New York City Department of Environmental Protection

Bureau of Water Supply

LiDAR Applications for Wetland Mapping and Connectivity Assessment

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NYC Environmental Protection

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Executive Summary

In 2015, DEP completed a pilot study demonstrating that incorporation of high-resolution Light Detection and Ranging (LiDAR) data and orthoimagery into automated modeling protocols greatly increased the accuracy and completeness of wetland maps in the watershed. The pilot study also demonstrated that these high-resolution datasets significantly improved the ability to assess wetland connectivity to the stream network. Given the success of the pilot, DEP endeavored to update and expand the pilot methodology to the entire watershed. This report details the methodology and results of the watershed-wide effort.

As a first step, the modeling protocols were updated to incorporate methodological advances that have occurred since the completion of the pilot study. Modeling was followed by manual review and editing to produce a fully classified spatial dataset compliant with National Wetlands Inventory (NWI) protocols. Similar to the pilot, the acreage of open water systems and vegetated wetlands mapped by these protocols was significantly higher than in the most recent (2005) NWI. Mapped vegetated wetland acreage nearly doubled as compared to the NWI West of Hudson (WOH) and increased by approximately 70% East of Hudson (EOH). The greatest gains were in evergreen forested wetlands, which is understandable as these systems are most difficult to detect through standard photo interpretation. Additionally, the updated modeling appears to be more accurate EOH than WOH, as significantly more manual editing was required to correct errors of commission WOH.

The connectivity results were also similar to the pilot and demonstrated an increased ability to identify wetland connections to the stream network by using high resolution LiDAR and orthoimagery. By amending the local resolution National Hydrography Database (NHD) with over 400 miles of new connecting features, the percentage of wetlands estimated to be unconnected to the stream network decreased from 10 to 2% EOH, and from 8 to 3% WOH. This is a significant decrease from the 35% and 54% of wetlands that would be predicted to be unconnected using the medium resolution NHD.

While the wetland mapping datasets produced from this effort are more complete than the 2005 NWI, errors of commission and omission undoubtedly remain, as is the case with any remote sensing product. Since this is a novel approach, further assessment is required to understand the degree of such errors, and how they may affect application of these data. DEP will complete a full accuracy assessment of this geodata to determine whether there are systematic issues in accuracy and classification that require revision and to understand how to best incorporate these data into watershed protection programs.

1.0 Introduction

DEP relies on the NWI as one means of prioritizing sensitive areas for protection in the implementation of watershed protection programs. DEP and the U.S. Fish and Wildlife Service (USFWS) have partnered to produce and update the NWI for the watershed since the mid-1990s. Past mapping efforts relied solely on traditional methods that use visual interpretation of aerial photography to identify and map wetlands and waters.

In 2015, DEP completed a pilot study to determine whether the 2009 watershed-wide collection of LiDAR data and high resolution orthoimagery could be leveraged to improve the accuracy and completeness of wetland maps in the watershed (DEP 2015). A second objective of the pilot study was to determine whether wetland connectivity to the stream network could be more accurately assessed with the LiDAR-derived, local resolution NHD as compared to previous lower resolution stream datasets.

After affirming that there were no gaps or quality issues in the LiDAR dataset that would negatively impact a wetlands mapping effort, protocols were developed to automate wetland mapping for the entire watershed. Wetlands were modeled using object-based image analysis (OBIA) incorporating a LiDAR-derived topographic index, orthoimagery, and other ancillary data. The draft model output was manually edited in 15 pilot areas to produce an NWI-compliant product. This coverage more than doubled the extent of vegetated wetlands mapped in the WOH watershed pilot areas and increased those mapped in the EOH pilot areas by 74% (DEP 2015).

The pilot study also demonstrated the utility of using LiDAR derivatives to improve the assessment of wetland connectivity in the watershed. Connectivity evaluation using medium resolution NHD indicated that 35% of wetlands in the pilot area lack connections to downstream waters. Assessment of connectivity using local resolution (1:1,000) NHD coupled with LiDAR-derived topography and high resolution orthoimagery indicated that just 2% of mapped wetlands in the pilot areas lack such connections (DEP 2015).

Based on these results, DEP endeavored to expand the pilot methodology to the entire watershed. Given advances in automated mapping methodology since completion of the 2015 pilot, this watershed-wide effort endeavored to first evaluate and update the pilot modeling protocols, followed by manual editing to correct errors of omission, commission, and classification; and then to perform connectivity analysis of all mapped wetland features.

2.0 Methods

This project was completed through a contract with Groundpoint Technologies, LLC who subcontracted the University of Vermont Spatial Analysis Laboratory to complete wetland modeling and Ramboll Americas Engineering Solutions, Inc. for field verification. Groundpoint Technologies completed manual editing of the model output and the connectivity analysis. DEP conducted field and desktop review and provided feedback on draft interim products.

2.1 Automated Wetland Mapping

While the pilot's overall framework of using OBIA followed by manual editing was maintained (DEP 2015), more recent modifications in modeling were incorporated in attempt to reduce the extent of manual editing required to produce an NWI-compliant product. Key modifications include the inclusion of Raney models (McFaden et al. 2021) in the OBIA sequence; additional pixel-based object resizing in morphological routines to smooth polygon edges; automated Cowardin classification assignment beyond the vegetation class level (FGDC 2013); and use of land use/land cover data to remove roads from wetland features. Based on input from the USFWS, perennial NHD streams were also buffered and included as riverine polygons.

The Raney method compiles elevation, aspect, temperature, soils, and precipitation data to statistically predict wetland occurrence using maximum entropy models (Maxent) at a $10m^2$ scale, with separate models produced for emergent and woody (forested and scrub-shrub) wetlands (McFaden et al. 2021). These models were developed after the 2015 pilot project and incorporated in the current project to potentially reduce both errors of commission (false positives) and errors of omission in OBIA. Features identified as likely wetland candidates in OBIA but that lack landscape-level indicators used in the Raney model may be errors of commission, while features that were not captured initially in OBIA but whose landscape characteristics are strongly indicative of wetlands may be errors of omission.

As with the pilot, automated feature extraction was performed in eCognition® (Trimble Navigation Limited, Westminster, Colorado, USA), an OBIA program that relies on user-defined rule sets to segment and classify input imagery. The 2009 LiDAR collection and leaf-off and leaf-on orthoimagery were used as the base data for the OBIA modeling protocols. While newer photography exists, 2009 data sources were selected given their spatial alignment, and to provide a new base layer upon which future status and trends studies can be conducted. Several additional LiDAR-derivatives were used in the automated mapping including digital elevation maps (DEMs), a flow accumulation layer, two-foot contour maps, a normalized digital surface model (nDSM), and a 3m Compound Topographic Index (CTI) (Rampi et al. 2014). A detailed description of the development and application of the CTI can be found in the pilot report (DEP 2015).

The first rule step in the automated feature extraction removed features unlikely to support wetlands including developed areas with high concentrations of buildings, roads, and other impervious surfaces. Unlike the pilot, protocols for this project did not exclude agricultural areas, and wetlands modeled in these areas were retained and attributed with farmed or ditched modifiers. Remaining areas were then segmented into objects based on their CTI characteristics, selecting objects with high CTI textures as the most likely wetland candidates. Further segmentation steps fused CTI texture, the Raney models, and spectral characteristics to identify additional wetland candidates, while also removing objects with little likelihood of supporting wetlands. Output from initial OBIA modeling was evaluated against field-verified wetlands from DEP’s delineation database and compared to pilot model output. This evaluation suggested that the Raney models were overly aggressive in their removal of forested wetlands and the selection routines were thereby modified to remove fewer objects. The edges of remaining wetland features were then automatically edited to remove upland inclusions based on a 1m resolution topographic position index (TPI) and smoothing routines were added to create more realistic wetland boundaries (Figures 1 through 3).

