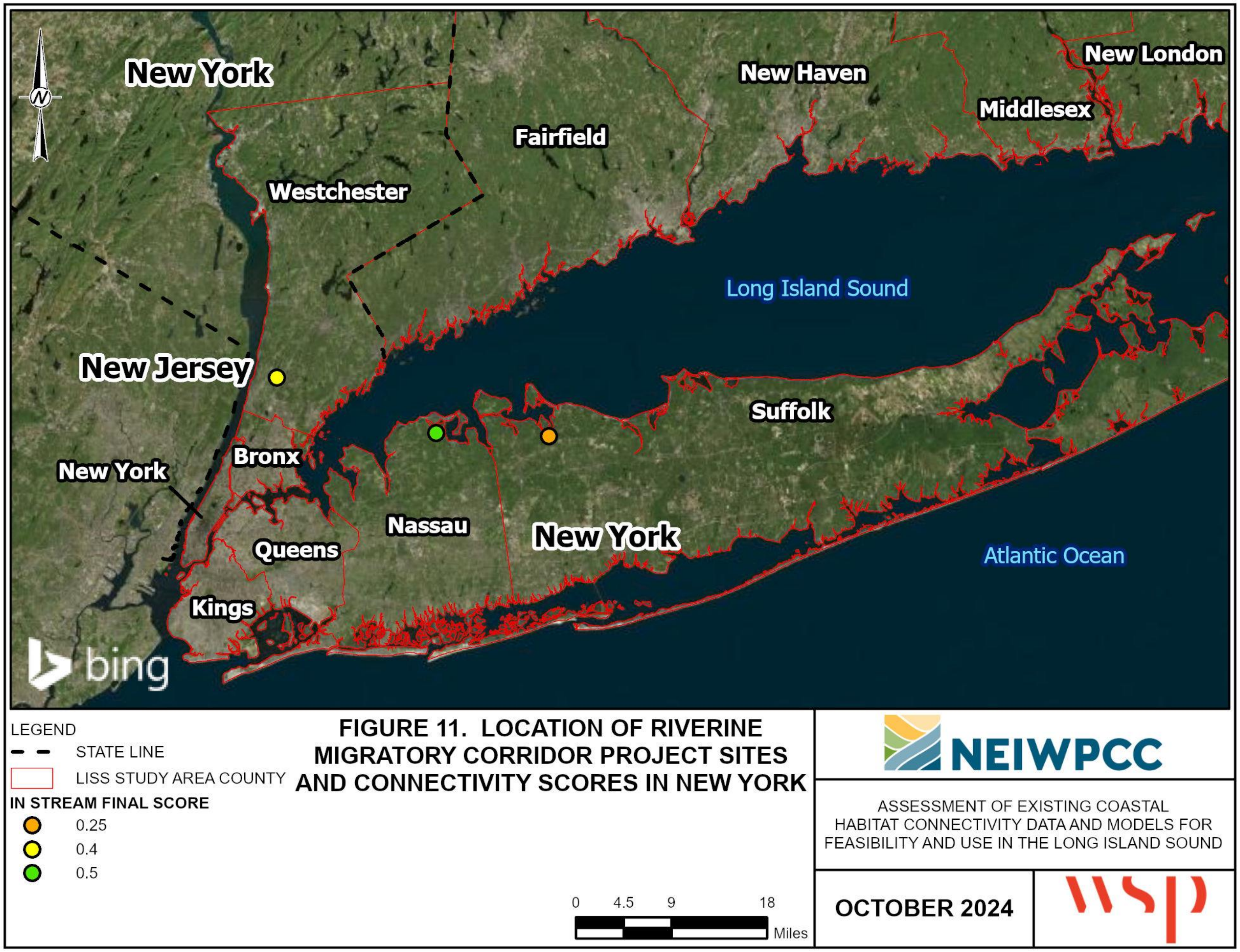


Figure 11. Location of Riverine Migratory Corridor Project Sites in New York and Connectivity Scores

5.0 SUMMARY OF FINDINGS

Identifying the habitat connectivity metrics useful in the Long Island Sound depends on the habitat in question. For the LISS priority habitats, a wide range of plant and animal species could be evaluated using species-specific connectivity models (Table 1). However, this approach involves several complexities, including confirming the appropriate focal species or species groups for a given priority habitat, and gathering the life history data and habitat requirements suitable for model development. Developing these models would require significant effort and may not necessarily apply to all species. Alternatively, structural habitat connectivity models are preferable because they focus on the physical arrangement of habitats, making them easier to apply across multiple species and ecosystems. Structural models rely on readily available data, are cost-effective, and can be updated more easily compared to the complex, species-specific data required for functional models.

