planYC

PRELIMINARY SURVEY OF WETLAND AREAS

SEPTEMBER 2010

A GREENER, GREATER NEW YORK

NYC Environmental Protection

The City of New York
Mayor Michael R. Bloomberg

This page left blank intentionally. Please print this document using the double-sided printer setting.

Introduction

The protection of wetlands is a key initiative of PlaNYC, the City's plan for a greener, greater New York. The City plays an active role in the stewardship of wetlands as an owner and manager of thousands of acres of wetlands. The City also works closely with State and Federal partners to establish regulations that restrict development in wetland areas.

As part of PlaNYC, the City released *New York City Wetlands: Regulatory Gaps and Other Threats* in January 2009 to identify areas not effectively addressed in Federal and State laws. This report found that existing Federal and State protections protect New York City's tidal wetlands and large freshwater wetlands from threats related to land use and development. Freshwater wetlands smaller than 12.4 acres are mostly not protected by State law and are vulnerable to determinations that they are outside of the scope of Federal protection. Unfortunately, the extent and location of these smaller freshwater wetlands is not accurately known, and therefore we cannot determine the appropriate policy prescriptions to fill the regulatory gap without new wetlands maps.

The New York City Council passed Local Law 31 of 2009, which designates the Mayor's Office of Long-Term Planning and Sustainability to create a citywide wetlands strategy by no later than March 1, 2012. This law also requires the City to submit by September 1, 2010 a "preliminary survey of likely wetland areas based upon satellite or aerial imagery." Pursuant to this requirement, the following pages contain preliminary wetlands maps as well as a technical paper explaining methodology used to develop these maps. This work was completed by the Lamont-Doherty Earth Observatory at Columbia University under the management of the New York City Department of Environmental Protection.

The process of mapping inevitably results in some distortion and loss of information. Mapping wetlands is particularly challenging because of their complex and dynamic nature. Wetlands change continuously in response to the water table and tidal height, erosion, sedimentation, and ecological succession of vegetation communities.

This preliminary survey was completed by combining current, high-resolution satellite imagery with archival imagery to identify potential wetland areas on the basis of multiple factors such as topography, soil moisture, standing water, and vegetation dynamics. These maps utilize an alternative approach to traditional wetlands mapping. Prior to this effort, most wetland maps have been based on visual interpretation of aerial photographs followed by field verification. This process of visual interpretation and manual digitizing of wetland boundaries is inherently subjective, time consuming, expensive, difficult to update, and potentially error-prone.

This preliminary wetlands survey provides a unique perspective that is impossible to obtain from the ground. While remote sensing does not eliminate the need for field verification, this imagery does provide a valuable reconnaissance tool to help scientists and decision-makers focus field validation efforts. This effort is the first step in a long process to correctly identify and better interpret the data on the maps.

The enclosed maps depict a range of wetlands by showing the potential minimum and potential maximum extent of wetlands areas as identified using remote-sensing satellite imagery. As such, these preliminary surveys are not yet definitive wetlands maps; instead, they illustrate potential wetland areas that require further analysis and field verification. With refinements to the methodology and field verification, this preliminary wetlands survey has the potential to evolve into a final wetlands map.

These maps are subject to limitations in accuracy as a result of the available data, the methodology used in their development, and the inherent challenge of depicting a dynamic environment in a static map. Many areas that are currently regulated as wetlands by the New York State Department of Environmental Conservation (DEC) were not identified as potential wetlands through this preliminary survey. These areas should be field verified to identify the presence of wetlands. Therefore, these maps should not be used to develop or comply with land use regulations.

In spite of the limitations in this preliminary wetlands survey, the results highlight inconsistencies between existing DEC maps (which were created in 1974 for tidal wetlands and from 1987-1995 for freshwater wetlands) and the potential current extents of wetlands in NYC.

The enclosed maps are an important step toward better understanding the location and extent of wetlands in New York City; however, additional analysis and field verification is needed to finalize these maps and resolve some of the outstanding questioned outlined above. The enclosed technical paper describes potential refinements to the methodology and offers possible next steps. The City will work with DEC and other partners to explore opportunities to turn these preliminary surveys into a final wetlands map for New York City. This effort will be incorporated into the process to create a citywide wetlands strategy.

NYC Environmental Protection

Preliminary Minimum Extent of Wetlands
for Bronx, Brooklyn, Manhattan and Queens Using Satellite Imagery

Lamont-Doherty Earth Observatory of Columbia University

planYC

Copyright:© 2010 i-cubed

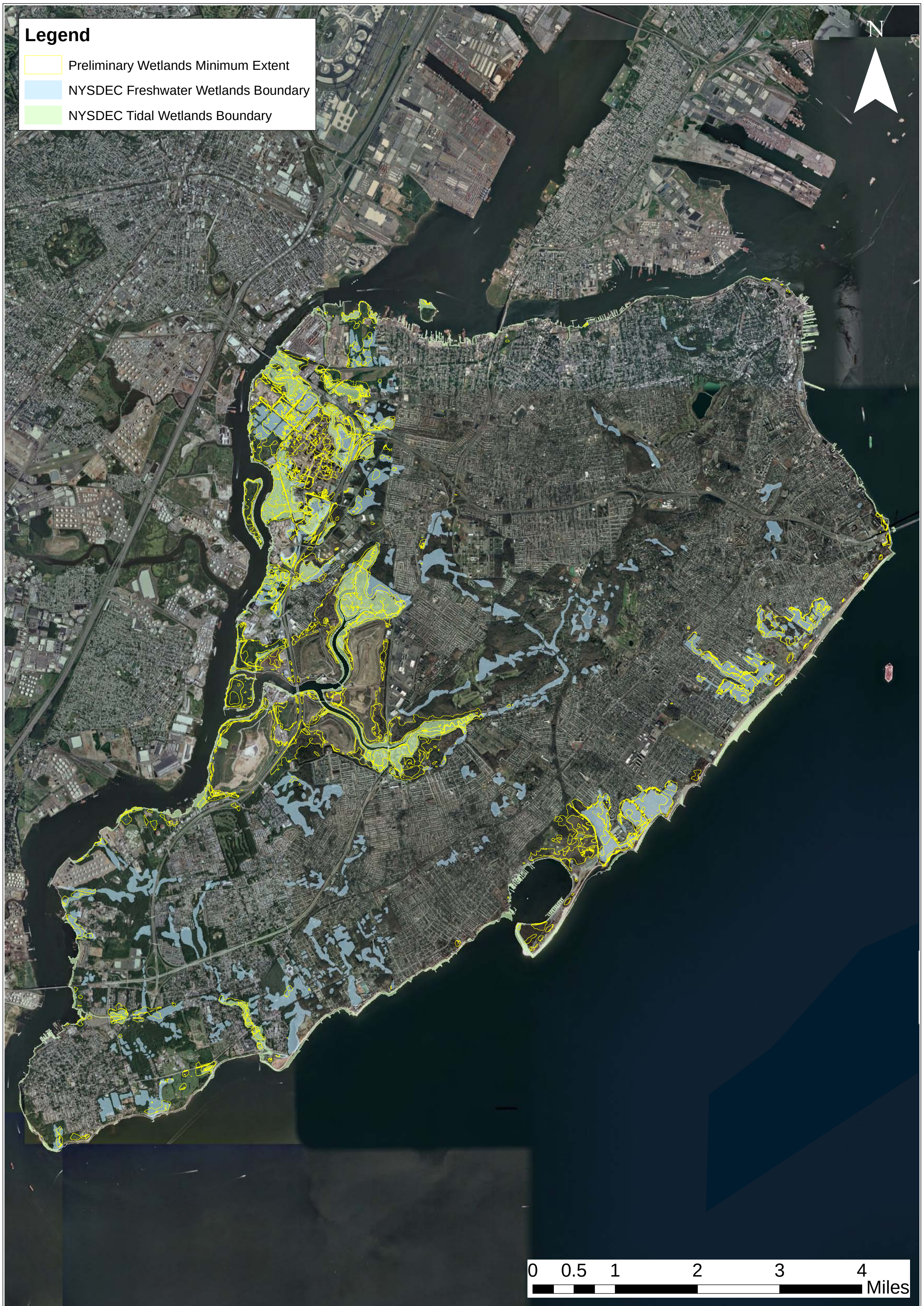
Preliminary Maximum Extent of Wetlands
for Bronx, Brooklyn, Manhattan and Queens Using Satellite Imagery

NYC Environmental Protection

planYC

Lamont-Doherty Earth Observatory of Columbia University

Copyright:© 2010 i-cubed



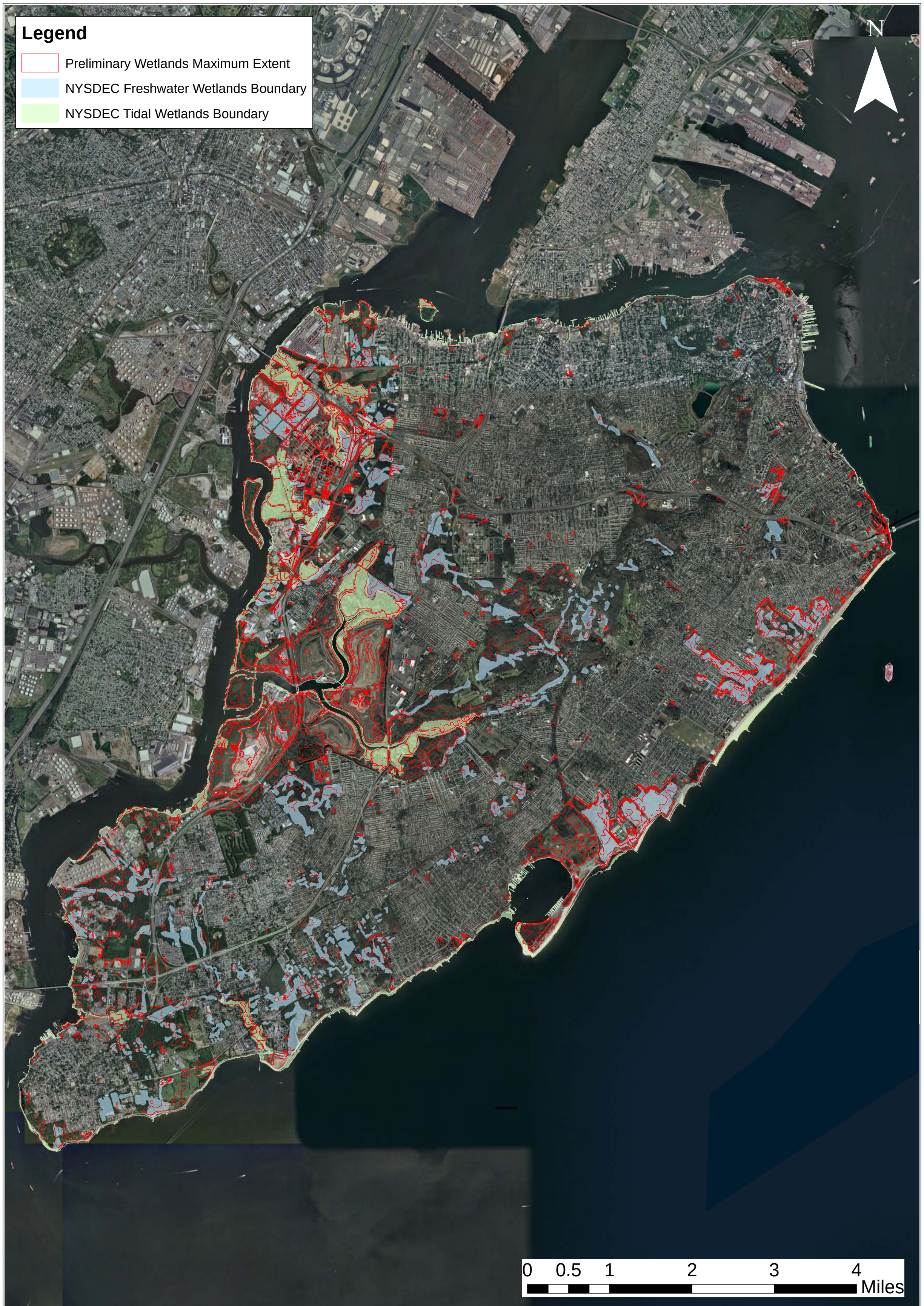
NYC Environmental Protection

Preliminary Minimum Extent of Wetlands
for Staten Island Using Satellite Imagery

Lamont-Doherty Earth Observatory of Columbia University

planYC

Copyright:© 2010 i-cubed



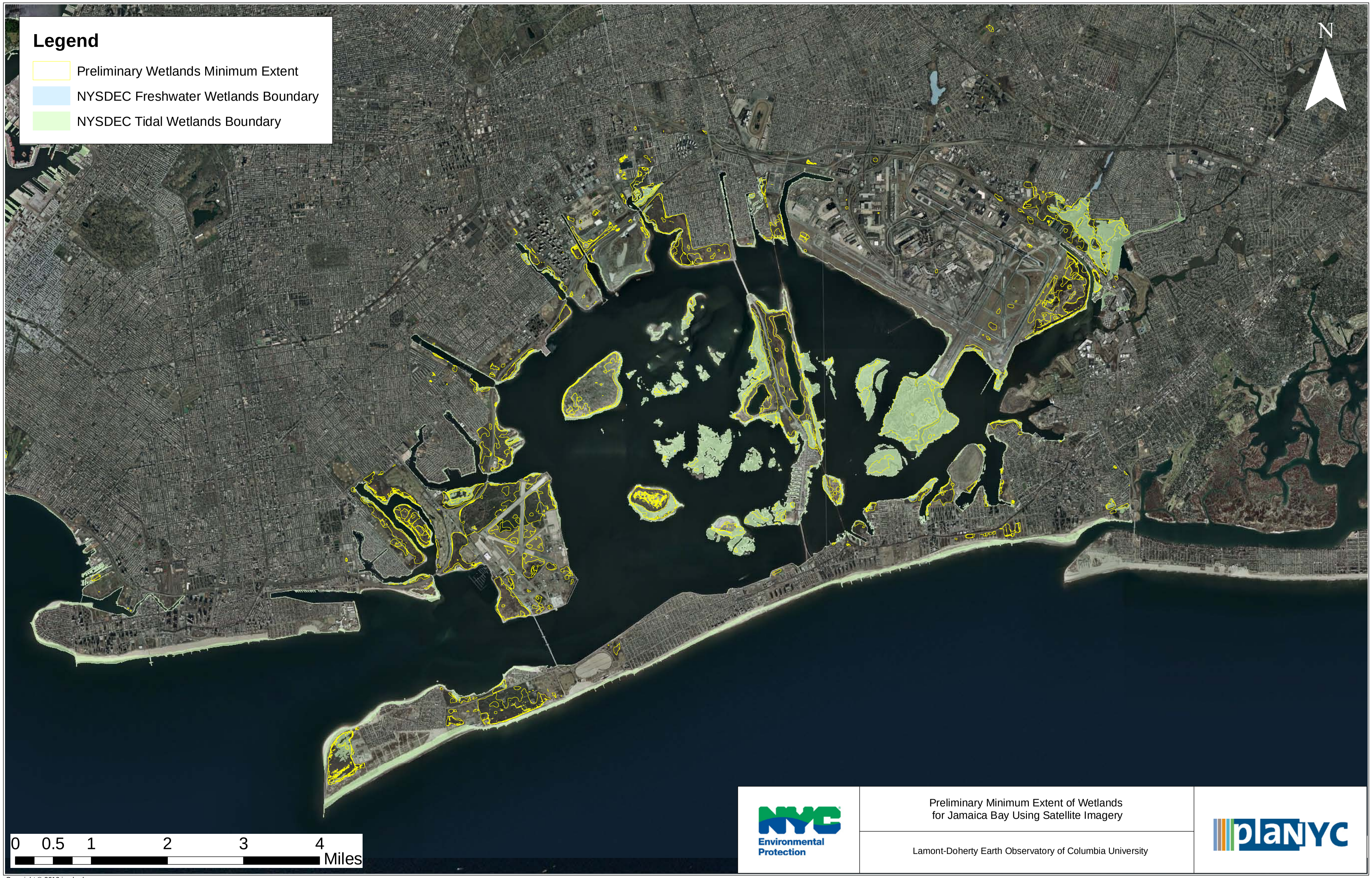
Preliminary Maximum Extent of Wetlands
for Staten Island Using Satellite Imagery