Vegetated wetland objects were automatically classified based on vegetation height determined from the LiDAR-derived nDSM. Areas with an average vegetation height of less than 2m were classified as emergent, those between 2m and 6m as scrub-shrub, and those greater than 6m as forested. Forested wetlands were further classified as deciduous or evergreen based on spectral characteristics. Generalization was then conducted to consolidate all objects smaller than 0.5 acre into larger adjacent polygons. While high resolution LiDAR makes it possible to map much smaller objects within larger polygons, the minimum mapping unit (MMU) of 0.5 acre for adjacent objects improves the interpretability of the final maps, at a scale reasonable to land use managers. Non-adjacent individual vegetated wetlands were included at an MMU of 0.1 acres. Water features (PUB) were retained with no minimum size, given the ability to reliably map these features using high resolution datasets, and the relative importance of small water bodies such as vernal pools.

The attribution of NWI water regime and special modifiers was automated, rather than manually interpreted as in the pilot, and then assessed based on field verification (FGDC 2013). The default classifications that were implemented after an iterative process of modeling and field evaluation are provided in Table 1. A total of 90 field checks were conducted to inform the modeling and classification process (Figures 4 and 5). The fully classified wetland coverage was then exported for manual editing to correct errors of omission, commission, and classification. It should be noted that the OBIA protocol was designed to over map wetlands, as errors of commission are easier to correct than errors of omission, and that some errors of commission may remain in the final database.

Figures 1 through 3. The addition of pixel-based smoothing routines into the 2021 modelling protocols (right) resulted in more realistic wetland boundaries than produced by both the pilot (center) and NWI (left). Also note that the 2021 model output (right) produces subclass and water regime modifiers unlike the pilot, designating these two wetland polygons as broad-leaved deciduous and needle-leaved evergreen, palustrine forested, seasonally flooded/saturated wetland (PFO1E and PFO4E, respectively). This wetland is located adjacent to the Kensico Reservoir.

Table 1. Default classifications applied during automated mapping. See FGDC (2013) and Appendix 1 for further description of the classification codes.

Cowardin Class	Description	Modeling Workflow
L1UB3H	Lacustrine, Limnetic, Unconsolidated Bottom, Mud, Permanently Flooded	National Hydrography Dataset (NHD) Waterbody ≥ 20 ac
PUB3H	Palustrine, Unconsolidated Bottom, Mud, Permanently Flooded	NHD Waterbody < 20 ac (if not already mapped as wetland), and all remaining water (mapped using multispectral imagery)
R3UB1G	Riverine, Upper Perennial, Unconsolidated Bottom, Cobble-Gravel, Intermittently Exposed	NHD Area (if not already mapped as wetland)
R3RB2G	Riverine, Upper Perennial, Rock Bottom, Rubble, Intermittently Exposed	NHD Flowlines buffered 10’ on each side (if not already mapped as wetland)
PEM1E	Palustrine, Emergent, Persistent, Seasonally Flooded/Saturated	Emergent features identified by vegetation height that are adjacent to L or PUB features.
PEM1B	Palustrine, Emergent, Persistent, Seasonally Saturated	Emergent features identified by vegetation height that are NOT adjacent to L or PUB, not associated with a legacy NWI feature, and with no apparent stream intersection.
PFO1E	Palustrine, Forested, Broad-leaved Deciduous, Seasonally Flooded/Saturated	Forested features identified by vegetation height that are adjacent to L or PUB features.
PFO1B	Palustrine, Forested, Broad-leaved Deciduous, Seasonally Saturated	Forested features identified by vegetation height that are NOT adjacent to L or PUB, not associated with a legacy NWI feature, and with no apparent stream intersection.
PFO4E	Palustrine, Forested, Needle-leaved Evergreen, Seasonally Flooded/Saturated	Evergreen forested features identified by vegetation height that are adjacent to L or PUB features.
PFO4B	Palustrine, Forested, Needle-leaved Evergreen, Seasonally Saturated	Evergreen forested features identified by vegetation height that are NOT adjacent to L or PUB, not associated with a legacy NWI feature, and with no apparent stream intersection.
PSS1E	Palustrine, Scrub-Shrub, Broad-Leaved Deciduous, Seasonally Flooded/Saturated	Remaining vegetated features with >50% deciduous cover assigned to this class
PSS1B	Palustrine, Scrub-Shrub, Broad-Leaved Deciduous, Seasonally Saturated	Remaining vegetated features with >50% deciduous cover assigned to this class that are NOT adjacent to L or PUB, not associated with a legacy NWI feature, and with no apparent stream intersection.
PSS4E	Palustrine, Scrub-Shrub, Broad-Leaved Deciduous, Seasonally Flooded/Saturated	Remaining vegetated features with >50% evergreen cover assigned to this class
PSS4B	Palustrine, Scrub-Shrub, Broad-Leaved Deciduous, Seasonally Saturated	Remaining vegetated features with >50% evergreen cover assigned to this class that are NOT adjacent to L or PUB, not associated with a legacy NWI feature, and with no apparent stream intersection.

Figures 4 and 5. Field work was conducted in the spring of 2021 (left) by USFWS, contractors, and DEP to inform modeling protocols and again by DEP in the fall of 2021 (right) to review model output. The spring photo was taken in the East Branch basin, and the fall photo is from a site near Kensico Reservoir.

2.2 Manual Editing

Evaluation of random points, direct comparison with various legacy data, and a rigorous screening of class codes and modifiers were conducted to inform the manual editing effort. These approaches were used to identify and correct errors of commission, omission, and classification at specific locations as well as uncover general issues to inform broad editing needs.

A total of 441 random points were generated inside the draft wetlands data polygons (241), DEP field delineated polygons (100), and within wetland polygons previously accepted as viable for NWI update mapping during the Pilot Project (100). Points were evaluated at a scale of 1:2,500 to determine if the assigned classification and morphology appeared appropriate against the 2009 imagery, NHD and CTI layers. In addition, the full “scene” on the monitor display at that scale (approx. 155 acres or 0.25 mi^2) was evaluated for any additional visible issues. While there was agreement in wetland presence and classification at roughly 86% of these checkpoints, issues of omission, commission, and classification were identified and corrected through manual editing.

Legacy NWI data were used to edit the draft data in multiple ways. First, all NWI orphans, regardless of size, were evaluated. NWI orphans are defined as those features more than 20m (approx. 1 MMU or 400 m^2) away from any of the newly mapped wetlands. Since these features were included in the NWI but not in the newly mapped coverage they were evaluated as potential errors of omission. Over 1,000 NWI orphans were evaluated and 487 were added to the draft wetland coverage with boundary adjustments made as needed. The remaining orphans were determined to be errors of commission in the NWI.

Legacy NWI data were also used to evaluate the classification of riverine features. The model defaulted all NHD river and perennial streams as upper perennial (R3) (Table 1). The NWI was queried to identify riverine systems that had been previously designated as lower perennial (R2). These features were evaluated and R2 was applied to riverine features in the draft dataset that both were previously coded as such in the NWI and exhibited meander and floodplain characteristics more typical of lower perennial rivers.