The project team developed a draft qualitative metric for evaluating an individual project site's contribution to regional habitat connectivity for tidal marshes and riverine migratory corridors. Metrics to quantify connectivity for these habitats, and other terrestrial habitats, are relatively straightforward compared to marine habitats. In terrestrial habitats and rivers/streams, which includes 5 of 12 LISS priority habitats, well-established methods and existing models are available to measure structural and functional connectivity by evaluating physical barriers and corridors like roads or dams. These models often rely on detailed land cover maps, species movement data, and the physical layout of the landscape to predict how species move between habitat patches. However, within the remaining 7 LISS priority habitats, connectivity is influenced by dynamic and complex factors such as tides, ocean currents, and fluctuating salinity and temperature gradients. This variability makes it challenging to apply traditional habitat connectivity models and connectivity often requires hydrodynamic models that account for the movement of water to simulate the dispersal pathways for marine organisms. The transient nature of marine habitats, where organisms rely on both estuarine and marine habitats at different life stages, adds to the complexity of modeling efforts. Instead of using complex models, simpler distance metrics could be used to approximate the relationship of a particular habitat patch to the surrounding natural/semi-natural habitats that could facilitate flows of species and ecosystem services; however, this approach requires more assumptions and increased levels of uncertainty.

The project team also identified several items related to the project data provided by NYSDEC and CT DEEP that would need to be adjusted and improved to effectively use in a GIS-based model and to limit the number of assumptions. Some of the project data issues include:

NYSDEC:

- Shapefiles of each project site with attribute data are not available.
- Coordinates for some sites are miles away from actual location (recently updated by NYSDEC).
- Data entries are missing or not completed in a consistent manner.
- Project completion dates are missing.
- Categories are not clearly defined.

CT DEEP:

- Detailed information is not consistently provided for each project site.
- Planned projects are listed with completed projects.

- Dates are missing for when projects were completed.
- Breakdown of acreage by type of habitat and restoration action is not provided.
- Some stream lengths are undercalculated (did not follow actual channel meanders)
- Tributaries lengths not included - potential to use NAACC culvert data to assess expansion of reconnected stream channels.

The project team recommends taking the following steps to ensure consistent and organized project site data is collected and entered into the project database using a format that will support future evaluations, GIS modeling and reporting. Inconsistencies in data entry reduce data quality and model outputs.

1. Develop a protocol to standardize data entry into the database and improve consistency in data collection.
2. Define each criterion, the purpose for data collection, and, if applicable, the data source.
3. Obtain shapefiles as part of the As-Built deliverable which should include metadata for the project and acreage by habitat type that aligns with the LISS priority habitat list.

6.0 REFERENCES

Albrecht, R., B. Clow, N. Gould, J. Miller, and R. Saldivar. 2020. Proposing and Demonstrating an Improved Habitat Connectivity Assessment Framework. March 2020. Available: https://bren.ucsb.edu/media/1983/download. Accessed August 29, 2024.

Anderson, M., A. Barnett, M. Clark, J. Prince, A. Olivero Sheldon, and B. Vickery. 2016. Resilient and Connected Landscapes for Terrestrial Conservation. The Nature Conservancy, Eastern Conservation Science, Eastern Regional Office. Boston, MA. Available: http://easterndivision.s3.amazonaws.com/Resilient_and_Connected_Landscapes_For_Terrestial_Conservation.pdf. Accessed August 29, 2024.

Anderson, M.G., M. Clark, A.P. Olivero, and D.R. Cameron. 2023. A resilient and connected network of sites to sustain biodiversity under a changing climate. *Proceedings of the National Academy of Sciences* 120 (7): e2204434119. Available: https://www.pnas.org/doi/10.1073/pnas.2204434119. Accessed September 18, 2024.]

Ani, C., V. Haller-Bull, J. Gilmour, and B. Robson. 2024. Connectivity modelling identifies sources and sinks of coral recruitment within reef clusters. *Scientific Reports* 14: 13564). Available: https://www.nature.com/articles/s41598-024-64388-8.pdf. Accessed September 20, 2024.