Lamont-Doherty Earth Observatory of Columbia University

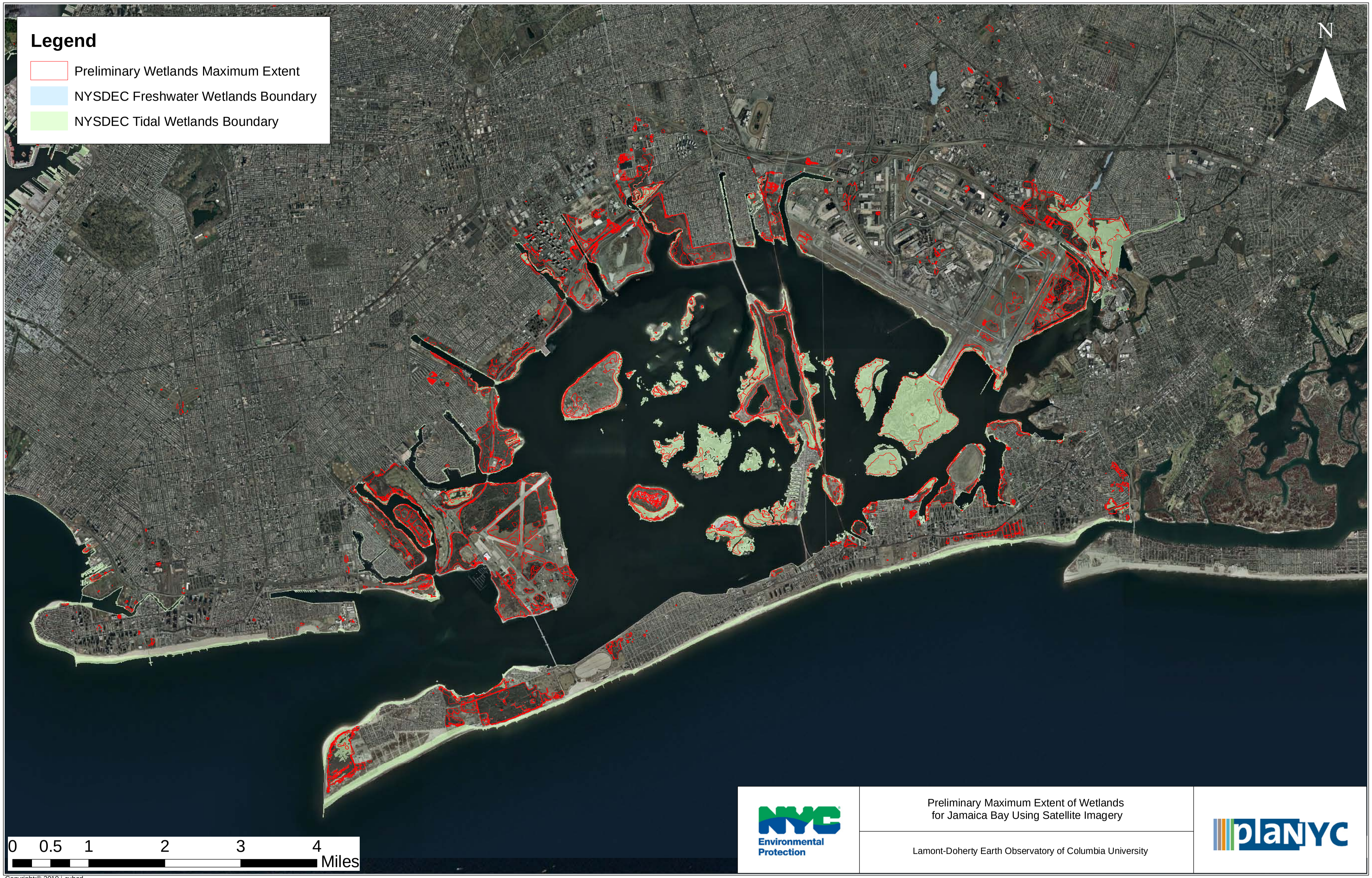
NYC Environmental Protection

planYC

Copyright:© 2010 i-cubed



Copyright:© 2010 i-cubed



Copyright:© 2010 i-cubed

This page left blank intentionally.

Preliminary Dynamic Reconnaissance Wetlands Mapping in New York City

Prepared by

Christopher Small

Lamont-Doherty Earth Observatory
Columbia University

For the New York City Department of Environmental Protection

September 1, 2010

Executive Summary

Traditional methods of mapping wetland extent by manual interpretation of aerial photographs are labor intensive and result in a static product that is difficult to update. The increasing availability, and diminishing cost, of high resolution satellite imagery, combined with deep archives of moderate resolution imagery collected since the early 1980s, may allow for an alternative approach to wetland mapping and monitoring. Decision tree classification systems, combined with multi-temporal satellite imagery and GPS-enabled field observations, make it feasible for NYC to develop and implement a Dynamic Reconnaissance Wetlands Mapping (DRWM) system. Decision tree classification allows wetland extent maps to be produced and updated continuously without the need for collection and manual interpretation of air photos. Combining current, relatively inexpensive, high resolution satellite imagery with archival imagery makes it possible to identify potential wetland areas on the basis of multiple factors such as topography, soil moisture, standing water and vegetation dynamics. This report describes a feasibility study to develop a first generation DRWM system to generate bounding spatial extents for potential wetland areas not identified in existing wetland maps.

The Perfect Wetland Map

No map is perfect. The process of mapping inevitably results in some distortion and loss of information. It is important to understand the limitations of any map before drawing conclusions from it. Mapping wetlands is challenging because of their complex and dynamic nature. Wetlands change continuously in response to the water table and tidal height, erosion, sedimentation and ecological succession of vegetation communities. Mapping wetlands using remotely sensed imagery is particularly challenging because some of the most important features of wetlands can be very difficult to identify in imagery. However, remote sensing does provide a unique synoptic perspective that is impossible to obtain from the ground. Remote sensing does not obviate the need for field verification but remotely sensed imagery does provide a valuable reconnaissance tool to help scientists and decision-makers focus field validation efforts.

To date, most wetland maps have been based on visual interpretation of aerial photographs – supplemented by field validation. The process of visual interpretation and manual digitizing of wetland boundaries is inherently subjective, time consuming, expensive and potentially error-prone. Because the mapped wetland boundaries are based on the knowledge and experience of the individual interpreter, it is difficult to accurately quantify changes in wetlands using maps produced by different interpreters. The disparity between the features and functions of wetlands further complicate efforts to depict their complexity on static maps. The analysis described in this report is intended to eventually help streamline and standardize the wetland mapping process by producing reconnaissance maps that accommodate the dynamic nature of wetlands. The objective is to produce a map that can be easily updated and serves multiple purposes for both scientists and decision-makers as well as satisfying the needs of regulators. The approach described here is intended to facilitate the mapping process and reduce the time and effort required to produce wetland maps.

This report introduces the concept of the ***Dynamic Reconnaissance Wetlands Map*** (DRWM). It describes preliminary analyses to assess the feasibility of using ***Decision Tree Classification*** as a tool for producing reconnaissance maps from remotely sensed measurements of land surface properties. The DRWM can be used as part of an iterative process of refinement and validation by scientists conducting field surveys. The map is dynamic in the sense that it can be continuously updated with new information without the need to duplicate the interpretation process. The map is a reconnaissance tool because it highlights potential wetland sites for focused field validation thereby saving time and effort. Because it is based on explicit criteria applied to actual measurements, the basis for each land cover class is clearly defined and easily refined as warranted by new information. As the name suggests, decision tree classification uses a sequence of Yes or No decisions to classify each geographic location on the map as one of a limited number of land cover classes. The appeal of the decision tree is both its intuitive simplicity and its flexibility.

Caveats and Warnings

The primary caveats of the DRWM are related to the limitations of the input data and the inherent challenge of depicting a dynamic environment in a static map. The DRWM is intended to demonstrate proof of concept for a process of iterative mapping. As such, it is not yet a definitive wetland map – although it has the potential to evolve into one. Like all maps, the DRWM is subject to both ***error of commission*** (misidentification) and ***error of omission*** (missed identification). In comparison to existing wetland maps, both types of error will be apparent – in both the DRWM and existing maps. In spite of the limitations in the preliminary DRWM, it does highlight inconsistencies between existing wetland maps (which are now several years old) and the current extents of wetlands in NYC. Numerous examples of these inconsistencies are given in the Examples section of this report.

It is important to recognize the preliminary DRWM as the first step in a process of iterative refinement. This preliminary version provides a relatively simple illustration of how three new types of input can be combined with a new mapping tool to provide a new type of wetland map. If this new mapping approach is adopted, additional inputs could be incorporated to improve the accuracy and flexibility of the resulting maps. Several of these inputs are described near the end of the report. The intention is develop the DRWM as a tool for both scientists and decision-makers to produce a dynamic map that will eventually surpass the existing maps in both accuracy and detail. However, the DRWM is subject to several caveats described below.

The maps presented here are not definitive wetland maps. Rather they are intended to represent potential wetland areas that may warrant field verification. The reconnaissance map can provide the cartographic basis for regulatory wetland maps but only when supplemented by extensive field validation. In many cases, the actual boundary of a wetland may be difficult to identify – even by an experienced wetland ecologist in the field. However regulatory wetland maps are required to identify wetland extents with discrete boundaries. If the spatial extent of the wetland changes, the boundary on the map will no longer be accurate. This is part of the rationale for developing a dynamic wetland map that is easily updated without the need to replicate the entire interpretation process.

The challenge of mapping wetlands is related to their dynamic nature. While many maps represent relatively static features on the landscape, wetlands change constantly in response to fluctuations in sea level and the water table – as well as geomorphic processes like erosion and sedimentation. This is part of the rationale for using remotely sensed imagery as inputs to the DRWM. Remotely sensed imagery offers the benefit of a synoptic (i.e. snapshot) view of an entire region at one instant in time – extendable through time by repeat imaging. Dynamic environments like wetlands and other coastal environments require repeated imaging to capture change on different time scales. A major benefit of satellite imagery is the capacity for repeat imaging from the same vantage point at a fraction of the cost of an airborne survey without the logistical complexity of navigating an already crowded airspace. Repeat satellite imaging makes it possible to stack images collected at different times to depict spatial and temporal changes. This is the basis of the vegetation phenology map on which the DRWM is based.

Maps derived from remotely sensed measurements have two primary limitations: Non-uniqueness and limited spatial resolution. ***Non-uniqueness*** arises from the fact that different land cover types can be the same color (or indistinguishably different). For example, the color of soil changes with moisture content. The same soil is darker when wet than when dry. The same moisture darkening process applies to asphalt and cement as well. Soils span a wide range of colors when dry and an even wider range when wet. Asphalt tends to become lighter in color with exposure to sun and rain. Cement tends to become darker with exposure to dirt and soot. For this reason, soils are often spectrally indistinguishable from asphalt and cement. This is rarely a problem for the human eye-brain system because it relies on shape, texture and spatial context more than color to identify land cover. However, computer algorithms operating on remotely sensed images still rely primarily on color and are therefore vulnerable to spectral non-uniqueness. The evolving field of computer vision and object-based classification attempts to replicate the processes used by the human eye-brain system. Decision trees provide the logical basis for object-based classification and offer an intuitive tool for mapping based on the same criteria that expert interpreters use when digitizing boundaries from air photos. Decision trees offer the benefit or repeatability, transparency and consistent application of clearly defined criteria. A partial solution to the problem of spectral non-uniqueness is to make use of a wider range of colors as described in greater detail below.

Spatial resolution of a sensor determines the smallest object or feature it can accurately represent. Optical sensors are basically digital cameras. The spatial resolution is the size of the individual pixels that comprise the image. Objects smaller than the pixel resolution contribute to the aggregate brightness of the pixel but are not recognizable since they are smaller than the pixel. Objects slightly larger than the pixel are resolved but are rarely recognizable. Generally, objects must be several times larger than the pixel size to be distinguished reliably. The two types of satellite imagery used in this analysis have spatial resolutions of 2 meters (6.6 feet) and 30 meters (98 feet) so one sensor is capable of resolving individual houses and trees but the other can only detect their presence or absence by their contribution to the overall color of the pixel. The fixed spatial resolution of the imaging sensors limits our ability to recognize characteristic features on the landscape. However, a partial solution this problem is provided by repeat imaging. This allows us to characterize landscape features not only by their instantaneous appearance but by the way it changes through time. This is the basis of mapping different vegetation types by their annual phonological cycle of greening and senescence. The following sections first explain the process of static imaging of infrared color then explain the process of multi-temporal imaging of land cover change processes.