The NWI was also queried to locate features attributed with the aquatic bed class, dead and phragmites subclasses, or beaver special modifier (Appendix A). These features were evaluated on the orthoimagery to determine whether these classification codes should be propagated to the draft coverage. Evaluation of aquatic bed, dead, phragmites, and beaver classifications was limited to those features that coincide with legacy NWI data. No other features in the draft coverage were evaluated for these modifiers.

The morphology and classification of all palustrine unconsolidated bottom (PUB) systems (ponds) were reviewed, and special modifiers were added to designate diked/impounded (h) and excavated (x) features as appropriate. Legacy NWI data were also considered in this evaluation.

Ancillary NHD and land use/land cover datasets were also used to edit the draft wetland coverage. NHD data were used to identify and remove underground connections from riverine polygons, with all above ground NHD perennial streams and rivers remaining as R3 and R2 polygons. In many instances the automated mapping consumed roadways into wetlands and wetland complexes, and the 2009 land-use/land-cover data were used to erase roads out of mapped wetland polygons (Figure 6).

Any polygons removed through manual editing were exported to a separate coverage ("Removed Wetlands") as future mapping efforts may benefit from knowing that there were at least some strong indicators of wetlands in these areas.

Figure 6. Road features were erased from this wetland polygon within the Cannonsville Basin using land use/land cover data.

Retained polygons were attributed with confidence codes. A "New" confidence code was assigned to all newly mapped features that occurred at least 20m away from any legacy NWI feature. A "New Manual" code was added for features that were not mapped during the NWI or automated mapping procedure, but photointerpretation determined the likely presence of a wetland. An "NWI" code was added to polygons not mapped during the automated mapping procedure but were included in the NWI and confirmed through photointerpretation.

DEP reviewed the draft databases after completion of the above editing routines. For EOH, DEP conducted a limited field review along with desktop analyses. DEP compared the area of vegetated wetlands within the EOH pilot areas as mapped by the 2015 pilot and current project and found a 7% increase in mapped wetland area (Table 2). This was deemed reasonable, considering model improvements were designed to further increase detection. DEP also used the 2015 pilot results to project anticipated acreage of vegetated wetlands that would be mapped in the current project and found strong agreement between predicted and mapped acreage (Table 3). Based on these analyses and a visual scan of the entire data set, DEP deemed the EOH draft data only in need of minor editing.

DEP's desktop review of WOH draft data revealed significant commission. The draft data showed a 61% increase in mapped vegetated wetlands in the pilot areas as compared to the 2015 project, and a nearly 100% increase over DEP's pilot-based watershed-wide projections. Forested wetlands were the most significant source of commission, as the draft coverage mapped over three times the area as predicted from the pilot. Evergreen wetlands (PFO4) were particularly over-mapped, comprising more than half (12,599) of the 23,143 acres of forested wetlands in the draft maps. It is noteworthy that evergreen forested wetlands comprise only 605 acres WOH in the NWI, which is certainly an underestimate due to difficulties in detecting wetlands beneath coniferous canopies through traditional photo interpretation (Figures 7 and 8). However, it is highly unlikely that these wetlands were under-mapped in the NWI by a factor of 20 as the draft model suggests.

Table 2. Acreage of vegetated wetlands in pilot areas as mapped in the final manually edited 2015 pilot as compared to those in the 2021 draft coverage.

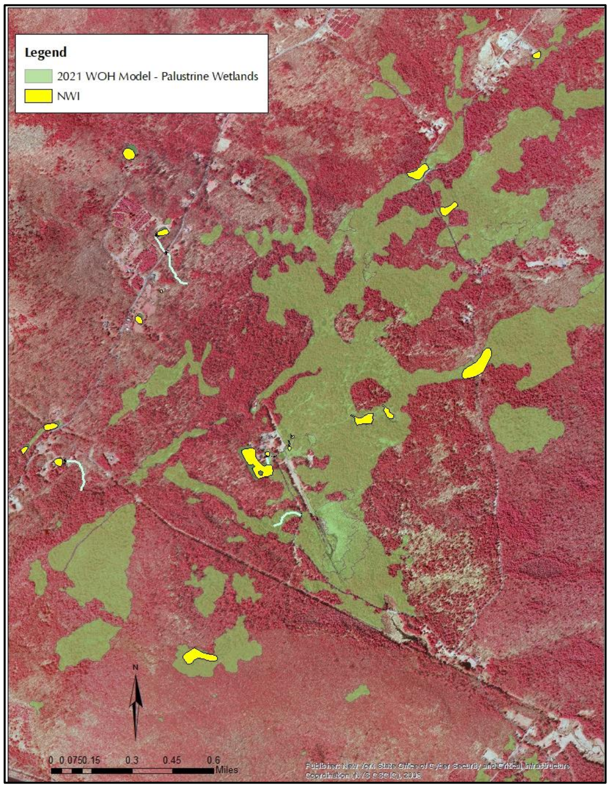
	West of Hudson				**East of Hudson**			
	2005 NWI	**2015 Pilot**	**2021 Draft**	**Percent Change**	**2005 NWI**	**2015 Pilot**	**2021 Draft**	**Percent Change**
PEM	116	236	284	20%	41	63	70	11%
PSS	40	95	88	-8%	53	148	61	-59%
PFO	44	140	388	177%	347	558	692	24%
Total	199	471	760	61%	441	769	823	7%

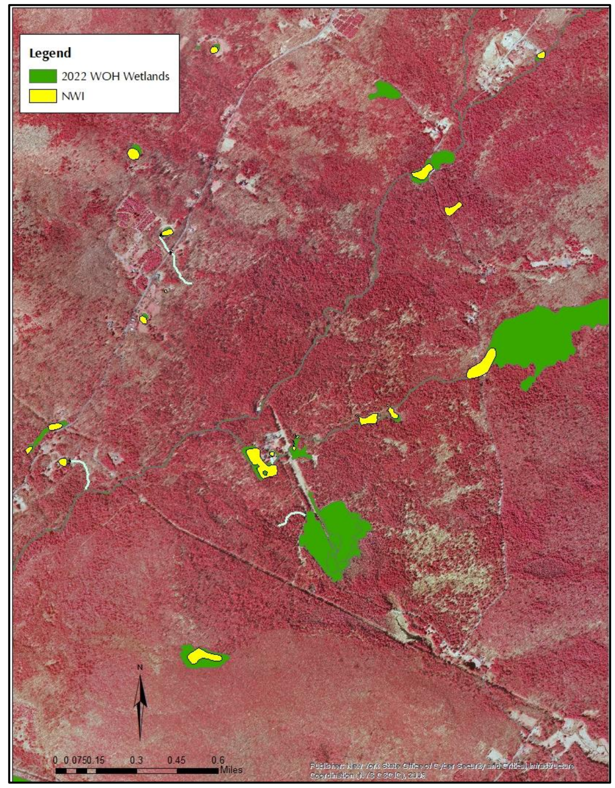
Table 3. Watershed-wide anticipated increases in mapped wetland acreage based on percent increase by wetland type in the pilot areas.