Arkilanian, A., G. Larocque, V. Lucet, D. Schrock, C. Denépoux, and A. Gonzalez. 2020. A review of ecological connectivity analysis in the Region of Resolution 40-3. Report presented to the Ministère de la faune, de la forêt et des parcs du Québec for the New England Governors and Eastern Canadian Premiers working group on ecological connectivity. 79 pp. Available: https://ecologicalconnectivity.com/sites/default/files/2021-07/Connectivity-Analysis-40-3_Report.pdf. Accessed August 29, 2024.

Ayram, C., M. Mendoza, A. Etter, and D.Pérez-Salicrup. 2016. Habitat connectivity in biodiversity conservation; A review of recent studies and applications. *Progress in Physical Geography Earth and Environment* 40(1):7-37. Available: https://www.researchgate.net/profile/Andres-Etter/publication/281408475_Habitat_connectivity_in_biodiversity_conservation_A_review_of_recent_studies_and_applications/links/56a6247d08ae2c689d39d995/Habitat-connectivity-in-biodiversity-conservation-A-review-of-recent-studies-and-applications.pdf. Accessed August 29, 2024.

Baguette, M., Van Dyck, H., 2007. Landscape connectivity and animal behavior: functional grain as a key determinant for dispersal. *Landscape Ecology* 22: 1117–1129. Available: https://link.springer.com/article/10.1007/s10980-007-9108-4. Accessed August 29, 2024.

Basso, G., J. Vaudrey, K. O'Brien, and J. Barrett. 2018. Advancing Coastal Habitat Resiliency Through Landscape-Scale Assessment, *Coastal Management*, 46(1): 19–39. Available: https://repository.library.noaa.gov/view/noaa/33047. Accessed August 29, 2024.

Becker, S., S. Jackson, A. Jordaan, and A. Roy. 2018. Impacts of Tidal Road-Stream Crossings on Aquatic Organism Passage. U.S. Department of Interior, Fish and Wildlife Service, Cooperator Science Series FWS/CSS-131-2018, Washington, D.C. Available: https://www.google.com/url?sa=t&source=web&rct=j&opi=89978449&url=https://digitalmedia.fws.gov/digital/api/collection/document/id/2238/download&ved=2ahUKEwjgy-_9s6eIAxUYl-4BHYQaLjgQFnoECBUQAQ&usg=AOvVaw1lRwsFY064-kseWJD114J8. Accessed August 29, 2024.

Beier, P., D. Majka, and J. Jenness. 2007. Designing Wildlife Corridors with ArcGIS. corridordesign.org. Watsonville, CA. December 7, 2007. Available: http://www.elkhornsloughctp.org/uploads/files/1197586062CorridorDesigner%20Workbook.pdf. Accessed August 29, 2024.

Carroll, C. 2023. Connectivity Analysis Toolkit User guide. Available: http://www.klamathconservation.org/CAT/v1_3_1/ToolkitManual.pdf. Accessed August 29, 2024.

Chernoff, G. 2016. Pulling the Levers: A Guide to Modelling and Mapping Ecological Connectivity. Prepared for the Calgary Regional Partnership. March 2016. Available: https://prism.ucalgary.ca/server/api/core/bitstreams/546de25d-b1dc-460b-94e2-8553cef7f3f5/content. Accessed August 29, 2024.

CLEAR (Center for Land Use Education and Research). 2007. Landscape Fragmentation Tool, LFT v2.0. The University of Connecticut Department of Agriculture Center for Land Use Education And Research (CLEAR). Storrs, CT. Available: https://clear.uconn.edu/mapping/tools/. Accessed August 29, 2024.

Compton, B. 2024. Personal communication via phone call between Brad Compton, Research Associate, University of Massachusetts Amherst, Department of Environmental Conservation, and Ed Samanns and Phil Baigas, WSP. January 11, 2024.

Compton, B., E. Plunkett, W. DeLuca, J. Grand, and S. Jackson. 2023. ecoConnect: Ecosystem-based Regional Connectivity to Inform Conservation Networks at Multiple Scales. University of Massachusetts Amherst, Department of Environmental Conservation. December 12, 2023. https://landeco.umass.edu/web/lcc/dsl/ecoconnect/dsl_documentation_ecoConnect.pdf. Accessed August 29, 2024.