Mapping From Space

The analysis described here is based on two types of remotely sensed imagery and an elevation model derived from radar. The sensor on the ***WorldView-2*** satellite images in 8 spectral bands (colors) at 2 meter resolution. Five of the spectral bands are at visible wavelengths and measure colors seen by the human eye. Three of the spectral bands are at infrared wavelengths not detected by the human eye. Combining the relative brightnesses of these spectral bands allows us to distinguish billions of visible and infrared colors. In addition, WorldView-2 collects panchromatic (gray shade) imagery at 50 cm (~1.6 feet) resolution. Panchromatic imagery is useful for visual interpretation but not used for spectral classification.

The Thematic Mapper sensors on the ***Landsat 5*** and ***Landsat 7*** satellites image in three visible and three infrared spectral bands at 30 meter resolution. In addition, the Thematic Mapper sensors image surface temperature at 120 meter (Landsat 5) and 60 meter (Landsat 7) resolution. The challenge of working with Landsat imagery is related to the relatively coarse spatial resolution. The benefits of working with Landsat imagery are the excellent calibration between sensors through time, the 16 day repeat imaging cycle (weather permitting), the wide swath (180 km), the low cost (free), and the 27+ year archive. Since 1982, the Landsat sensors have collected over 300 partially or totally cloud-free images of NYC. This makes it possible to map land cover changes on decadal time scales. This also makes it possible to map different types of vegetation on the basis of phenology. Phenology describes the familiar annual cycle of green-up and senescence by which deciduous trees produce and shed leaves. Grasses and other herbaceous vegetation also have characteristic phonological cycles distinct from those of deciduous trees. Mapping vegetation phenology provides a new and valuable tool for distinguishing wetlands on the basis of vegetation type and its response to temperature. This is described in greater detail below. A comparison of Landsat and WorldView-2 imagery is shown in Figure 1.

The third type of imagery used in the DRWM is synthetic aperture radar used to produce Digital Elevation Models (DEM). The NASA ***Shuttle Radar Topography Mission*** (SRTM) used synthetic aperture radar on board the space shuttle Endeavor to map global topography at a spatial resolution of 30 meters in February 2000. The DEM derived from these data is used to constrain wetland extent on the basis of elevation above sea level.

This initial version of the DRWM is based primarily on vegetation. Mapping vegetation from space is relatively straightforward because vegetation has a unique spectral signature (i.e. color). At visible wavelengths, vegetation foliage is relatively dark because pigments in leaves absorb red and blue light to derive energy for photosynthesis. Leaves appear green to the human eye because red and blue light are selectively absorbed while green light is reflected. However, vegetation is extremely reflective (bright) at near infrared wavelengths. This visible/infrared contrast is what makes vegetation spectrally distinctive from other types of land cover. Different types of vegetation (e.g. trees and grass) can often be distinguished on the basis of internal shadow related to canopy structure and height variations. In this analysis, we use multi-scale spectral mixture analysis (described in detail in Small and Lu, 2005) to derive vegetation fraction maps from both Landsat and WorldView-2 imagery. These maps provide estimates of the vegetated area of each pixel at the time the image was captured. For the WorldView-2 imagery this provides a high resolution (2 m) map of vegetation abundance on the two dates that different parts of NYC were imaged (23 April and 1 May 2010). On these dates, lawn grasses and herbaceous vegetation (i.e. weeds) were fully green and tree canopies were partially leafed out. However, most wetland vegetation had not yet emerged so wetland areas did not yet show vegetation signatures. In addition to vegetation, bright substrates (soils, sands, mud flats and rocks), shadows, water and dark surfaces can also be distinguished. However, because of the non-uniqueness issues described above, dark features like shadows, wet soils, muds and shallow water are often very difficult to distinguish from one another.

The non-uniqueness issue is a fundamental limitation of using reflected sunlight as a mapping tool. While sunlight is free and abundant and conveys a tremendous amount of information, it is also limited by clouds and shadowing. However, we can supplement the information provided by the color of land cover with information on the shape, texture and elevation of the land surface. The elevation model described above provides a coarse depiction of the land surface elevation at a spatial resolution of 30 meters but most of the distinctive features we use to identify wetlands are considerably smaller than 30 meters and are not resolved in the SRTM data. Fortunately, NYC has recently contracted Sanborn LLC to collect very detailed Light Detection and Ranging (LiDAR) elevation measurements for all of NYC. In April 2010, airborne laser scanners imaged the 3D structure of the entire city at with a point density of 8 to 12 point measurements per square meter. These LiDAR measurements make it possible to map not only the elevation but the surface texture of the land and water. This is critical because it enables us to detect the presence of standing water and mud flats on the basis of their smooth, level surfaces. The LiDAR also penetrates tree canopy to provide both a first return measurement of tree canopy height and a last return measurement of ground elevation beneath the tree canopy. These LiDAR measurements could be incorporated into the DRWM to distinguish between different types of mud and soil, pavement and asphalt. The decision tree classifier at the heart of the DRWM is intentionally designed to incorporate additional inputs like the LiDAR data recently collected for NYC.

Figure 1 Pelham Bay Park and Co-Op City as seen by WorldView-2 and Landsat 5. With 2 meter spatial resolution WorldView-2 can resolve individual buildings, cars, roads and trees. With 30 meter resolution Landsat 5 does not resolve these small features but it does detect the light reflected from them as it contributes to the spatially averaged color of the pixel containing the features. In these images, the green channel corresponds to Near Infrared brightness rather than visible green. This causes vegetation to stand out in greater contrast to other materials. These images were acquired one day apart in late April 2010 before wetland grasses had emerged so wetlands appear brown.

Mapping Change Through Time

The 27-year archive of Landsat imagery allows us to map changes in land cover through time. Using the spectral mixture analysis described above, we produce vegetation abundance maps from 97 cloud-free Landsat images collected on the dates shown in Figure 2. When these vegetation maps are stacked by Julian day they provide a multi-year average phonological cycle of green-up and senescence for each 30 meter pixel in the image. We use a principal component analysis to quantify the most statistically distinctive phonological patterns observed in NYC vegetation. The three most distinctive patterns, shown in Figure 3, correspond to lawn grasses and evergreen vegetation (red curve), deciduous trees and early greening herbaceous vegetation (green curve) and late greening warm weather grasses characteristic of wetlands (blue curve). After we identify these three phonological patterns we use a temporal factor analysis to estimate the relative abundance of each phonological type in each pixel in the image. The details of this analysis are discussed in Small (2010). We represent these relative abundances as the red, green and blue colors on the phenology map in Figure 3.

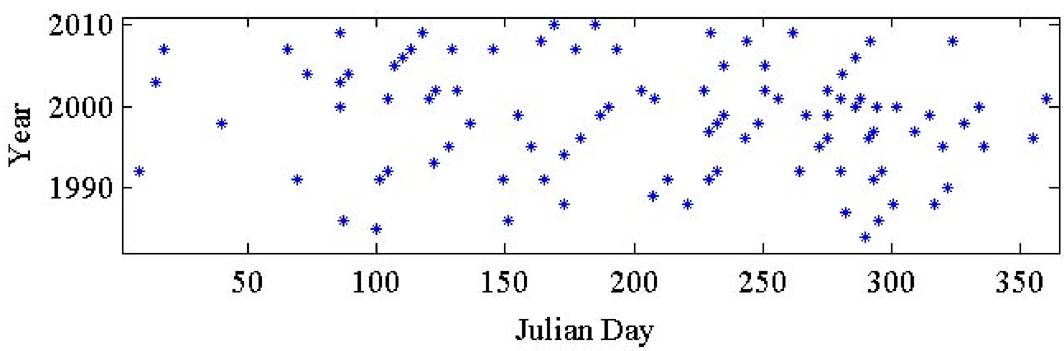


Figure 2. Dates of cloud-free Landsat images used for the vegetation phenology map.

The average phenology of each Landsat pixel is used as an indicator of the relative abundance of the three classes of vegetation most common in NYC. The more blue a given area appears on the map, the more abundant late greening vegetation is likely to be in that location. We use the abundance of late greening grasses like *Spartina alterniflor*a and *Phragmites australis* as a proxy for wetland conditions. However, we recognize that many wetlands do not host this type of vegetation so it is not an adequate proxy by itself. It is merely one of several spatial proxies the DRWM is designed to make use of.

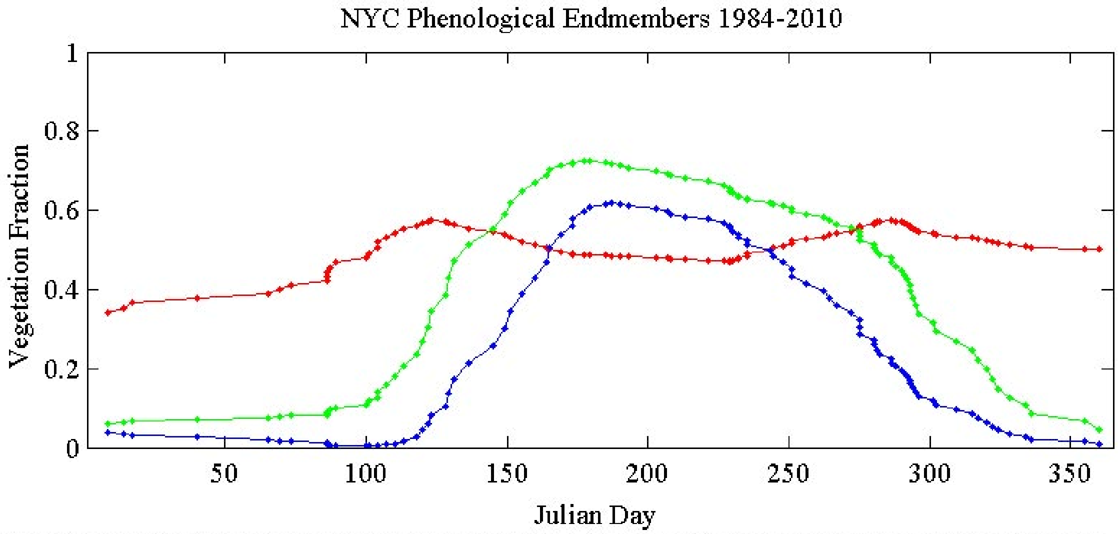


Figure 3 Phenological endmembers for NYC vegetation. These multi-year average green-up and senescence patterns are derived from 97 Landsat images acquired on the dates shown in Figure 2. They depict evergreen vegetation like lawn grasses (red), deciduous trees and herbaceous vegetation (green) and late-greening, early-senescing warm weather vegetation often associated with wetlands (blue).

The primary limitations of the phenology map are its spatial resolution and its temporal duration. The spatial resolution issues described above are partially offset by using high spatial resolution imagery to distinguish different types of land cover. This could be extended somewhat by using multiple acquisitions of high resolution imagery collected during different seasons. A substantial archive of high resolution satellite imagery has been acquired since 2002 by the NYC Department of Environmental Protection for the purpose of pervious surface mapping. This imagery could be incorporated into future versions of the DRWM to further refine wetland boundaries. This imagery could also help distinguish the spatial extent of tidal wetlands because the sensor images the wetlands at different phases of the tidal cycle.

The limitation of the temporal duration of the Landsat archive results from the fact that many wetland areas have changed over the 25 years of images used in the phenology map. Because of the 16 day repeat cycle of the Landsat satellites, and the presence of clouds, it is necessary to use several years of images to construct the detailed phenology curves shown in Fig. 3. However, the images used in this composite are all cloud-free. Using images with partial cloud cover would drastically increase the number of images in the composite and make it possible to limit the duration to only the past 10 years. This would eliminate the outdated phonological information from areas that are no longer vegetated, or where the vegetation types may have changed. While considerably more information is available from the Landsat archive, the cost and complexity of the analysis are greater when partial cloud cover imagery are included.

The limited time frame and funding available for development of the preliminary DRWM did not allow for us to incorporate partial cloud Landsat, alternate year high resolution imagery or LiDAR data. However these, and other additional inputs, could be incorporated into future refinements of the DRWM.

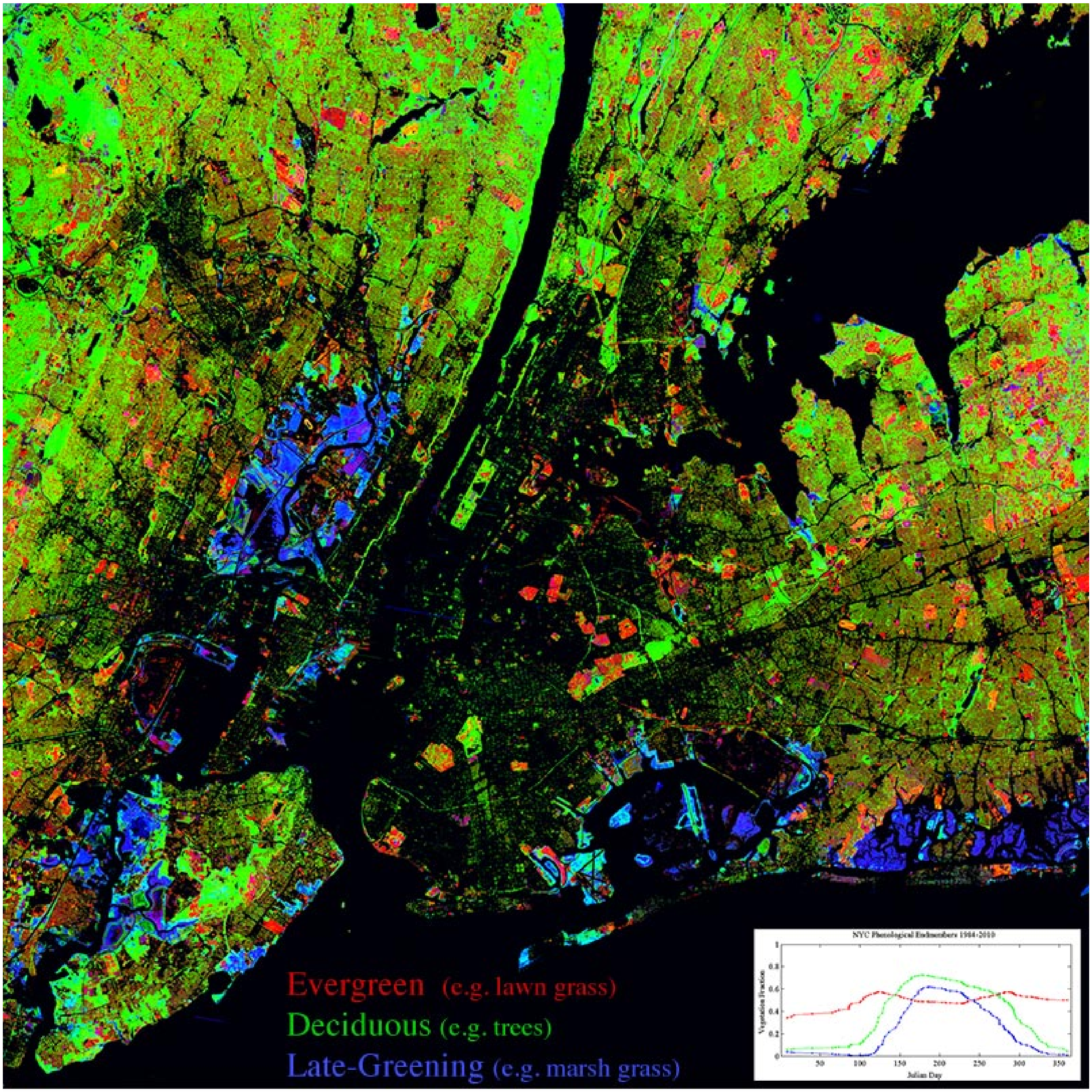


Figure 4. Vegetation phenology map for NYC and surrounding areas. The color of each pixel shows the relative abundance of the three principal classes of vegetation as mixtures of red, green and blue. Many, but not all, wetlands appear blue because of the presence of late greening marsh grasses. Transitional environments and many wetlands contain mixtures of early greening herbaceous and deciduous vegetation and late greening vegetation so appear light blue or cyan on the map.