	West of Hudson				East of Hudson			
	2005 NWI	**Increase in Pilot Areas**	**Projected Watershed-Wide**	**2021 Draft**	**2005 NWI**	**Increase in Pilot Areas**	**Projected Watershed-Wide**	**2021 Draft**
PEM	2,999	104%	6,128	10,492	1,101	55%	1,703	1,417
PSS	1,573	137%	3,721	2,019	1,182	179%	3,300	1,947
PFO	2,261	222%	7,282	23,143	10,872	61%	17,481	18,876
Total	6,833		17,131	35,654	13,154		22,484	22,239

While a certain degree of commission is expected when trying to capture omitted wetlands, commission levels were deemed too high in the WOH data, and the contractor developed additional manual editing protocols to address them. Additional manual editing WOH focused on evaluating forested areas that were modeled as wetlands in the current project but not in the 2015 pilot, polygons attributed with the “New” confidence code, and wetlands with ditched and farmed modifiers, as DEP’s review of these areas indicated significant commission of these features (Figures 9 and 10). Finally, each reservoir basin was visually reviewed and edited as needed, focusing on stream corridors since the majority of mapped wetlands WOH are in riparian zones. It is noted that some of these additional protocols may have resulted in excessive omission, hence all removed features were retained in the “Removed Wetlands” shapefile and will be further evaluated in DEP’s ongoing review of the databases.

As a final step, the manually edited EOH and WOH coverages were checked for topological issues and processed through the USFWS Verification Toolset to ensure the data meets NWI digital data requirements (Dahl et al. 2009, FGDC 2009, FGDC 2013). Final geodatabases were delivered in March 2022.





Figures 7 and 8. A portion of the Rondout Basin showing significant commission in a hemlock forested area in the 2021 draft model (left). The figure on the right shows the extent of mapped wetlands after implementation of additional manual editing protocols.

Figures 9 and 10. An agricultural field in the Cannonsville basin inaccurately mapped as a farmed wetland in the draft WOH coverage. Areas such as this were removed as errors of commission.

2.3 Connectivity Assessment

Palustrine and lacustrine features from the final dataset were evaluated to determine their connectivity to the local resolution NHD. Features directly connected to the NHD stream network were identified using the Select by Location tool in ArcGIS. The Select by Location tool was then used to iteratively identify wetlands adjacent to previously selected connected features. The selection was reversed to include only unconnected polygons, which were exported to a new coverage.

Next, all polygons unconnected to the local resolution NHD were evaluated at a scale of 1:400 to determine whether they could be connected to the local resolution NHD based on visible evidence in either the LiDAR surface or the imagery. Features were then attributed as "unconnected" or "connected via a previously unmapped connection". New connections were digitized based on LiDAR surface and guided by imagery. New connection features were attributed as flowlines, ditches, or culverts etc. based on NHD standards. Metrics were then calculated to summarize the extent of palustrine features connected to local resolution NHD as amended with the new connections digitized in this project.

The Select by Location tool was also used to calculate metrics describing connectivity to medium resolution (1:100,000) and unamended local resolution (1:1,000) NHD. These metrics were calculated for both the 2005 NWI and 2022 wetlands dataset produced by this project.

3.0 Results

3.1 Wetland Mapping

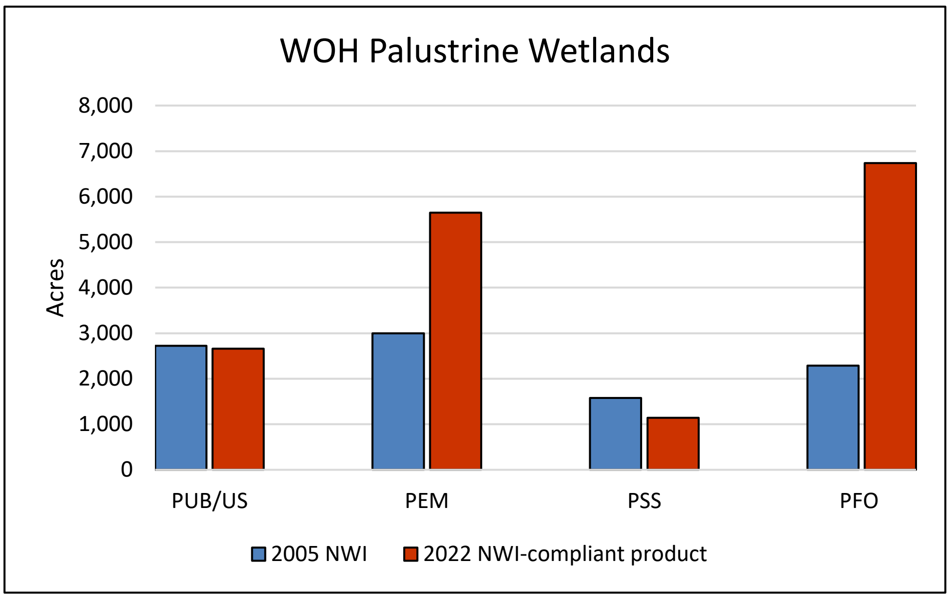
Overall, automated feature extraction followed by manual editing resulted in greater acreages of both open water and vegetated wetland habitats mapped both EOH and WOH as compared to the NWI, with some variation among cover types (Table 4).

Table 4. Acreage of wetlands and waters mapped by the 2005 NWI as compared to the NWI-complaint product produced by the current project using LiDAR-based automated feature extraction. See Table 1 and Appendix 1 for wetland/waters code descriptions.

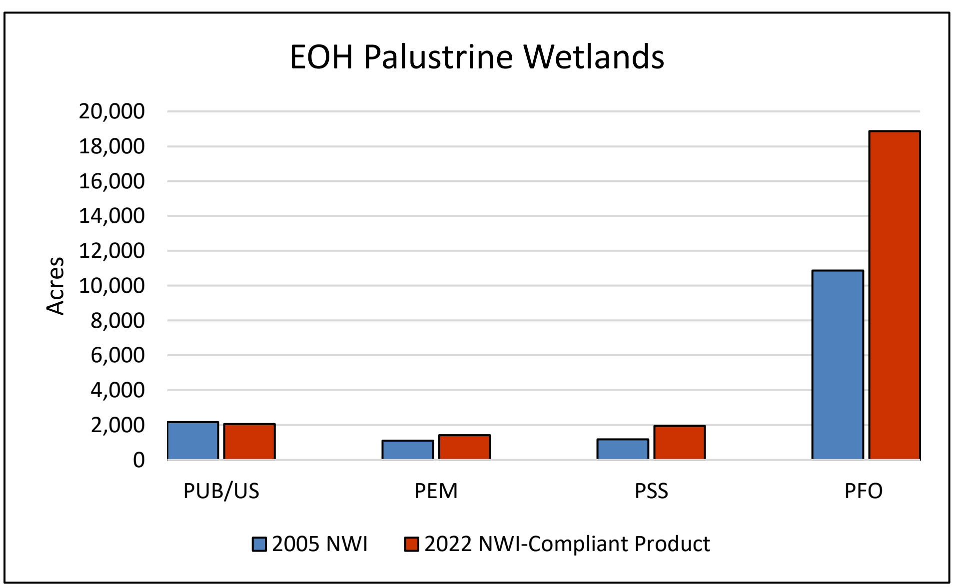
	West of Hudson			East of Hudson		
	2005 NWI	**2022 NWI-Compliant**	**Percent Change**	**Original NWI**	**2022 NWI-Compliant**	**Percent Change**
Waters/Unvegetated Systems						
RUB/RUS	1,301	5,522	324%	43	440	931%
L1UB	23,232	24,117	4%	14,939	15,603	4%
L2US	587	0	-100%	2	0	-100%
PUB/US	2,726	2,663	-2%	2,181	2,056	-6%
Total	27,846	32,301	16%	17,165	18,099	5%
Vegetated Wetlands						
PAB	0	0	0%	26	0	-100%
PEM	3,001	5,649	88%	1,101	1,417	29%
PSS	1,574	1,145	-27%	1,188	1,947	64%
PFO (total of FO1, FO4, FO5)	2,289	6,739	194%	10,864	18,876	74%
PFO1	*1,622*	*3,351*	*107%*	*10,745*	*18,633*	*73%*
PFO4	*605*	*3,384*	*459%*	*111*	*231*	*108%*
PFO5	*62*	*5*	*-92%*	*8*	*12*	*45%*
Total	6,864	13,534	97%	13,152	22,239	69%
Grand Total Waters and Vegetated Wetlands	34,710	45,835	32%	30,317	40,338	33%