Compton, B., S. Jackson, and K. McGarigal. 2020. Conservation Assessment and Prioritization System (CAPS) Statewide Massachusetts Assessment: December 2020. University of Massachusetts Amherst, Department of Environmental Conservation, Landscape Ecology Program. Available: https://umassdsl.org/masscaps/caps_2020_massachusetts_assessment.pdf. Accessed August 29, 2024.

Conservation Corridor. 2023. Connectivity Toolbox, Programs and Tools. Available: https://conservationcorridor.org/corridor-toolbox/programs-and-tools/. Accessed August 29, 2024.

Costanza, J., and A. Terando. 2019. Landscape Connectivity Planning for Adaptation to Future Climate and Land-Use Change. *Current Landscape Ecology Reports* 4 (2019): 1–13. Available: https://www.srs.fs.usda.gov/pubs/ja/2019/ja_2019_costanza_002.pdf. Accessed August 29, 2024.

Cote, D., D. Kehler, C. Bourne, and Y. Wiersma. 2009. A new measure of longitudinal connectivity for stream networks. *Landscape Ecology* 24 (2009): 101–113. Available: https://link.springer.com/article/10.1007/s10980-008-9283-y. Accessed August 29, 2024.

DeLuca. W., B. Compton, E. Plunkett, and K. McGarigal. 2020. Designing sustainable landscapes Phase 5: what's new? Report to the US Fish and Wildlife Service, Northeast Atlantic-Appalachian Region. Available:

https://umassdsl.org/DSLdocs/DSL_documentation_Phase5_whats_new.pdf. Accessed August 29, 2024.

Drielsma, M., J. Love, S. Taylor, R. Thapa, and K.J. Williams. 2022. General Landscape Connectivity Model (GLCM): a new way to map whole of landscape biodiversity functional connectivity for operational planning and reporting. *Ecological Modeling* 465 (2022) 109858. Available: https://researchonline.jcu.edu.au/71255/1/Drielsma%20et%20al%202022%20Ecol%20Modeling.pdf. Accessed August 29, 2024.

Dutta, T., S. Sharma, N.F.V. Meyer, J. Larroque, and N. Balkenhol. 2022. An overview of computational tools for preparing, constructing and using resistance surfaces in connectivity research. *Landscape Ecology* 37: 2195-2224. https://link.springer.com/article/10.1007/s10980-022-01469-x. Accessed August 29, 2024.

Fagan, W. 2002. Connectivity, fragmentation, and extinction risk in dendritic metapopulations. *Ecology* 83: 3243–3249. https://esajournals.onlinelibrary.wiley.com/doi/abs/10.1890/0012-9658%282002%29083%5B3243%3ACFAERI%5D2.0.CO%3B2/. Accessed August 29, 2024.

Fang, X., X. Hou, X. Li, and W. Hou. 2017. Ecological connectivity between land and sea: a review. *Ecological Research* 33(1):1–11. Available: https://www.researchgate.net/publication/322265245_Ecological_connectivity_between_land_and_sea_a_review. Accessed August 29, 2024.

Ferree, C., and M. Anderson. 2013. A Map of Terrestrial Habitats of the Northeastern United States: Methods and Approach The Nature Conservancy, Eastern Conservation Science, Eastern Regional Office. Boston, MA. Available: https://www.conservationgateway.org/ConservationByGeography/NorthAmerica/UnitedStates/edc/Documents/HabitatMap_Methods.pdf. Accessed August 29, 2024.

Franklin, P., T. Bašić, P. Davison, K. Dunkley, J. Ellis, M. Gangal, A. González-Ferreras, C. Gutmann Roberts, G. Hunt, D. Joyce, C. Klöcker, R. Mawer, T. Rittweg, V. Stoilova, and L. Gutowsky. 2024. Aquatic connectivity: challenges and solutions in a changing climate. *Journal of Fish Biology* 105(2): 10.1111/jfb.15727. Available: https://api.repository.cam.ac.uk/server/api/core/bitstreams/ee8afb32-e10c-423a-b3ae-9089736bd626/content. Accessed September 19, 2024.

Fullerton, A., K. Burnett, E. Steel, R. Flitcroft, G. Pess, B. Feist, C. Torgersen, D. Miller, and B. Sanderson. 2010. Hydrological connectivity for riverine fish: measurement challenges and research opportunities. *Freshwater Biology* 55(11) 2215-2237. Available: https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1264&context=usdeptcommercepub/. Accessed August 29, 2024.