Dynamic Mapping

The DRWM is constructed by combining different spatial maps as inputs in a decision tree. The decision tree is a simplified, but powerful, analogue for the process humans use to categorize objects according to characteristic features. In this prototype version of the DRWM we use an overly simple decision tree to illustrate how only three input maps can be combined to distinguish potential wetlands on the basis of infrared color, vegetation phenology and elevation. A schematic diagram of the decision tree is shown in Figure 5. Each 2x2 meter pixel in NYC is classified as either potential wetland or another category by following the sequence of decisions shown in Figure 5.

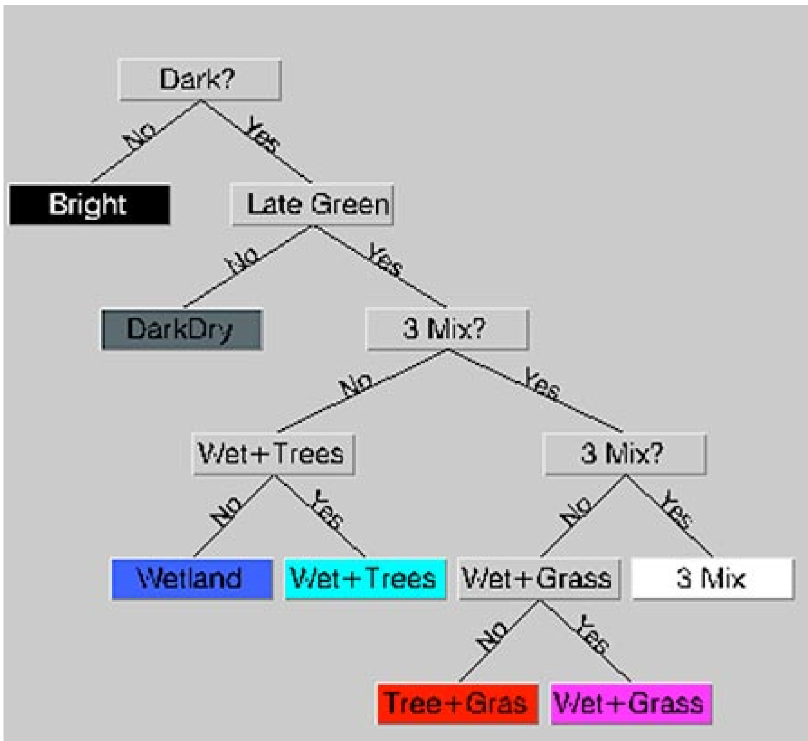


Figure 5 Simple decision tree to classify potential wetlands on the basis of phenology, brightness and elevation. Each branch point represents a decision involving one or more of the input variables. The resulting map is easily updated or modified by changing the decisions or adding additional input variables.

The criteria used to identify potential wetlands in this version of the DRWM are elevation above sea level, relative abundance of phonological vegetation class and relative abundance of vegetation and dark substrates (e.g. mud) or water. Analysis of several unambiguous wetland areas throughout NYC reveals an inverse linear relationship between dark substrates and vegetation. In wetland areas, when the dark fraction of a WorldView-2 pixel exceeds the vegetation fraction by an empirically determined threshold the pixel generally corresponds to wet soil, mud or water. This threshold automatically excludes all bright pixels not associated with wetland substrates. The linear relationship between dark fraction and vegetation fraction is incorporated into the first branch of the decision tree (Dark?) as an inequality. This inequality then excludes all pixels that are either too bright or too vegetated (in late April) to be wetland substrates. An additional criterion of elevation less than 9 meters above sea level is added to this branch of the decision tree to eliminate all areas at higher elevation. The subsequent branches of the tree leading to the wetland class use different phenology criteria to specify that potential wetland pixels must contain more than 50% late greening vegetation and less than 20% deciduous or herbaceous vegetation by area. These threshold percentages were also determined by empirical observations of unambiguous wetland areas on the phenology map. However, these criteria can easily be changed to incorporate new observations or field-derived criteria.

The flexibility of the decision tree is illustrated by producing two similar, but distinct, maps of potential wetland sites. The same decision structure is used but different criteria are applied to produce both a conservative underestimate and a liberal overestimate of wetland extent. This enables the analyst to incorporate uncertainty into the map by producing bounding estimates. When the object being mapped cannot be defined precisely it is often more accurate to specify a range of criteria bounding the object than to attempt to identify the extent precisely. Bounding estimates can also be more useful to decision-makers when considering scenarios where uncertainty in the extent of the wetland is a factor in decisions. In this example of the DRWM the lower bound (more conservative estimate of potential wetland extent) is based on the criteria given above (9 m, 50%, 20%) while a less conservative upper bound allows areas higher than 9 meters above sea level, with more than 25% late greening and less than 40% deciduous vegetation by area.

It is important to recognize that these empirical criteria were chosen merely to illustrate how the decision tree works – *not to produce a definitive wetland map*. In actual practice, the decision tree would incorporate additional inputs both from remotely sensed measurements (e.g. estimated soil moisture, surface temperature) and field observations (e.g. measured soil moisture, hydraulic conductivity, salinity, indicator species). Specific improvements are discussed in greater detail in the next section of the report.

The Future

Five specific refinements can be made to the DRWM using data currently available. The first, and probably most important, is to ***extend the decision tree to incorporate field observations*** made by scientists conducting wetland mapping and evaluation. Because the inputs to the decision tree must be spatially explicit gridded quantities (like satellite images and elevation models) the point observations collected in the field could be used primarily to establish and refine the empirical relationships with the quantities derived from the imagery. For instance, sets of GPS positions collected along the edges of wetlands could be used to better define the decision threshold applied to fractions of dark substrates and vegetation by superimposing them on the high resolution satellite image and extracting these fractions from pixels on either side of the field-observed boundary. This would allow any scientist collecting field observations to contribute geographic boundaries to a central repository used to refine the decision boundaries used in the decision tree. This type of information could be incorporated into a rapid assessment protocol to standardize the information collected by wetland ecologists while conducting field validation.

A potentially enormous refinement would ***replace the crude SRTM elevation model with a more accurate and detailed LiDAR elevation model***. The 30 meter SRTM model is adequate to eliminate elevated landfills with dark substrates and late greening vegetation but it also eliminates actual wetlands in local basins at higher elevations like those within the green belt on Staten Island. These basins are often too small to be accurately resolved in the 30 meter SRTM data. However, the LiDAR data collected by Sanborn in April 2010 have a point density of 8 to 12 measurements per square meter. These elevation data could be used to map local topographic basins where water accumulates at higher elevations. The high spatial resolution of the resulting elevation model will also allow for a much more accurate delineation of the landward extent of wetlands at low elevations also.

An additional, and equally critical, refinement would be the ***identification of forested wetlands using a LiDAR elevation model***. The primary limitation of the phenology map is its inability to identify forested wetlands containing deciduous trees with phenology indistinguishable from trees in non-wetland areas. However, the LiDAR dataset collected in April 2010 contains both first return elevations from canopy top and last return elevations from the ground surface. This makes it possible to identify both topographic depressions and standing water beneath tree canopies. Incorporating detailed topographic constraints into the decision tree would extend the utility of the DRWM considerably. *These data are already available for NYC so this would be a particularly cost effective extension of the DRWM.*

A fourth potential refinement would ***incorporate surface temperature measurements to identify areas of wet soil and standing water***. Every Landsat overpass of NYC captures both visible and infrared brightness as well as emitted surface temperature. Wet soil and standing water have considerably greater thermal inertia than dry soil, asphalt or vegetation. As a result, wet soils and water are measurably cooler at the 11am overpass time of Landsat for much of the year. Incorporating surface temperature imagery could provide strong constraints on the spatial extent of saturated soils and standing water. *These data are already available so this would be a particularly cost effective extension of the DRWM.*

A fifth potential refinement would ***incorporate temporal variability of soil brightness as an indication of soil moisture***. As described above, the brightness of soils changes drastically when wet. These brightness variations are imaged by Landsat and could be analyzed in a manner similar to temporal variation in vegetation abundance. While some research would be necessary to establish the accuracy and consistency of these measurements, the potential return on investment could be enormous as it would make possible retrospective analysis of soil moisture dynamics throughout NYC since the early 1980s.

Examples and Comparisons

In this section, a number of comparisons are presented between the existing NYSDEC wetland maps (tidal and freshwater) and the two potential wetland extents produced with the DRWM using the criteria discussed above. In each case, the vector boundaries are superimposed on both the 23 April 2010 WorldView-2 image and the Landsat-derived phenology map for comparison. The Max and Min bounding extents derived from the DRWM have not been validated and are only intended to illustrate the utility of producing bounding extents - and the need for field validation and additional inputs like those discussed above.

Each image pair highlights both the agreement and the errors in both the existing DEC wetland extents and the extents that can be obtained from the DRWM. The benefit of the DRWM is related to its ability to evolve and improve continuously. These examples illustrate some of the challenges of using only two inputs. With each successive input added to the DRWM its accuracy and information content would increase.

Richmond Creek Staten Island   4/23/2010

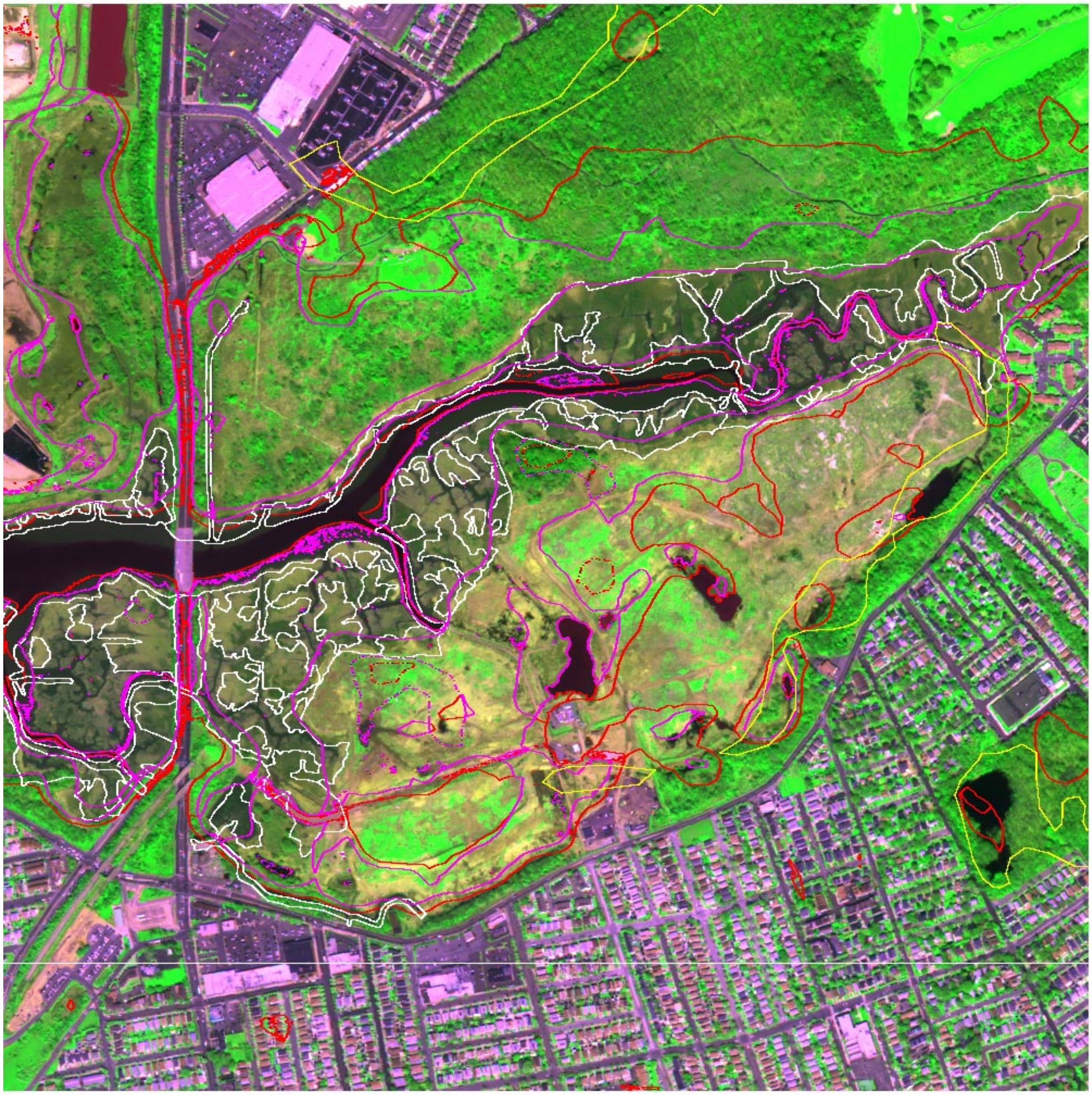


Figure 6a Wetland extents from NYSDEC and DRM bounding extents superimposed on visible-infrared WorldView-2 image from April 23, 2010. NYSDEC tidal (white) and freshwater (yellow) boundaries distinguish different classes of wetland with reasonable accuracy but do not capture some pools further from the creek and extend into developed area in upper left-center. The DRM exents (magenta=Min, red=Max) capture the mud flats exposed at low tide as well as more densely vegetated areas further from the creek.