Compared to the NWI, the mapped acreage of open water/unvegetated systems increased both EOH and WOH (Table 4). This is partially due to increases in mapped riverine features resulting from USFWS guidance to include perennial NHD streams and rivers as riverine systems in the updated coverage. Increases in mapped lacustrine systems (L1UB) were largely due to modification of reservoir boundaries incorporated in DEP's update of the NHD for the watershed. The adjustment of reservoir boundaries in DEP's NHD update changed the classification of areas mapped as lacustrine unconsolidated shore (L2US) in the 2005 NWI to deepwater lacustrine habitat (L1UB) in the current project. The L2US class was therefore not carried forth in the current project. There was a slight reduction in mapped ponds (PUB) both EOH and WOH. This could be due to many factors, such as succession of open water to vegetated systems and more accurate boundary delineations by the NHD and LiDAR wetlands mapping efforts.

The area of vegetated wetlands is significantly greater than that mapped in the 2005 NWI both EOH and WOH, with greater increases WOH (Table 4, Figures 11 and 12). As compared to the NWI, the area of mapped vegetated wetlands increased by 69% EOH and nearly doubled (97% increase) WOH, with the largest gains in forested wetlands in both regions. Evergreen forested wetlands WOH showed the largest gain of any vegetated wetland type, more than quadrupling in mapped acreage (Table 4). Increased detection of evergreen systems was expected since they are more difficult to identify through standard photo interpretation given their dense persistent canopies.



Figures 11 and 12. Acreage of palustrine (P) wetlands mapped by the 2005 NWI and the 2022 automated wetland mapping project. Palustrine wetland types include ponds (PUB/US), emergent (PEM), scrub-shrub (PSS) and forested (PFO) systems.



The area of emergent wetlands mapped in this project was also greater than that in the NWI, though the mapped acreage increased at a lower rate than predicted by the pilot (Tables 3 and 4, Figures 11 and 12). Some variation from the pilot results is expected due to changes in modeling protocols and because the pilot areas may not be fully representative of watershed-wide conditions. Similarly, the area of mapped scrub-shrub wetlands increased at a lower rate EOH than predicted by the pilot and decreased as compared to the NWI WOH. Based on a preliminary review, deviation from the pilot predictions of scrub-shrub wetland mapping did not affect overall wetland mapping acreages. Rather it appears that scrub-shrub areas were frequently generalized into adjacent wetland types, or mis-classified as emergent or forested types, likely due to changes in how modeling algorithms calculated average vegetation height (Figure 13). Finally, the palustrine aquatic bed class (PAB) was a minor component of the 2005 NWI and was not propagated forth into the current data. Features mapped as PAB in the NWI were manually examined and determined to be either open water (PUB) or emergent (PEM) systems.

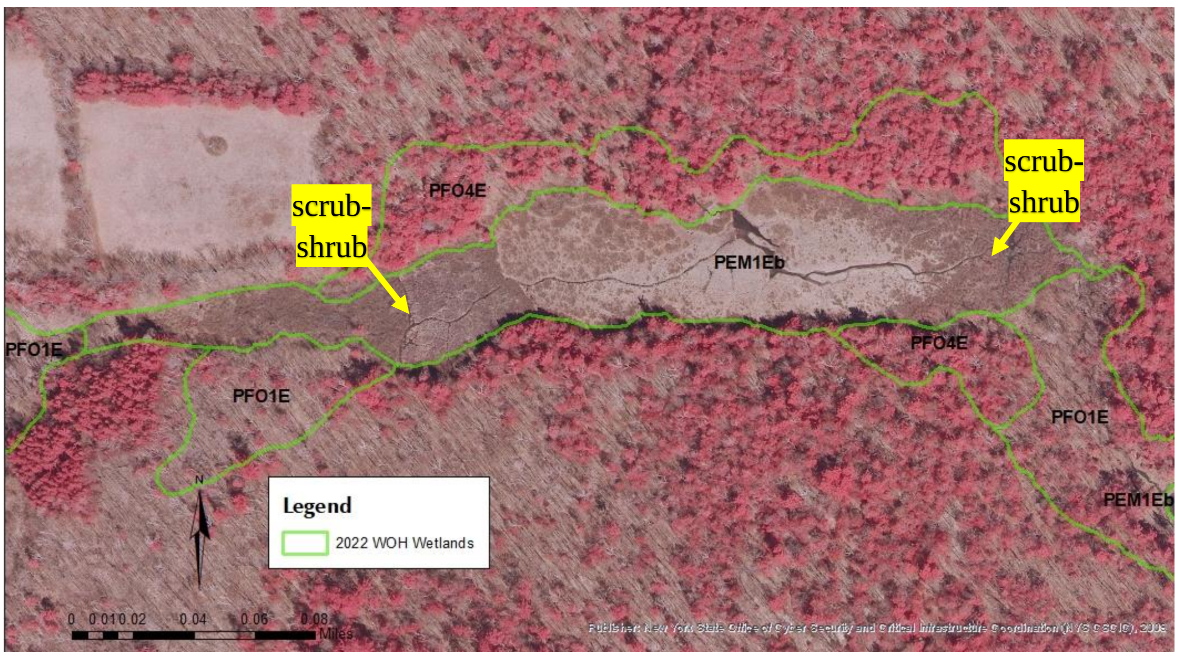


Figure 13. Dark portions within emergent wetland (PEM1b) are likely scrub-shrub areas generalized into the larger polygon.

3.2 Connectivity

Over 6,000 features were initially identified as unconnected to the local resolution NHD and subsequently evaluated for previously unmapped connections. Of the 3,179 features evaluated EOH, 2,104 were determined to be connected through previously unmapped connections. WOH, 1,118 of the 2,842 features evaluated were determined to be connected. These new connections resulted in the digitization of 257 and 166 miles of features for amendment to the local resolution NHD EOH and WOH, respectively (Figure 14).