Gallo, J., and R. Greene. 2018. Connectivity Analysis Software for Estimating Linkage Priority. Conservation Biology Institute, OR. Available: https://figshare.com/ndownloader/files/30679214. Accessed August 29, 2024.

Howard, T., and M. Schlesinger. 2012. PATHWAYS: Wildlife habitat connectivity in the changing climate of the Hudson Valley. New York Natural Heritage Program, Albany, New York. https://www.nynhp.org/documents/17/PATHWAYS_final_report_2012.pdf. Accessed August 29, 2024.

Howard, T., and M. Schlesinger. 2013. Wildlife habitat connectivity in the changing climate of New York's Hudson Valley. June 2013. *Annals of the New York Academy of Sciences* 00 (2013) 1–17. Available: https://www.researchgate.net/publication/239946559_Wildlife_habitat_connectivity_in_the_changing_climate_of_New_York%27s_Hudson_Valley. Accessed August 29, 2024.

Jumani, S., M. Deitch, D. Kaplan, E. Anderson, J. Krishnaswamy, V. Lecours, and M. Whiles. 2020. River fragmentation and flow alteration metrics: a review of methods and directions for future research. *Environmental Research Letters* 15 (2020) 123009. Available: https://iopscience.iop.org/article/10.1088/1748-9326/abcb37/pdf. Accessed August 29, 2024.

Keeley, A., D. Ackerly, D. Cameron, N. Heller, P. Huber, C. Schloss, J. Thorne, and A. Merenlender. 2018. New concepts, models, and assessments of climate-wise connectivity. *Environmental Research Letters* 13 (2018) 073002. Available: https://iopscience.iop.org/article/10.1088/1748-9326/aacb85/pdf. Accessed August 29, 2024.

Keeley, A., P. Beier, and J. Jenness. Connectivity metrics for conservation planning and monitoring. 2021. *Biological Conservation* 225 (2021) 109008 . Available: https://www.sciencedirect.com/science/article/pii/S0006320721000604. Accessed August 29, 2024.

Kindlmann, P., and F. Burel. 2008. Connectivity measures: A review. *Landscape Ecology* 23: 879-890. Available: https://www.researchgate.net/publication/226251940_Connectivity_measures_A_review. Accessed September 19, 2024.

Krosby, M, I. Breckheimer, D. Pierce, P. Singleton, S. Hall, K. Halupka, W. Gaines, R. Long, B. McRae, B. Cosentino, and J. Schuett-Hames. 2015. Focal species and landscape "naturalness" corridor models offer complementary approaches for connectivity conservation planning. *Landscape Ecology* 30 (10): 2121-2132. Available: https://www.fs.usda.gov/pnw/pubs/journals/pnw_2015_krosby001.pdf. Accessed August 29, 2024.

Landguth, E., C. Muhlfeld, and G. Luikart. 2012. CDFISH: an individual-based, spatially-explicit, landscape genetics simulator for aquatic species in complex riverscapes. *Conservation Genetics Resources* 4: 133–136. Available: https://files.cfc.umt.edu/cesu/USGS/FY10/10Hauer_UM_cc_aquatic%20ecosystems_final%20rpt.pdf. Accessed August 29, 2024.

Lausche, B., A. Laur, and M. Collins. 2021. Marine Connectivity Conservation 'Rules of Thumb' for MPA and MPA Network Design. Version 1.0. IUCN WCPA Connectivity Conservation Specialist Group's Marine Connectivity Working Group. Available: https://conservationcorridor.org/wp-content/uploads/Marine-Connectivity-Conservation-Rules-of-Thumb-for-MPA-and-MPA-Network-Design_2021.pdf. Accessed August 29, 2024.

La Peyre, M.K., Marshall, D.A., and Sable, S.E., 2021, Oyster model inventory: Identifying critical data and modeling approaches to support restoration of oyster reefs in coastal U.S. Gulf of Mexico waters: U.S. Geological Survey. Open-File Report 2021–1063. Available: https://pubs.usgs.gov/publication/ofr20211063. Accessed September 20, 2024.

Liebowitz, D., K. Nielsen, J. Dugan, S. Morgan, D. Malone, J. Largier, D. Hubbard, and M. Carr. 2016. Ecosystem connectivity and trophic subsidies of sandy beaches. Ecosphere 7(10): e01503. Available: https://esajournals.onlinelibrary.wiley.com/doi/full/10.1002/ecs2.1503. Accessed September 20, 2024.