Richmond Creek Staten Island   Phenology

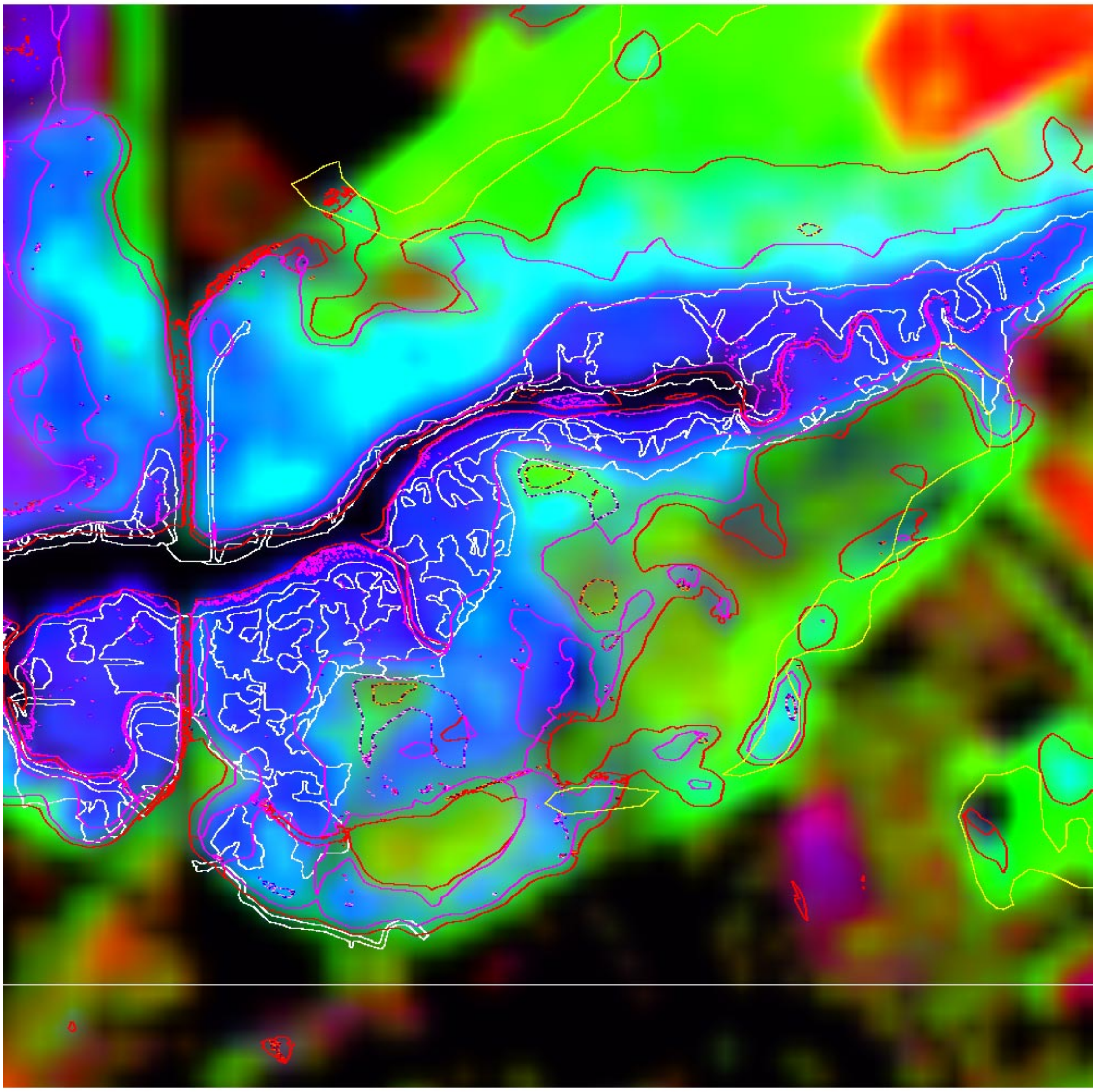


Figure 6b Wetland extents from NYSDEC and DRM bounding extents superimposed on Landsat-derived phenology map in Fig. 4.. NYSDEC tidal (white) and freshwater (yellow) boundaries distinguish different classes of wetland with reasonable accuracy but do not capture some pools further from the creek and extend into developed area in upper left-center. The DRM exents (magenta=Min, red=Max) capture the mud flats exposed at low tide as well as more densely vegetated areas further from the creek.

Fresh Kills Creek Staten Island 4/23/2010

Figure 7a Wetland extents from NYSDEC and DRM bounding extents superimposed on visible-infrared WorldView-2 image from April 23, 2010. NYSDEC tidal (white) and freshwater (yellow) boundaries distinguish different classes of wetland with reasonable accuracy but do not capture the mud flats on the main channel or the late greening area in the lower left. The DRM exents (magenta=Min, red=Max) capture the mud flats exposed at low tide and the smaller late-greening areas at center-upper left. The maximal extents (red) do not capture some isolated freshwater patches in the forest surrounding the creek and misidentify areas on the landfill center bottom.

Fresh Kills Creek Staten Island   Phenology

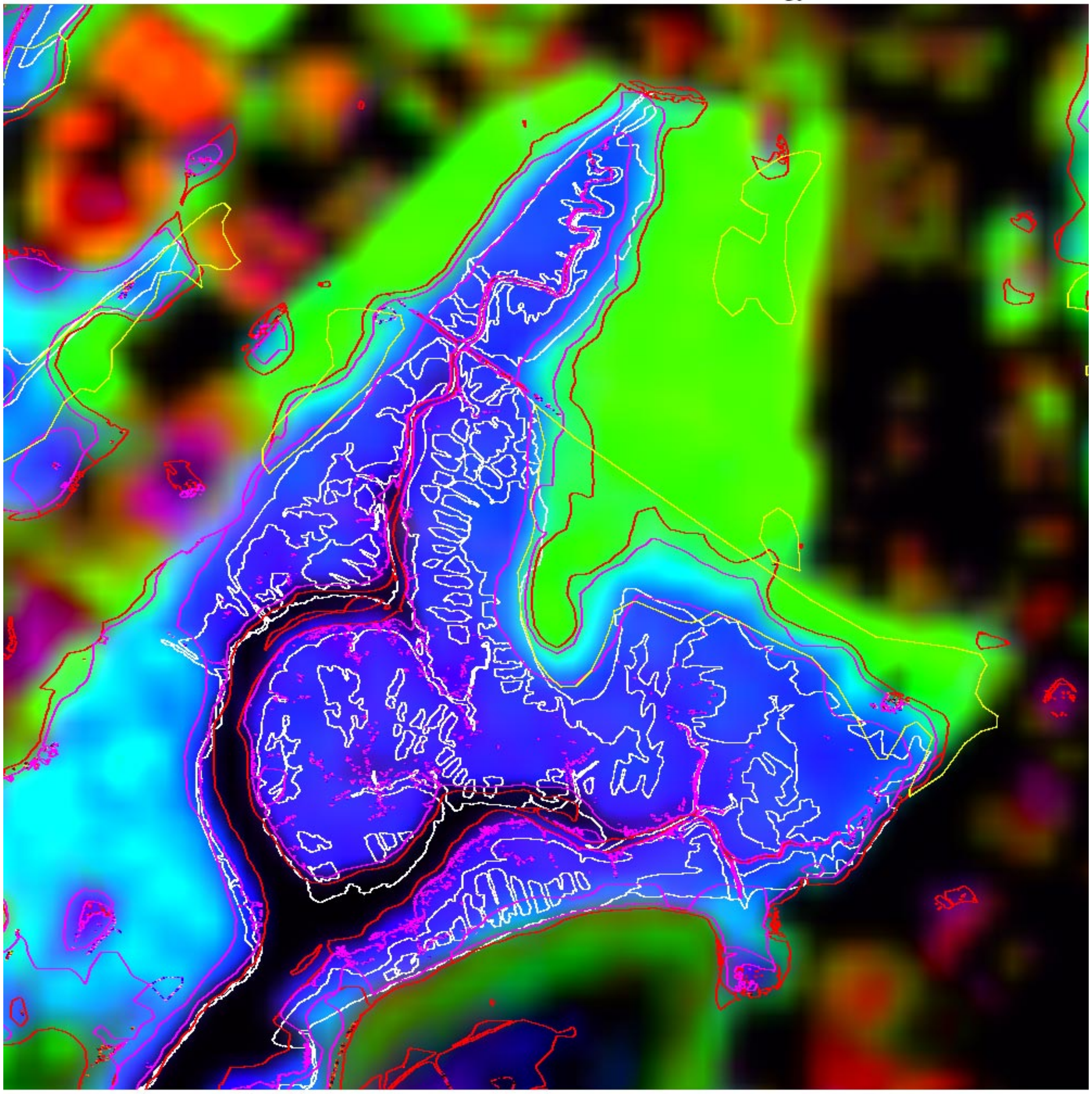


Figure 7b Wetland extents from NYSDEC and DRM bounding extents superimposed on Landsat-derived phenology map in Fig. 4.. NYSDEC tidal (white) and freshwater (yellow) boundaries distinguish the landward extent of the late greening marsh grasses but do not capture potential wetland areas where marsh grasses occur together with early greening vegetation (lower left). The DRM exents (magenta=Min, red=Max) extend slightly further into the surrounding forest than the DEC tidal boundaries.

Brookfield Staten Island   4/23/2010

Figure 8a Wetland extents from NYSDEC and DRM bounding extents superimposed on visible-infrared WorldView-2 image from April 23, 2010. NYSDEC tidal (white) and freshwater (yellow) boundaries distinguish the main creek channel and adjacent flats but the freshwater extents do not capture the ponds (left center). The DEC freshwater and tidal extents overlap in several locations (see yellow arrows) The DRM exents (magenta=Min, red=Max) capture both freshwater and tidal wetlands consistly but does not distinguish between them.

Brookfield Staten Island   Phenology

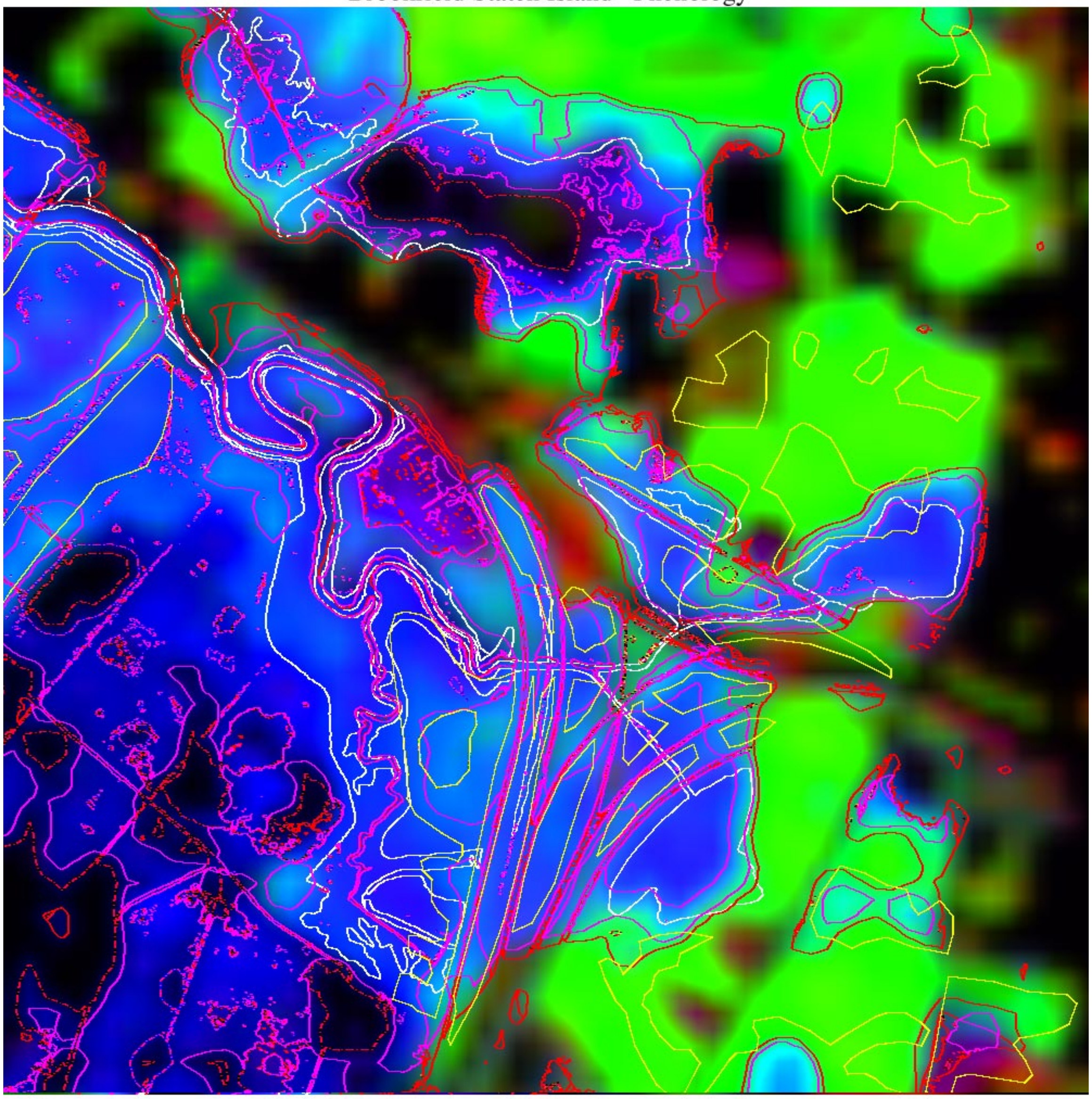


Figure 8b Wetland extents from NYSDEC and DRM bounding extents superimposed on Landsat-derived phenology map in Fig. 4.. NYSDEC tidal (white) and freshwater (yellow) boundaries clearly underestimate the extent of late-greening vegetation. The DRM exents (magenta=Min, red=Max) capture the late greening vegetation but may underestimate the extent of the foested freshwater wetlands compared to the DEC boundaries. The maximal DRM extents erroneously capture some paved parking areas near the center of the image. Possibly a resuilt of recent paving.