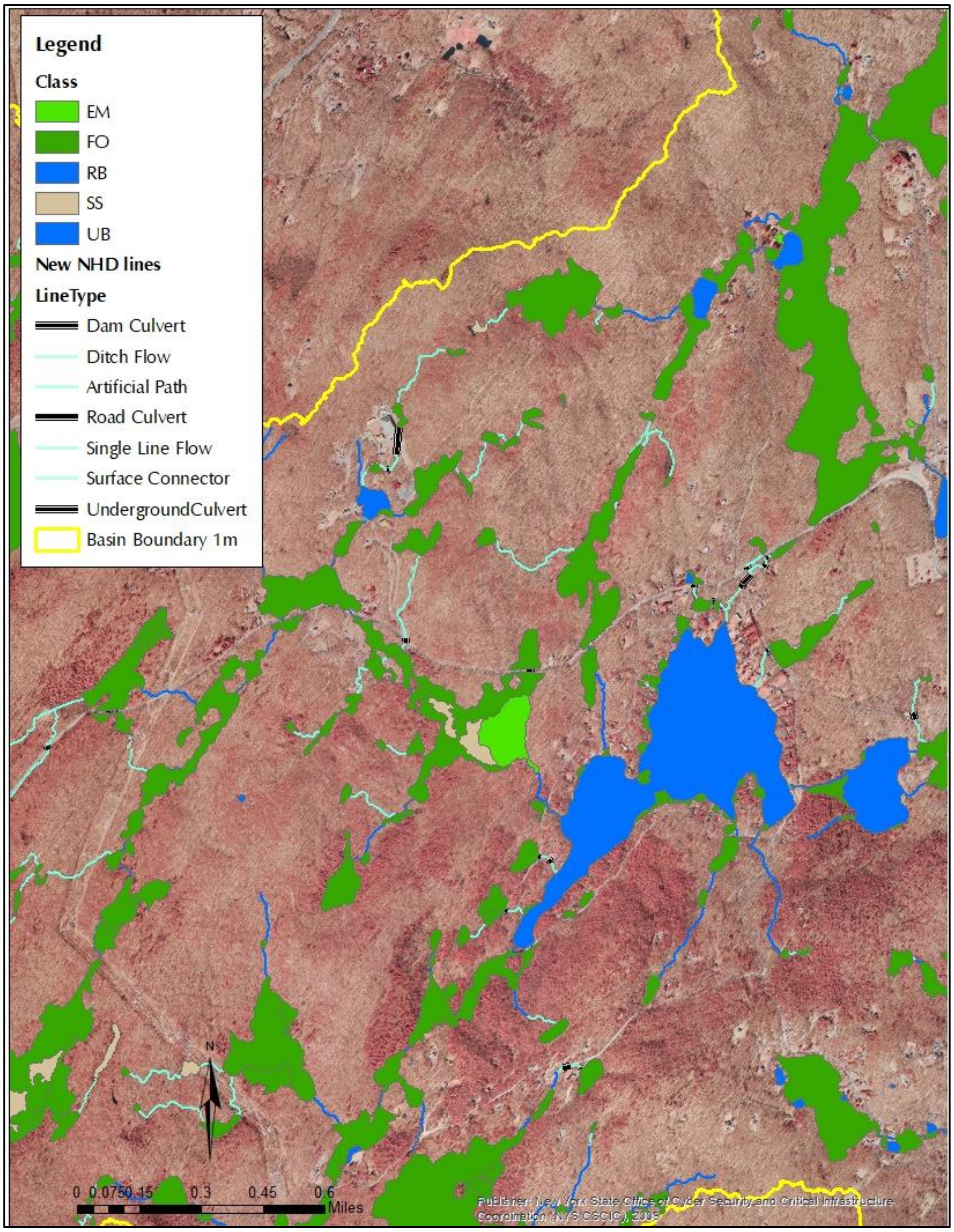


Figure 14. Portion of the Boyd Corners reservoir basin showing newly mapped wetland connection lines (turquoise) digitized in this project for amendment to the local resolution NHD. Existing NHD lines are shown in dark blue.

Metrics based on the unamended local resolution NHD show that 10% of EOH palustrine wetlands are unconnected to surface waters. After amending the NHD with the new connections identified in this project, just 2% of EOH palustrine wetlands lack surface connections to downstream waters. Similarly, the percentage of unconnected palustrine wetlands drops from 8% to 3% WOH, using the local resolution and amended local resolution NHD, respectively. This project demonstrated tremendous gains in the ability to predict wetland connectivity by using high resolution data sources. Prior to local resolution NHD availability, lower resolution sources were used to estimate wetland connectivity. Metrics using medium resolution data would estimate 35% and 54% of palustrine wetlands EOH and WOH to be unconnected, respectively (Figure 15).

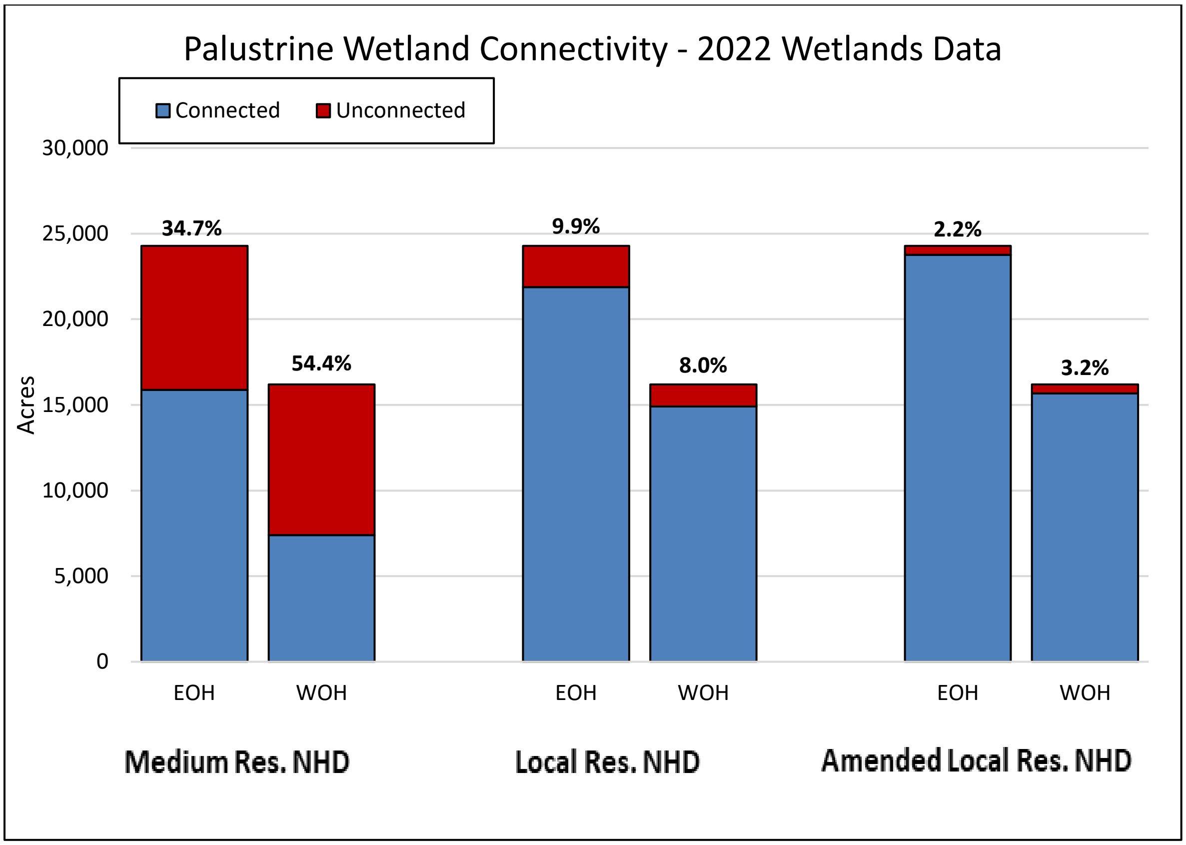


Figure 15. The percentage of connected and unconnected palustrine wetlands using the 2022 wetlands data and medium and local resolution NHD, and local resolution data as amended with new connections identified in this project. The percentages shown are for unconnected palustrine wetlands.

The percentage of unconnected palustrine vegetated wetlands did not vary significantly with cover type. The percentage of emergent, forested, and scrub shrub wetlands that are unconnected ranged from 1 to 2% (Figure 16). A larger percentage of ponds lack discernable surface water connections, which is unsurprising as many of these features are manmade features created in uplands or small isolated natural systems such as vernal pools.