LISS (Long Island Sound Study). 2003. Long Island Sound Habitat Restoration Initiative; Technical Support for Coastal Habitat Restoration. February 2003. Available: https://longislandsoundstudy.net/wp-content/uploads/2010/03/LIS.Manual.pdf. Accessed August 29, 2024.

LISS. 2015. Long Island Sound Comprehensive Conservation and Management Plan 2015: Returning the Urban Sea to Abundance. Prepared by the Long Island Sound Study, with significant support from the New England Interstate Water Pollution Control Commission and its contractor, WaterVision, LLC. Available: https://longislandsoundstudy.net/2015/09/2015-comprehensive-conservation-and-management-plan/. Accessed August 29, 2024.

LISS. 2020. Returning the Urban Sea to Abundance: A five-year review of the 2015 Comprehensive Conservation and Management Plan. December 2020. Available: https://longislandsoundstudy.net/wp-content/uploads/2021/06/CCMP-2020-Final-rev02_singles.pdf. Accessed August 29, 2024.

LISS. 2023. "Ecosystem Targets and Supporting Indicators: Habitat Connectivity." LISS website. Available: https://longislandsoundstudy.net/ecosystem-target-indicators/habitat-connectivity/. Accessed August 29, 2024.

Magris, R., R. Pressey. R. Weeks, and N. Ban. 2014. Integrating connectivity and climate change into marine conservation planning. *Biological Conservation* 170: 207–221. https://www.researchgate.net/publication/260016425_Integrating_connectivity_and_climate_change_into_marine_conservation_planning. Accessed August 29, 2024.

Majka, D., J. Jenness, and P. Beier. 2007. CorridorDesigner: ArcGIS tools for designing and evaluating corridors. Available: http://corridordesign.org. Accessed August 29, 2024.

Malavasi, M., V. Bartak, M. Carranza, P. Simova, and A. Acosta. 2018. Landscape pattern and plant biodiversity in Mediterranean coastal dune ecosystems: Do habitat loss and fragmentation really matter? *Journal of Biogeography* 45 (2018): 1367–1377. Available: https://onlinelibrary.wiley.com/doi/10.1111/jbi.13215. Accessed September 19, 2024.

Marzialetti, F., G. Grosso, A. Acosta, M. Malavasi, L. Pinna, M. Sternberg, S. Gupta, G. Brundu, and M. Carranza. 2024 (In Press). Dunes under attack: untangling the effects of landscape changes on Iceplant invasion (*Carpobrotus* spp., *Aizoaceae*) in Mediterranean coasts. ARPHA Preprints Available: https://preprints.arphahub.com/article/133102/. Accessed September 19, 2024.

McRae, B., and D. Kavanagh. 2011. Linkage Mapper Connectivity Analysis Software. Seattle, WA: The Nature Conservancy. Available: https://linkagemapper.org/. Accessed August 29, 2024.

McGarigal, K., B. Compton, S. Jackson, E. Plunkett, and E. Ene. 2012. Critical Linkages Phase 1: Assessing Connectivity Restoration Potential for Culvert Replacement, Dam Removal and Construction of Wildlife Passage Structures in Massachusetts. University of Massachusetts Amherst, Department of Environmental Conservation, Landscape Ecology Program. July 13, 2012. Available: https://umasscaps.org/pdf/Critical-Linkages-Phase-1-Report-Final.pdf. Accessed August 29, 2024.

McGarigal, K., B. Compton, and S. Jackson. 2013. Critical Linkages Phase II: A Strategic Assessment of Increasing Regional Connectivity in Massachusetts Via the Installation of Wildlife Passage Structures University of Massachusetts Amherst, Department of Environmental Conservation, Landscape Ecology Program. April 30, 2013. Available: https://umasscaps.org/pdf/Critical%20Linkages%20Phase%20II%20Report.pdf. Accessed August 29, 2024.

McGarigal K., B. Compton, E. Plunkett, W. DeLuca, and J. Grand. 2017. Designing sustainable landscapes: tidal restrictions metric. Report to the North Atlantic Conservation Cooperative, US Fish and Wildlife Service, Northeast Region. https://umassdsl.org/DSLdocs/DSL_documentation_tidal_restrictions.pdf. Accessed August 29, 2024.

McGarigal K., B. Compton, E. Plunkett, W. DeLuca, and J. Grand. 2018a. Designing sustainable landscapes: modeling ecological integrity. Report to the North Atlantic Conservation Cooperative, US Fish and Wildlife Service, Northeast Region. Accessed August 29, 2024.