Fort Tilden Queens 4/23/2010

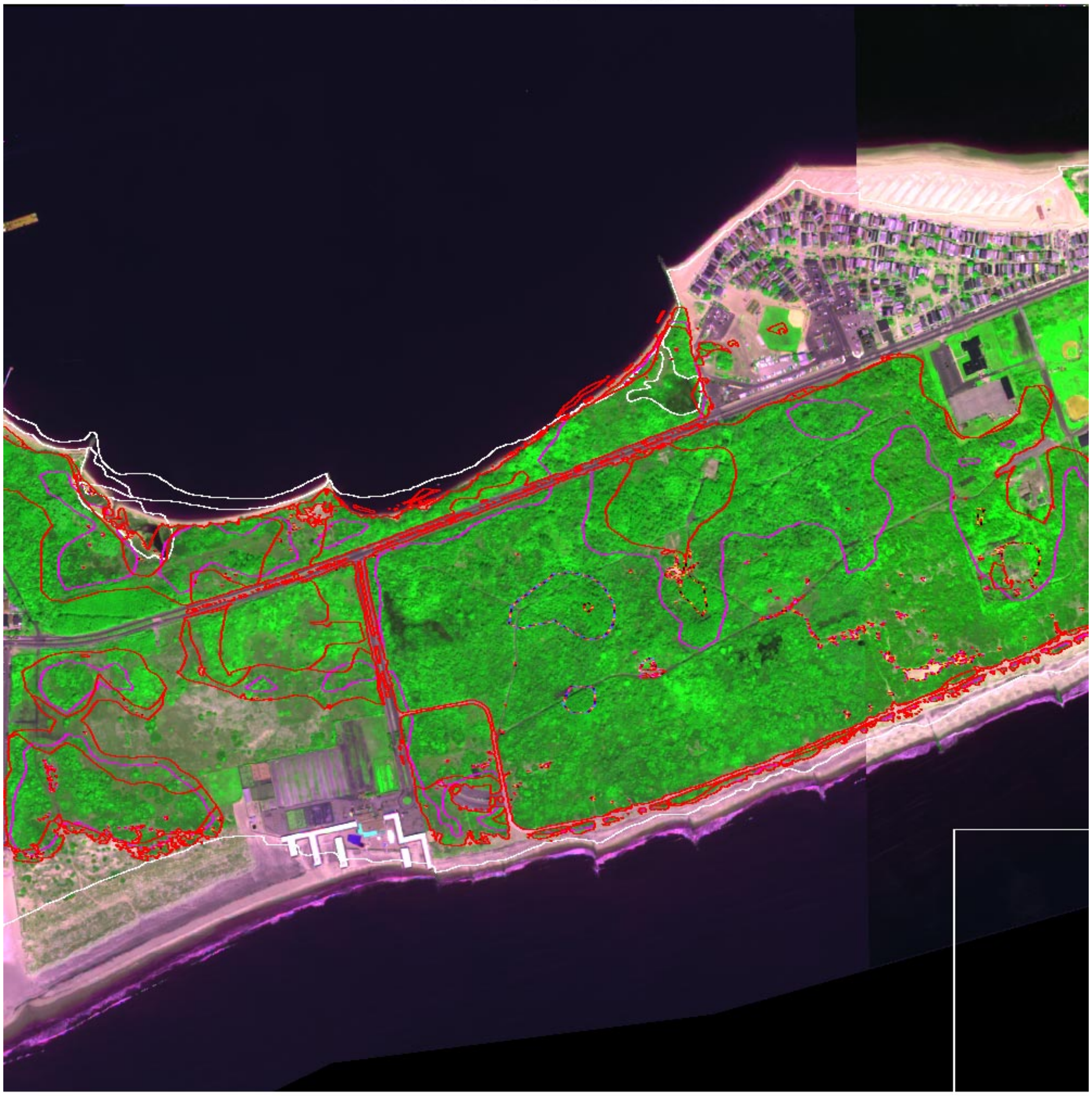


Figure 9a Wetland extents from NYSDEC and DRM bounding extents superimposed on visible-infrared WorldView-2 image from April 23, 2010. NYSDEC tidal (white) boundaries do not capture the large area of mixed early and late greening vegetation with numerous vernal pools visible throughout. The DRM exents (magenta=Min, red=Max) csuggest that this large area may be a previously unmapped wetland.

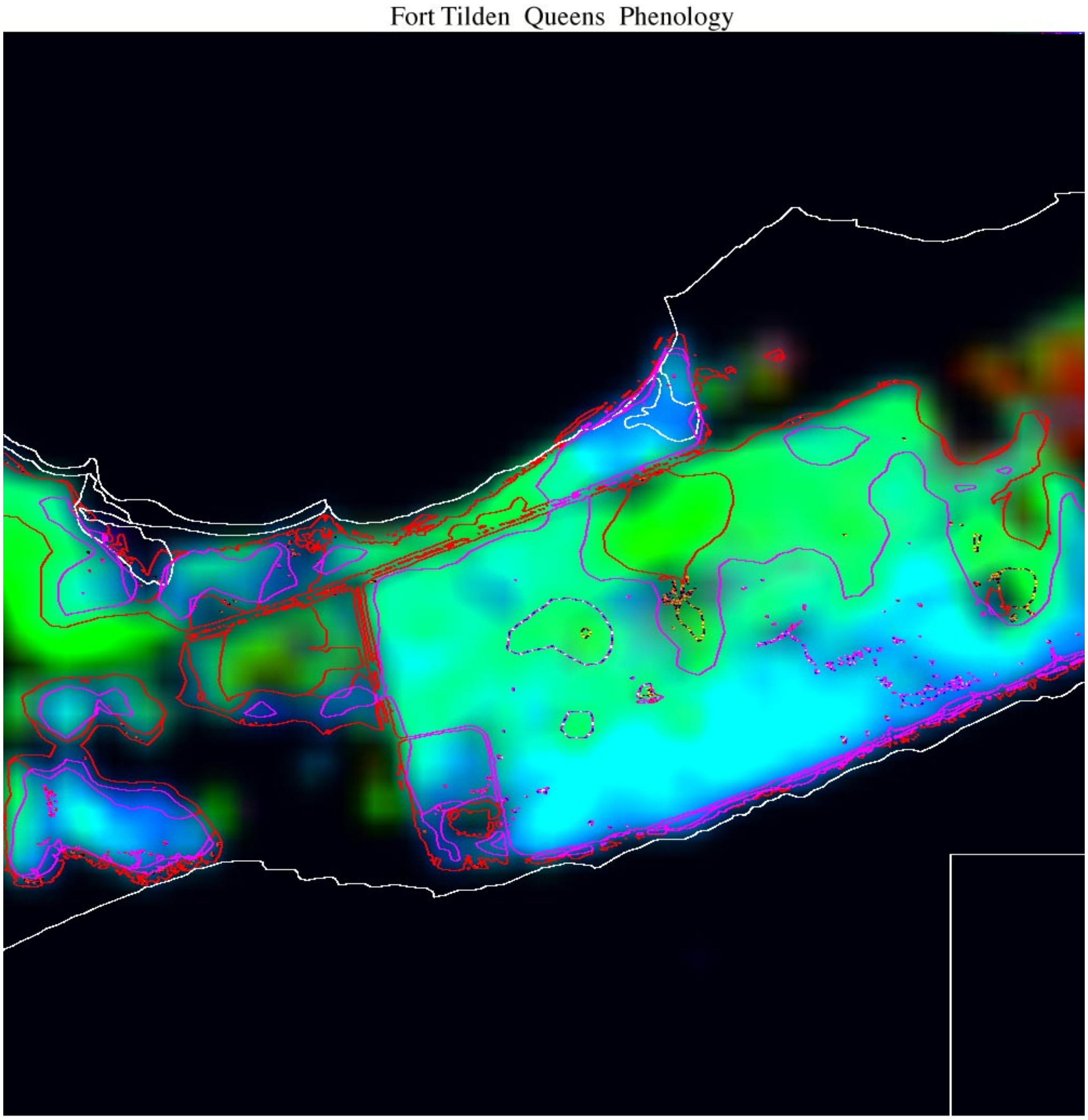


Figure 9b Wetland extents from NYSDEC and DRM bounding extents superimposed on Landsat-derived phenology map in Fig. 4.. NYSDEC tidal (white) show only the northern beach. The DRM exents (magenta=Min, red=Max) indicates large areas of mixed early and late greening vegetation suggesting a wetland.

Port Mobil Staten Island   4/23/2010

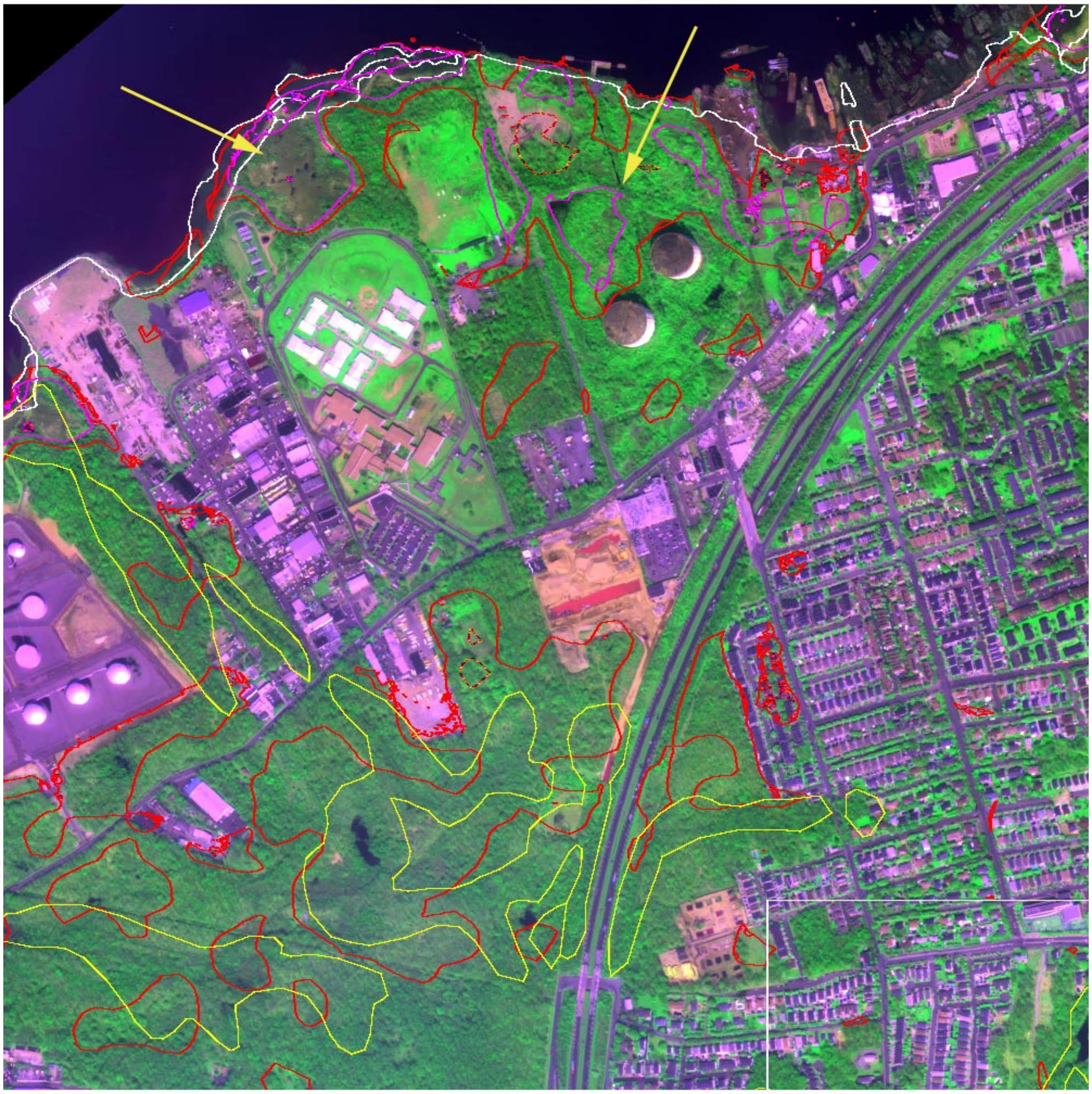


Figure 10a Wetland extents from NYSDEC and DRM bounding extents superimposed on visible-infrared WorldView-2 image from April 23, 2010. NYSDEC tidal (white) and freshwater (yellow) boundaries fail to capture the large potential wetland upper left or the late greening patches upper center (yellow arrows). The DRM exents (magenta=Min, red=Max) show very different coverage from the DEC freshwater extents for the forested area in the lower left