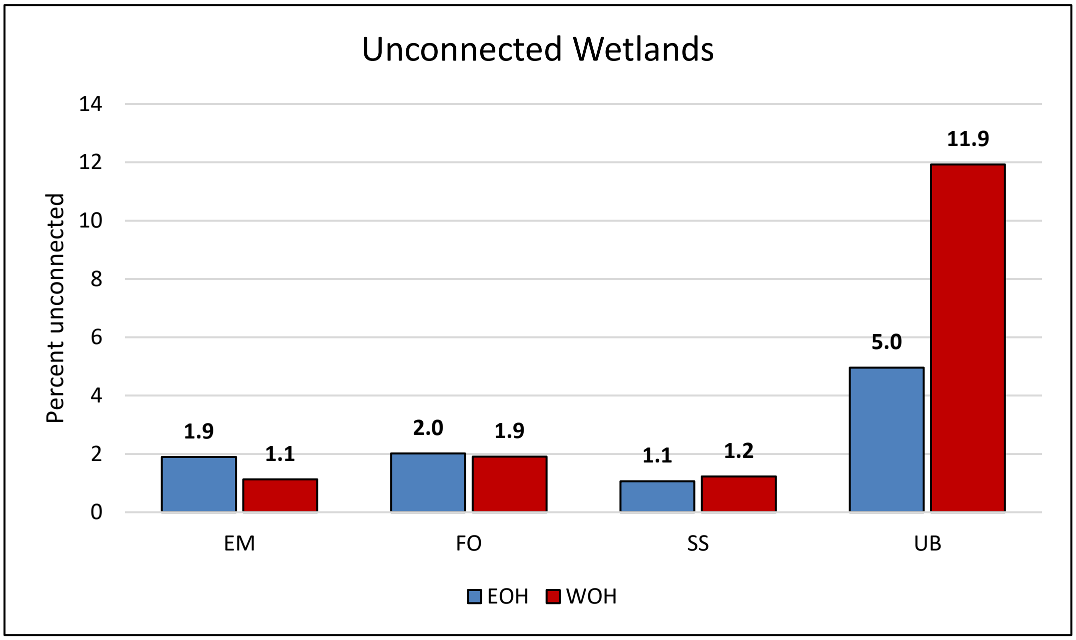


Figure 16. Percentage of unconnected wetlands within each cover type including emergent (EM), forested (FO), scrub-shrub (SS) and unconsolidated bottom (ponds, UB).

4.0 Conclusions and Future Work

As anticipated from the 2015 pilot project, the use of OBIA that incorporated high resolution LiDAR-derived datasets and orthoimagery improved the completeness of wetland mapping in the watershed, with the largest gains in wetland types that are most difficult to detect through manual photo interpretation. This project also demonstrated the utility in using high resolution data in connectivity assessment.

Updated modeling protocols resulted in smoother, more realistic boundaries and automated classifications beyond the class level to include water regime modifiers. However, the accuracy of water regimes ascribed by both this method and the NWI requires further evaluation. Automated mapping protocols are also currently unable to ascribe additional Cowardin classification modifiers such as those for areas that are phragmites-dominated, have beaver activity, or dead woody cover.

The updated protocols appear to have reduced the extent of manual editing required in the EOH watershed, but still produced significant commission WOH. It is important to note that some degree of commission is expected with automated methods, as they are designed to over map features in attempt to increase completeness. However, the appropriate balance between commission and accuracy remains elusive WOH. Significant manual editing was completed to remedy errors of commission WOH.

Additional evaluation is required to understand why there was significantly more commission WOH than EOH, but the higher prevalence of hemlock forests, higher degree of relief, and flashier tributaries are likely sources. Hemlock areas typically result in errors of omission in standard photointerpretation methods, and in commission in modeling approaches. Hemlock forests often occur in flat areas prone to flow accumulation, but the dense persistent canopy also results in fewer LiDAR ground returns, decreasing the accuracy of topographic models. The flashier hydroperiods in WOH tributaries result in frequent but not necessarily prolonged inundation. Surface accumulation models are able to detect these flow accumulation areas, but the duration of accumulated flow may not support wetland conditions in flashy areas. Additionally, the higher prevalence of wetlands EOH lowers the chance of commission as compared to WOH.

DEP will conduct accuracy assessments to evaluate errors of omission, commission, and classification both EOH and WOH. DEP will also evaluate the "Removed Wetland" database to determine whether wetland features were erroneously removed during manual editing. The wetland coverage produced by this project is undoubtedly more complete and further evaluation of these data will inform how this coverage may be applied to program implementation. Some programs, such as DEP's Forest Management Program will see immediate benefit by using these data to inform the location and extent of potential on-site wetlands in project planning. Applicability of these data to programs that require more precise information on the extent and locations of wetlands should be determined after the accuracy assessment is completed.

Amendment of local resolution NHD by adding wetland connections as determined from LiDAR surface data and high resolution orthoimagery significantly decreased the percentage of wetlands estimated to be unconnected from surface waters both EOH and WOH. While the percentage of unconnected wetlands is low, inferences may not be drawn about the flow regime or federal jurisdictional status of these connections. Some may be ephemeral, and while ecologically significant, no assumptions can be made about regulatory status.

Wetland mapping is an evolving technology, and DEP will share lessons learned with stakeholders beyond the watershed to help further advances in this field. Automated products undoubtedly increase completeness, but manual review and thorough accuracy assessments are critical to furthering the advancement of this technology and informing how the resultant data may be applied by land managers.

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List of Acronyms

CTI	Compound Topographic Index
DEM	Digital Elevation Model
DEP	New York City Department of Environmental Protection
EOH	East of Hudson
FAD	Filtration Avoidance Determination
FGDC	Federal Geographic Data Committee
LiDAR	Light Detection and Ranging
LUB	Lacustrine Unconsolidated Bottom
LULC	Land Use/Land Cover
nDSM	Normalized Digital Surface Model
NDVI	Normalized Difference Vegetation Index
NHD	National Hydrography Dataset
NIR	Near Infrared
NWI	National Wetlands Inventory
OBIA	Object Based Image Analysis
PAB	Palustrine Aquatic Bed
PEM	Palustrine Emergent
PFO	Palustrine Forested
PSS	Palustrine Scrub-Shrub
PUB	Palustrine Unconsolidated Bottom
RSS	Riverine Scrub-Shrub
RUB	Riverine Unconsolidated Bottom
TMU	Target Mapping Unit
USFWS	United States Fish and Wildlife Service
WOH	West of Hudson

Appendix A

Wetlands and Deepwater Habitats Classification (FGDC 2013)

WETLANDS AND DEEPWATER HABITATS CLASSIFICATION

System: M - Marine

- **Subsystem: 1 - Subtidal**
  - **Class: RB – Rock Bottom**
    - Subclass: 1 Bedrock; 2 Rubble
  - **Class: UB – Unconsolidated Bottom**
    - Subclass: 1 Cobble-Gravel; 2 Sand; 3 Mud
  - **Class: AB – Aquatic Bed**
    - Subclass: 1 Algal; 3 Rooted Vascular
  - **Class: RF – Reef**
    - Subclass: 1 Coral; 3 Worm
- **Subsystem: 2 - Intertidal**
  - **Class: AB – Aquatic Bed**
    - Subclass: 1 Algal; 3 Rooted Vascular
  - **Class: RF – Reef**
    - Subclass: 1 Coral; 3 Worm
  - **Class: RS – Rocky Shore**
    - Subclass: 1 Bedrock; 2 Rubble
  - **Class: US – Unconsolidated Shore**
    - Subclass: 1 Cobble-Gravel; 2 Sand; 3 Mud; 4 Organic