McGarigal, K., B. Compton, E. Plunkett, W. DeLuca, J. Grand, E. Ene, and S. Jackson. 2018b. A landscape index of ecological integrity to inform landscape conservation. *Landscape Ecology* 33:1029–1048.et al. 2011. Available: https://umassdsl.org/DSLdocs/McGarigal_2018_LandEco.pdf. Accessed August 29, 2024.

Milroy, S., K. Cambazoglu, J. Wiggert, and C. Pan. 2020. Habitat suitability index (HSI) model results for oyster larvae trajectory and condition, COAWST_2017_Grp06_Srf_d02 drifter simulation released from Drum Bay, Louisiana from 2017-05-19 to 2017-10-26. Distributed by: Gulf of Mexico Research Initiative Information and Data Cooperative (GRIIDC), Harte Research Institute, Texas A&M University–Corpus Christi. https://data.griidc.org/data/MS.x841.000:0004. Accessed September 20, 2024.

Mudd, J., S. Spector, and N. Tabak. 2017. The Hudson Valley Conservation Strategy: Conservation in a Changing Climate. Poughkeepsie, NY: Scenic Hudson, Inc. Available: https://scenichudson.org/wp-content/uploads/2019/10/Hudson-Valley-Conservation-Strategy.pdf. Accessed August 29, 2024.

NAACC (North Atlantic Aquatic Connectivity Collaborative). 2021. Aquatic Passability Scoring Systems for Tidal Stream Crossings. June 14, 2021. Available: https://streamcontinuity.org/resources/aquatic-passability-scoring-systems-tidal-stream-crossings. Accessed August 29, 2024.

New Jersey DFW (Division of Fish and Wildlife). 2019. Connecting Habitat Across New Jersey (CHANJ): Guidance Document, Version 1.0. New Jersey Department of Environmental Protection, Division of Fish and Wildlife, Endangered and Nongame Species Program. pp. 73. Available: https://dep.nj.gov/njfw/wp-content/uploads/njfw/chanj_guidance.pdf. Accessed August 29, 2024.

New York Natural Heritage Program. 2021. Assessments of Habitat Condition, Connectivity, Suitability. Updated February 8, 2021. Available: https://www.nynhp.org/habitat-assessments/. Accessed August 29, 2024.

NYSDEC (New York State Department of Environmental Conservation). 2015. New York State Wildlife Action Plan. September 2015. Albany, NY. Available: https://www.dec.ny.gov/docs/wildlife_pdf/swapfinaldraft2015.pdf. Accessed August 29, 2024.

Pastor, A., A. Ospina-Alvarez, J. Larsen, F. Hansen, D. Krause-Jensen, and M. Maar. 2022. A network analysis of connected biophysical pathways to advice eelgrass (Zostera marina) restoration. *Marine Environmental Research* 179 (2022): 105690. Available: https://www.sciencedirect.com/science/article/pii/S0141113622001350. Accessed August 29, 2024.

Pearson, S., B. Prooijen, E. Elias, S. Vitousek, and Z. Wang. 2020. Sediment Connectivity: A Framework for Analyzing Coastal Sediment Transport Pathways. Journal of Geophysical Research: Earth Surface. 125 (10): 1029/2020JF005595. Available: https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2020JF005595. Accessed September 19, 2024.

Powers, S., H. Roman, J. Meixner, D. Wirasaet, S. Brus, G. Fricano, and J. Westerink. 2023. Establishing connectivity patterns of eastern oysters (Crassostrea virginica) on regional oceanographic scales. *Ecosphere* 14(1): e4337. Available: https://esajournals.onlinelibrary.wiley.com/doi/full/10.1002/ecs2.4337. Accessed September 20, 2024.

Raposa, K., K. Wasson, E. Smith, J. Crooks, P. Delgado, S. Fernald, M. Ferner, A. Helms, L. Hice, J. Mora, B. Puckett, D. Sanger, S. Shull, L. Spurrier, R. Stevens, and S. Lerberg. 2016. Assessing tidal . marsh resilience to sea-level rise at broad geographic scales with multi-metric indices. *Biological Conservation* 204(B): 263–275. Available: https://www.sciencedirect.com/science/article/pii/S0006320716305742. Accessed September 19, 2024.