Port Mobil Staten Island   Phenology

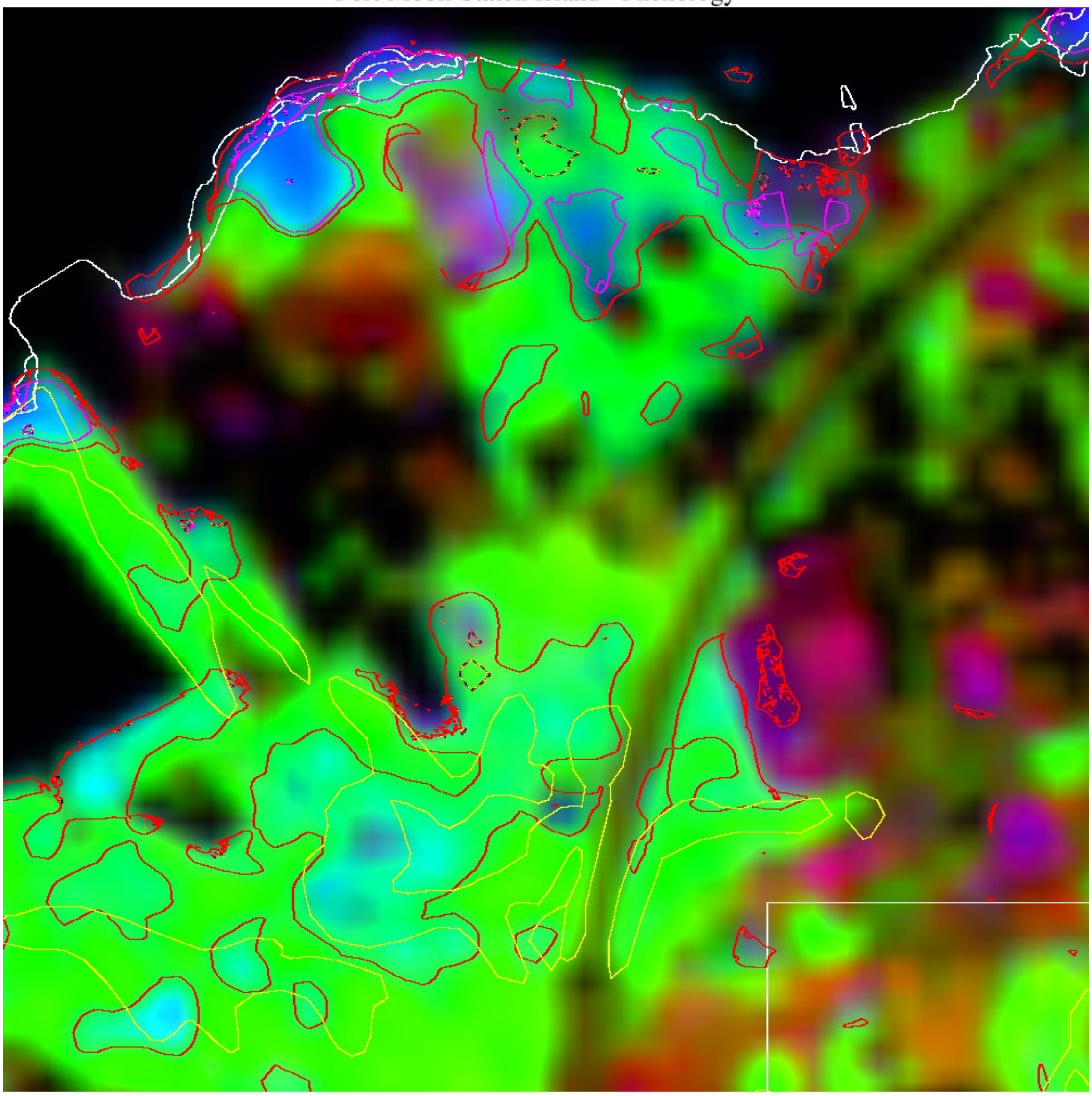


Figure 10b Wetland extents from NYSDEC and DRM bounding extents superimposed on Landsat-derived phenology map in Fig. 4.. NYSDEC freshwater (yellow) boundaries and the DRM exents (magenta=Min, red=Max) are very different for the forested areas but the DEC extents do not capture the areas of late greening top center.

Great Kills Park Staten Island 4/23/2010

Figure 11a Wetland extents from NYSDEC and DRM bounding extents superimposed on visible-infrared WorldView-2 image from April 23, 2010. NYSDEC tidal (white) boundaries are displaced more than 100 meters offshore (lower right) - even on this low tide miage. Freshwater (yellow) boundaries miss the large area of wet soil and standing water surrounding the ballfields and the panhandle on the north side of the park. The DRM exents (magenta=Min, red=Max) capture the extent of the wet soil accurately.

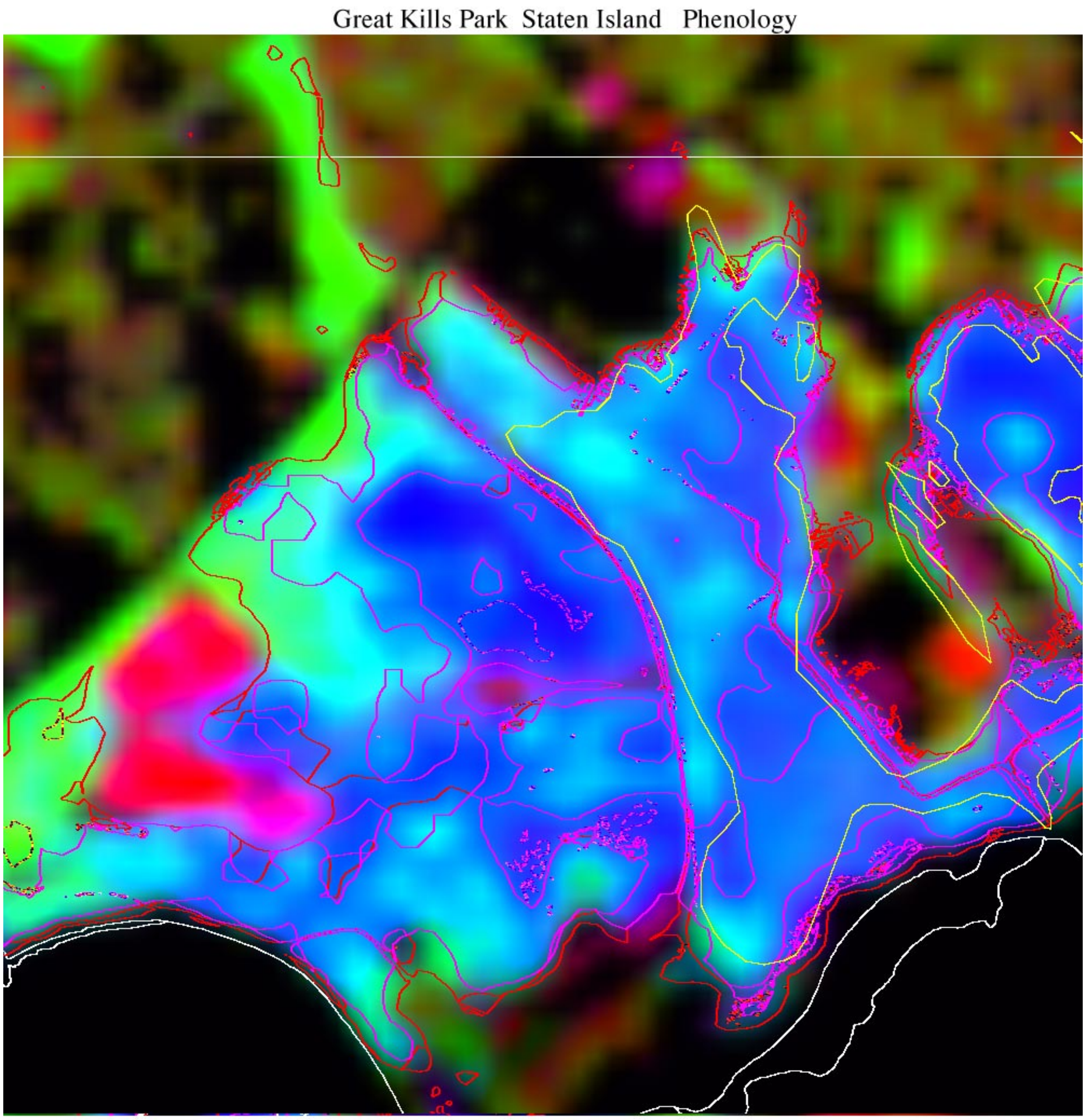


Figure 11b Wetland extents from NYSDEC and DRM bounding extents superimposed on Landsat-derived phenology map in Fig. 4.. NYSDEC tidal (white) and freshwater (yellow) boundaries do not classify any of the area west of main park road.The DRM exents (magenta=Min, red=Max) agree well with the location of sparsely vegetated soils throughout the park (see Fig. 11a).

Midland Beach Staten Island   4/23/2010

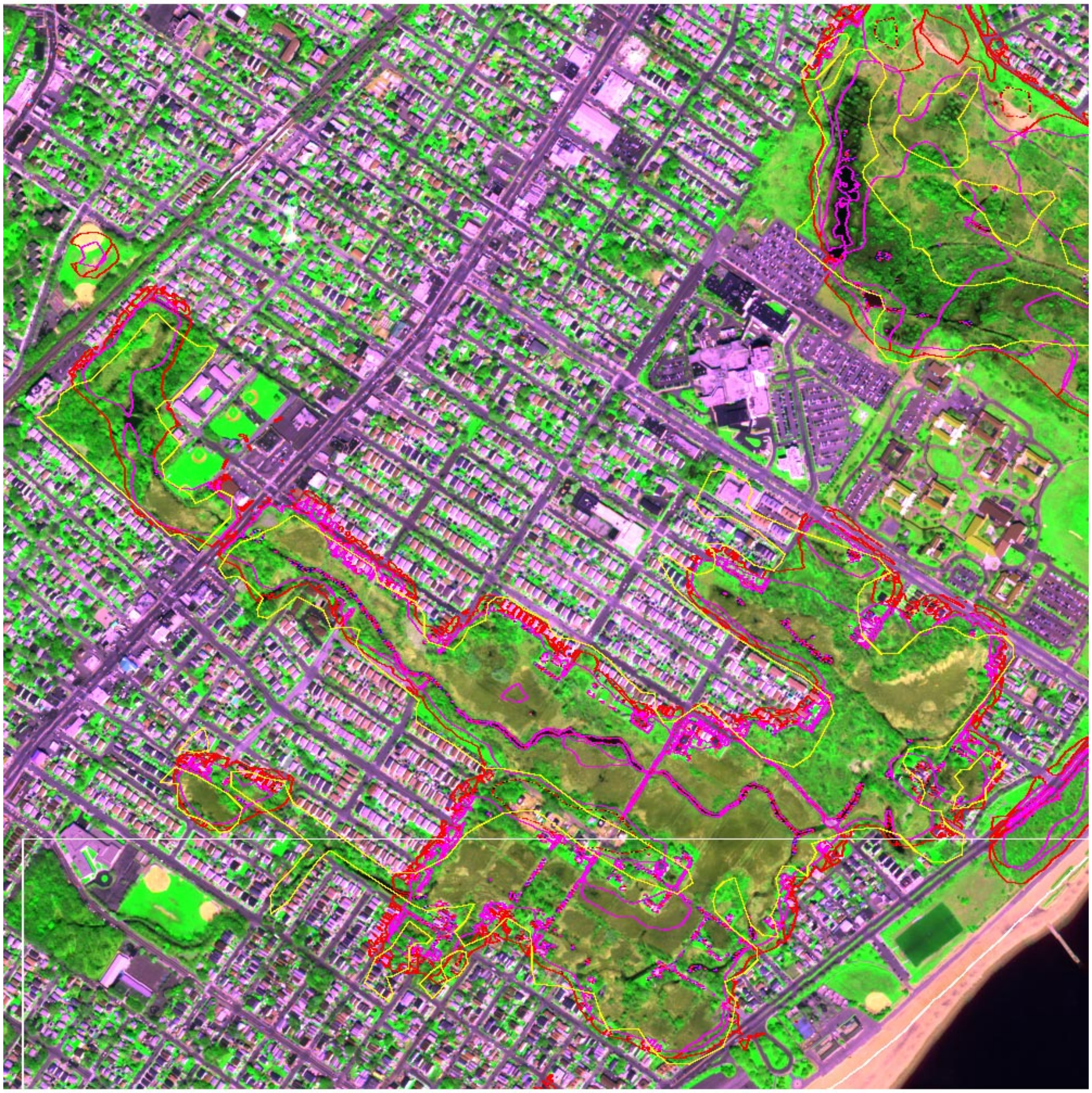


Figure 12a Wetland extents from NYSDEC and DRM bounding extents superimposed on visible-infrared WorldView-2 image from April 23, 2010. NYSDEC tidal (white) boundariess and DRM exents (magenta=Min, red=Max) agree reasonably well but both lap onto the edges of developed areas. Presumably these areas were developed more recently.

Midland Beach Staten Island Phenology

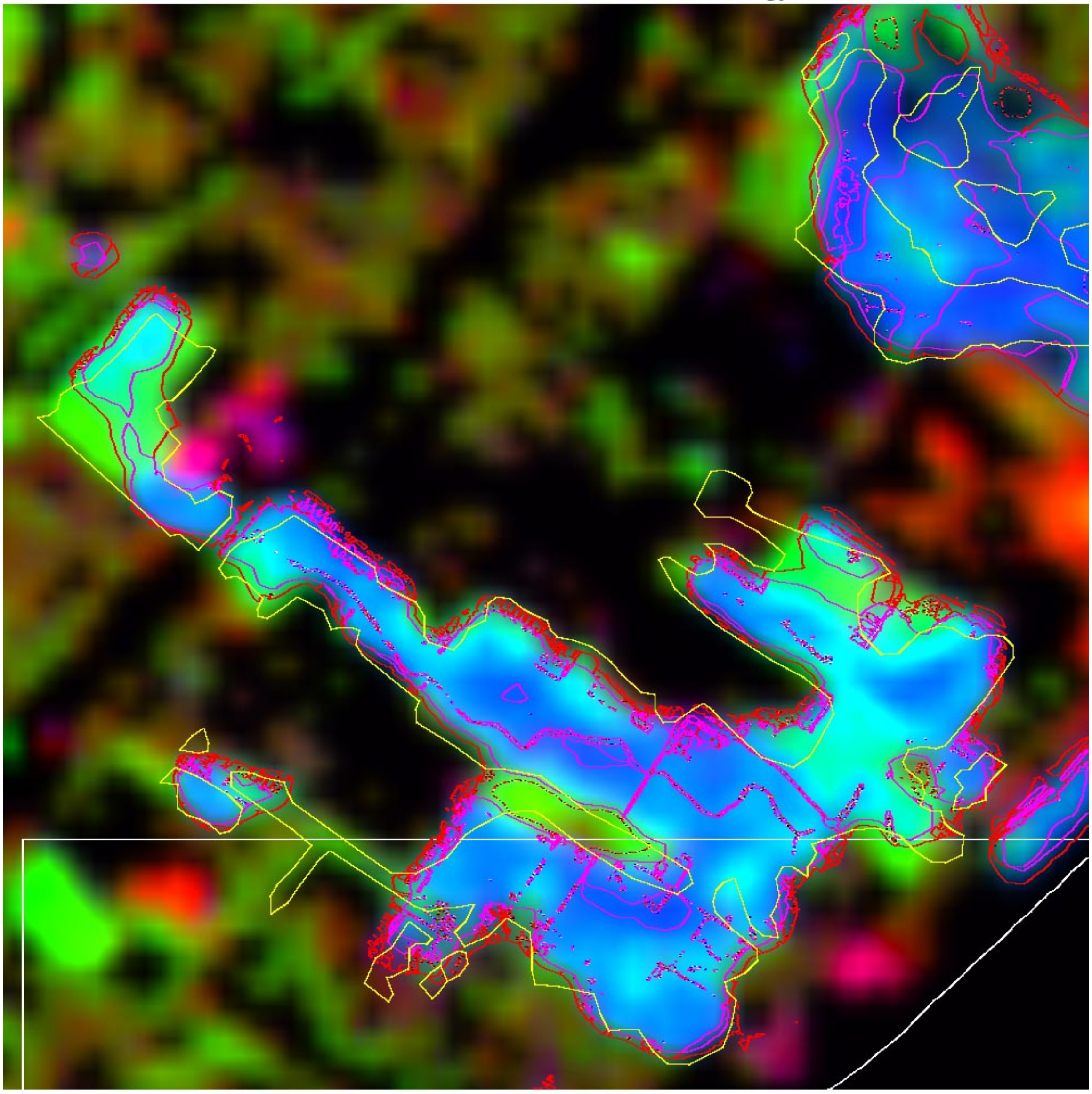


Figure 12b Wetland extents from NYSDEC and DRM bounding extents superimposed on Landsat-derived phenology map in Fig. 4.. NYSDEC tidal (white) and freshwater (yellow) boundaries and DRM exents (magenta=Min, red=Max) agree well but both overlap with presumably recent develoment shown in Fig. 12a).