System: E - Estuarine

- **Subsystem: 1 - Subtidal**
  - **Class: RB – Rock Bottom**
    - Subclass: 1 Bedrock; 2 Rubble
  - **Class: UB – Unconsolidated Bottom**
    - Subclass: 1 Cobble-Gravel; 2 Sand; 3 Mud; 4 Organic
  - **Class: AB – Aquatic Bed**
    - Subclass: 1 Algal; 3 Rooted Vascular; 4 Floating Vascular
  - **Class: RF – Reef**
    - Subclass: 2 Mollusk; 3 Worm
- **Subsystem: 2 - Intertidal**
  - **Class: AB – Aquatic Bed**
    - Subclass: 1 Algal; 3 Rooted Vascular; 4 Floating Vascular
  - **Class: RF – Reef**
    - Subclass: 2 Mollusk; 3 Worm
  - **Class: SB – Streambed**
    - Subclass: 1 Bedrock; 2 Rubble; 3 Cobble-Gravel; 4 Sand; 5 Mud; 6 Organic
  - **Class: RS – Rocky Shore**
    - Subclass: 1 Bedrock; 2 Rubble
  - **Class: US – Unconsolidated Shore**
    - Subclass: 1 Cobble-Gravel; 2 Sand; 3 Mud; 4 Organic
  - **Class: EM – Emergent**
    - Subclass: 1 Persistent; 2 Non-persistent; 5 *Phragmites australis*
  - **Class: SS – Scrub-Shrub**
    - Subclass: 1 Broad-Leaved Deciduous; 2 Needle-Leaved Deciduous; 3 Broad-Leaved Evergreen; 4 Needle-Leaved Evergreen; 5 Dead; 6 Deciduous; 7 Evergreen
  - **Class: FO – Forested**
    - Subclass: 1 Broad-Leaved Deciduous; 2 Needle-Leaved Deciduous; 3 Broad-Leaved Evergreen; 4 Needle-Leaved Evergreen; 5 Dead; 6 Deciduous; 7 Evergreen

System: R - Riverine

- **Subsystem:** 1 - Tidal; 2 – Lower Perennial; 3 – Upper Perennial; 4* - Intermittent
  - **Class: RB** – Rock Bottom**
    - Subclass: 1 Bedrock; 2 Rubble
  - **Class: UB – Unconsolidated Bottom**
    - Subclass: 1 Cobble-Gravel; 2 Sand; 3 Mud; 4 Organic
  - **Class: AB – Aquatic Bed**
    - Subclass: 1 Algal; 2 Aquatic Moss; 3 Rooted Vascular; 4 Floating Vascular
  - **Class: SB*** – Streambed**
    - Subclass: 1 Bedrock; 2 Rubble; 3 Cobble-Gravel; 4 Sand; 5 Mud; 6 Organic; 7 Vegetated
  - **Class: RS – Rocky Shore**
    - Subclass: 1 Bedrock; 2 Rubble
  - **Class: US – Unconsolidated Shore**
    - Subclass: 1 Cobble-Gravel; 2 Sand; 3 Mud; 4 Organic; 5 Vegetated
  - **Class: EM - Emergent**
    - Subclass: 2 Nonpersistent

* **Intermittent** is limited to the **Streambed** Class
** **Rock Bottom** is not permitted for the **Lower Perennial** Subsystem
*** **Streambed** is limited to **Tidal** and **Intermittent** Subsystems

Federal Geographic Data Committee, 2013. Classification of Wetlands and Deepwater Habitats of the United States.

February, 2019

WETLANDS AND DEEPWATER HABITATS CLASSIFICATION

System: L - Lacustrine

Subsystem: 1 - Limnetic

Class	RB – Rock Bottom	UB – Unconsolidated Bottom	AB – Aquatic Bed
Subclass	1 Bedrock 2 Rubble	1 Cobble-Gravel 2 Sand 3 Mud 4 Organic	1 Algal 2 Aquatic Moss 3 Rooted Vascular 4 Floating Vascular

Subsystem: 2 - Littoral

Class	RB – Rock Bottom	UB – Unconsolidated Bottom	AB – Aquatic Bed	RS – Rocky Shore	US – Unconsolidated Shore	EM – Emergent
Subclass	1 Bedrock 2 Rubble	1 Cobble-Gravel 2 Sand 3 Mud 4 Organic	1 Algal 2 Aquatic Moss 3 Rooted Vascular 4 Floating Vascular	1 Bedrock 2 Rubble	1 Cobble-Gravel 2 Sand 3 Mud 4 Organic 5 Vegetated	2 Nonpersistent

System: P - Palustrine

Class	RB – Rock Bottom	UB – Unconsolidated Bottom	AB – Aquatic Bed	US – Unconsolidated Shore	ML – Moss-Lichen	EM – Emergent	SS – Scrub-Shrub	FO – Forested
Subclass	1 Bedrock 2 Rubble	1 Cobble-Gravel 2 Sand 3 Mud 4 Organic	1 Algal 2 Aquatic Moss 3 Rooted Vascular 4 Floating Vascular	1 Cobble-Gravel 2 Sand 3 Mud 4 Organic 5 Vegetated	1 Moss 2 Lichen	1 Persistent 2 Nonpersistent 5 *Phragmites australis*	1 Broad-Leaved Deciduous 2 Needle-Leaved Deciduous 3 Broad-Leaved Evergreen 4 Needle-Leaved Evergreen 5 Dead 6 Deciduous 7 Evergreen	1 Broad-Leaved Deciduous 2 Needle-Leaved Deciduous 3 Broad-Leaved Evergreen 4 Needle-Leaved Evergreen 5 Dead 6 Deciduous 7 Evergreen

MODIFIERS

In order to more adequately describe the wetland and deepwater habitats, one each of the water regime, water chemistry, soil, or special modifiers may be applied at the class or lower level in the hierarchy.

Water Regime			Special Modifiers	Water Chemistry		Soil
Nontidal	**Saltwater Tidal**	**Freshwater Tidal**		**Halinity/Salinity**	**pH Modifiers for Fresh Water**	
A Temporarily Flooded B Seasonally Saturated C Seasonally Flooded D Continuously Saturated E Seasonally Flooded / Saturated F Semipermanently Flooded G Intermittently Exposed H Permanently Flooded J Intermittently Flooded K Artificially Flooded	L Subtidal M Irregularly Exposed N Regularly Flooded P Irregularly Flooded	Q Regularly Flooded-Fresh Tidal R Seasonally Flooded-Fresh Tidal S Temporarily Flooded- Fresh Tidal T Semipermanently Flooded-Fresh Tidal V Permanently Flooded-Fresh Tidal	b Beaver d Partly Drained/Ditched f Farmed m Managed h Diked/Impounded r Artificial Substrate s Spoil x Excavated	1 Hyperhaline / Hypersaline 2 Euhaline / Eusaline 3 Mixohaline / M ixosaline (Brackish) 4 Polyhaline 5 Mesohaline 6 Oligohaline 0 Fresh	a Acid t Circumneutral i Alkaline	g Organic n Mineral

Federal Geographic Data Committee, 2013. Classification of Wetlands and Deepwater Habitats of the United States.