Roberts, J., B. Best, D. Dunn, E. Treml, and P. Halpin. 2010. Marine Geospatial Ecology Tools: An integrated framework for ecological geoprocessing with ArcGIS, Python, R, MATLAB, and C++. *Environmental Modelling & Software* 25: 1197–1207. Available: https://www.sciencedirect.com/science/article/abs/pii/S1364815210000885?via%3Dihub. Accessed September 19, 2024.

Shah, V., and B. McRae. 2008. Circuitscape: A Tool for Landscape Ecology. *Proceedings of the 7th Python Science Conference* (2009). G. Varoquaux, T. Vaught, J. Millman (Eds), pp. 62–66. Available: https://circuitscape.org/pubs/Shah_McRae_Circuitscape_Python_Scipy08.pdf. Accessed August 29, 2024.

Treml E., and P. Halpin. 2012. Marine population connectivity identifies ecological neighbors for conservation planning in the Coral Triangle. *Conservation Letters* 5: 441–449. doi: 10.1111/j.1755-263X.2012.00260.x. Available: https://conbio.onlinelibrary.wiley.com/doi/10.1111/j.1755-263X.2012.00260.x. Accessed September 19, 2024.

Treml, E., P. Halpin, D. Urban, and L. Pratson. 2008. Modeling population connectivity by ocean currents, a graph-theoretic approach for marine conservation. *Landscape Ecology* 23: 19–36. Available: https://www.ialena.org/uploads/9/4/8/2/94821076/treml_etal_2008.pdf. Accessed August 29, 2024.

TNC (The Nature Conservancy). 2016. Resilient and Connected Landscapes for Terrestrial Conservation. Data download. Available: https://www.conservationgateway.org/ConservationByGeography/NorthAmerica/UnitedStates/edc/reportsdata/terrestrial/resilience/Pages/Downloads.aspx. Accessed August 29, 2024.

USFWS (US Fish and Wildlife Service). 2024. Nature's Network; Downloads. Developed by the U.S. Fish and Wildlife Service Science Applications program. Available: https://northeast-sa-fws.hub.arcgis.com/. Accessed August 29, 2024.

USGS (US Geological Survey). 2023. ScienceBase Catalog. Available: https://www.sciencebase.gov/catalog/items/get?filter0=party%3DStaying+Connected+Initiative. Accessed August 29, 2024.

Wade, A., K. McKelvey, and M. Schwartz. 2015. Resistance-Surface-Based Wildlife Conservation Connectivity Modeling: Summary of Efforts in the United States and Guide for Practitioners. Gen. Tech. Rep. RMRS-GTR-333. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 93 pp. Available: https://www.fs.usda.gov/rm/pubs/rmrs_gtr333.pdf. Accessed August 29, 2024.

Walker, R., and L. Craighead. 1997. Analyzing wildlife movement corridors in Montana using GIS. Available: https://proceedings.esri.com/library/userconf/proc97/proc97/to150/pap116/p116.htm. Accessed August 29, 2024.

White, J., M. Carr, J. Caselle, L. Washburn, C. Woodson, S. Palumbi, P. Carlson, R. Warner, B. Menge, J. Barth, C. Blanchette, P. Raimondi, and K. Milligan. 2019. Connectivity, dispersal, and recruitment: connecting benthic communities and the coastal ocean. *Oceanography* 32(3):50–59. Available: https://doi.org/10.5670/oceanog.2019.310. Accessed August 29, 2024.

Wood, S., K. Martins, V.Dumais-Lalonde, O. Tanguy, F. Maure, A. St. Denis, B. Rayfield, A. Martin, and A. Gonzalez. 2022. Missing Interactions: The Current State of Multispecies Connectivity Analysis. *Frontiers in Ecology and Evolution* 10 (2022) 830822. Available: https://www.biorxiv.org/content/10.1101/2021.11.03.466769v1.full.pdf. Accessed August 29, 2024.

Zeller, K., K. McGarigal, and A. Whiteley. 2012. Estimating landscape resistance to movement: A review. *Landscape Ecology*, 27(6), 777–797. Available: https://doi.org/10.1007/s10980-012-9737-0. Accessed August 29, 2024.

Zhai, R., C. Zhang, W. Li, M. Boyer, and D. Hanink. 2016. Prediction of Land Use Change in Long Island Sound Watersheds Using Nighttime Light Data. *Land* 2016, 5(4): 44. Available: https://doi.org/10.3390/land5040044. Accessed August 29, 2024.