Pelham Bay Park The Bronx 4/23/2010

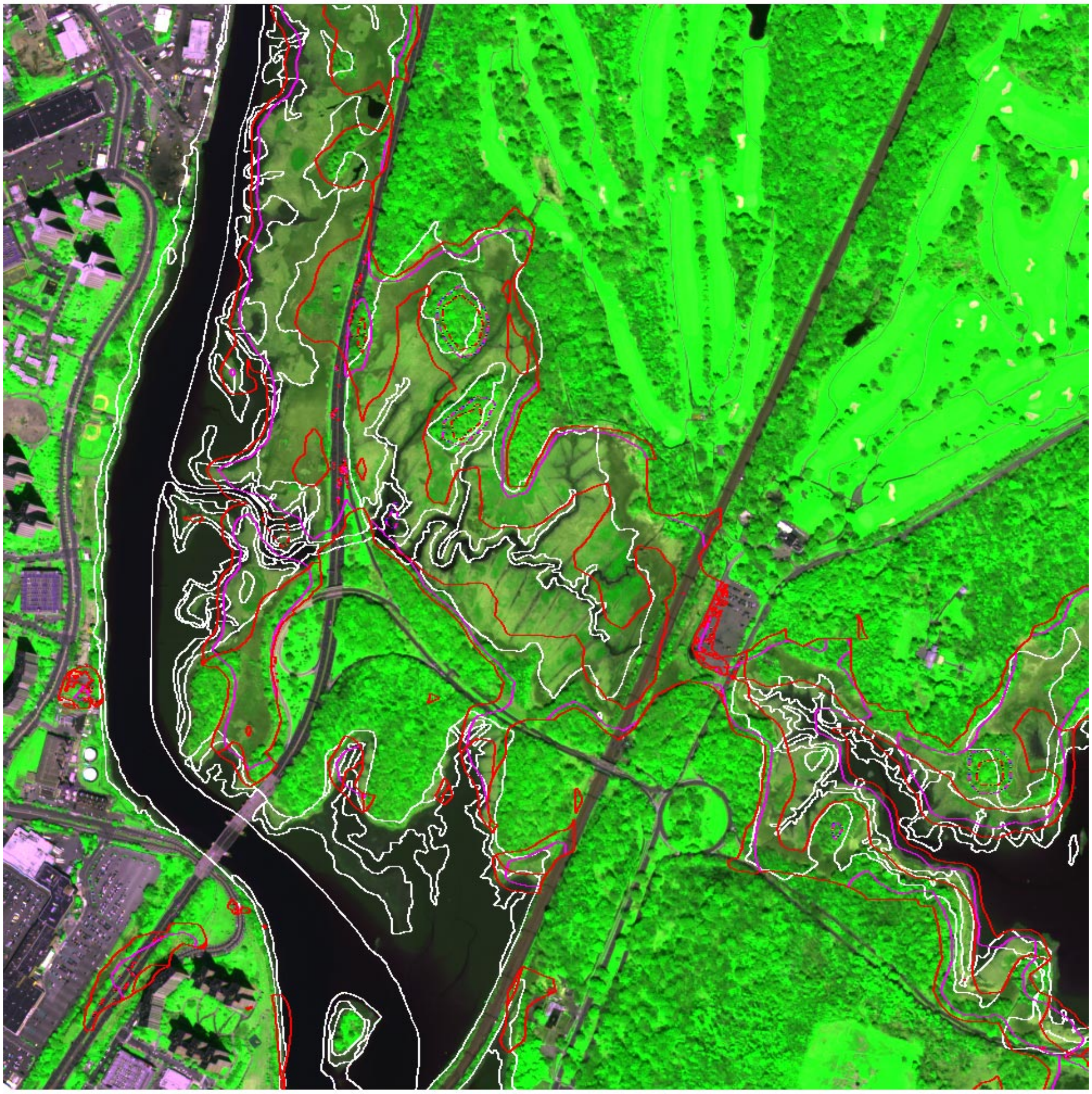


Figure 13a Wetland extents from NYSDEC and DRM bounding extents superimposed on visible-infrared WorldView-2 image from April 23, 2010. NYSDEC tidal (white) boundariess extend well beyond DRM exents (magenta=Min, red=Max) into the Huchinson River. The WorldView-2 image does show faint tidal flats within in the DEC boundaries but the extent is not as great as the DEC boudary suggests. Presumably because the outflow of the spring freshet in the river raised the water level above that when the earlier aerial photos were acquired. The inland extent of both DEC boundaries and DRM extents agree reasonably well in most areas but the DEC boundary may underestimate the northward extent of the wetland approaching the golf course.

Pelham Bay Park   The Bronx   Phenology

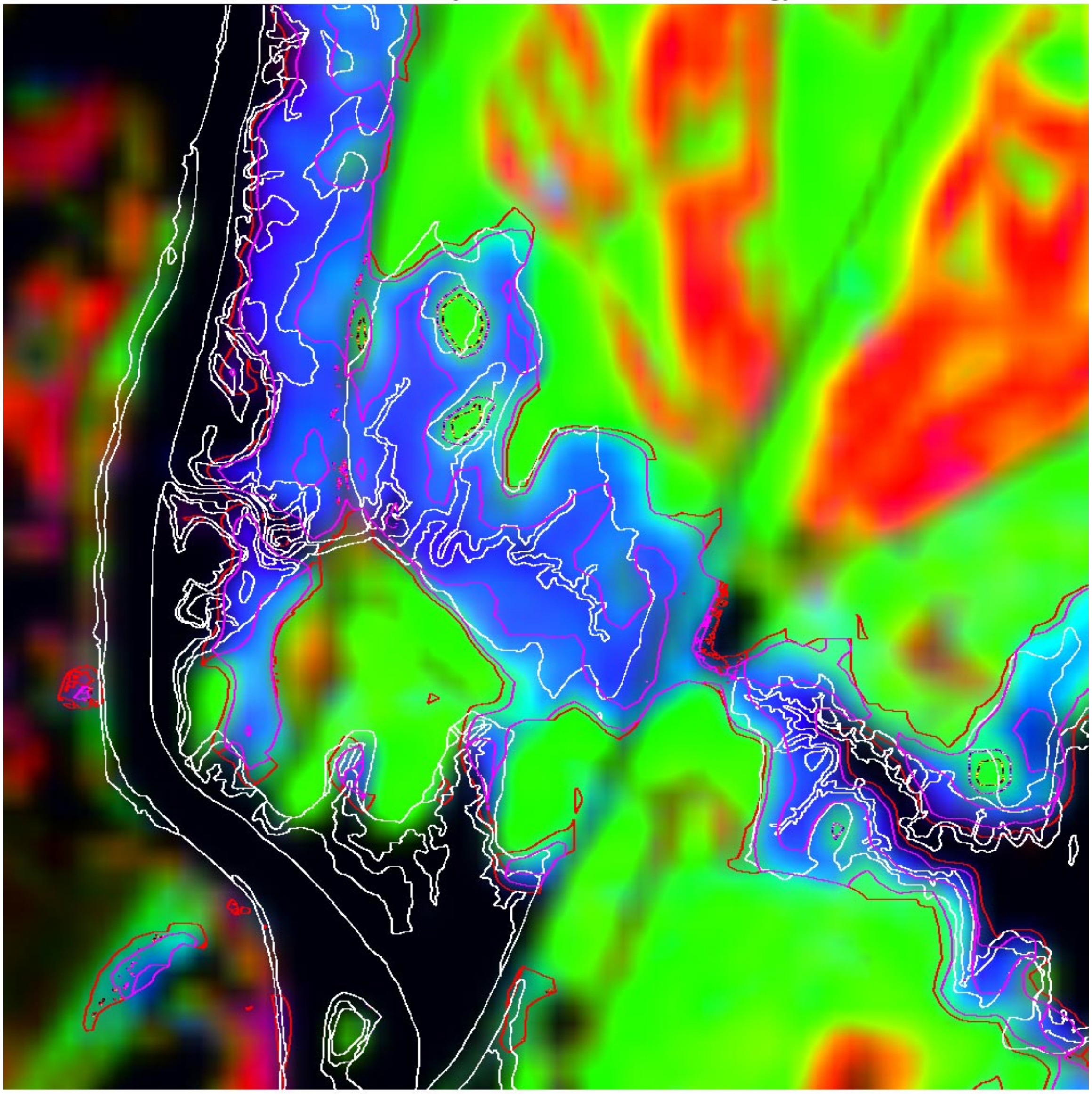


Figure 13b Wetland extents from NYSDEC and DRM bounding extents superimposed on Landsat-derived phenology map in Fig. 4.. NYSDEC tidal (white) boundaries and DRM exents (magenta =Min, red=Max) agree reasonably well but the DEC boundaries are more conservative.

Van Cortlandt Park The Bronx 4/23/2010

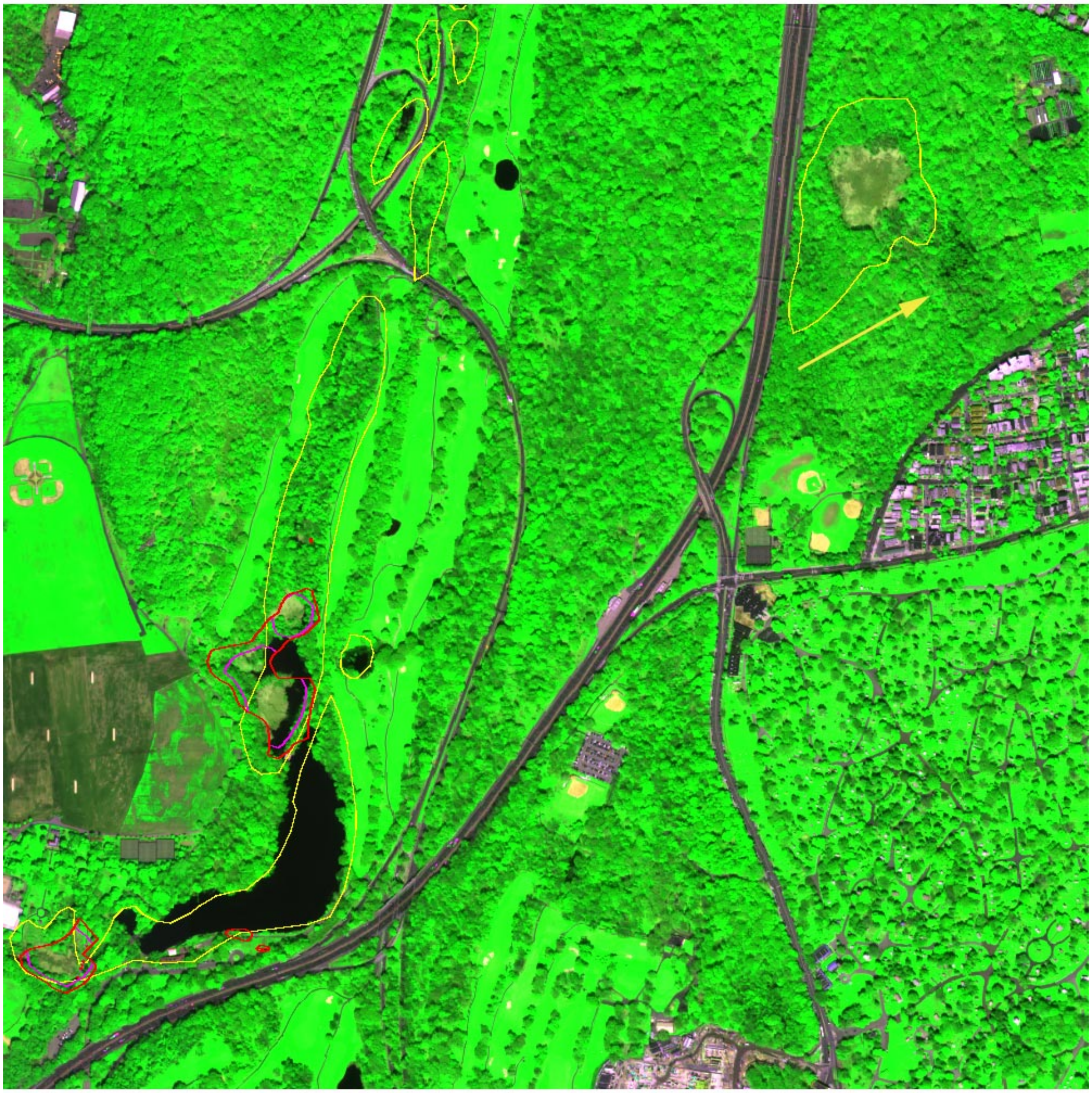


Figure 14a Wetland extents from NYSDEC and DRM bounding extents superimposed on visible-infrared WorldView-2 image from April 23, 2010. NYSDEC freeshwater (yellow) boundaries capture several forested wetlands not detected by the DRM exents (magenta=Min, red=Max). However, a known vernal pool wetland mapped by NYC Parks Natural Resources Group (yellow arrow upper right dark area) is not captured by either DEC or DRM but is resolved by the WorldView-2 image because of the effect of standing water below the partially closed canopy. Lidar elevation measurements would likely identify this type of forested wetland.

Van Cortlandt Park   The Bronx   Phenology

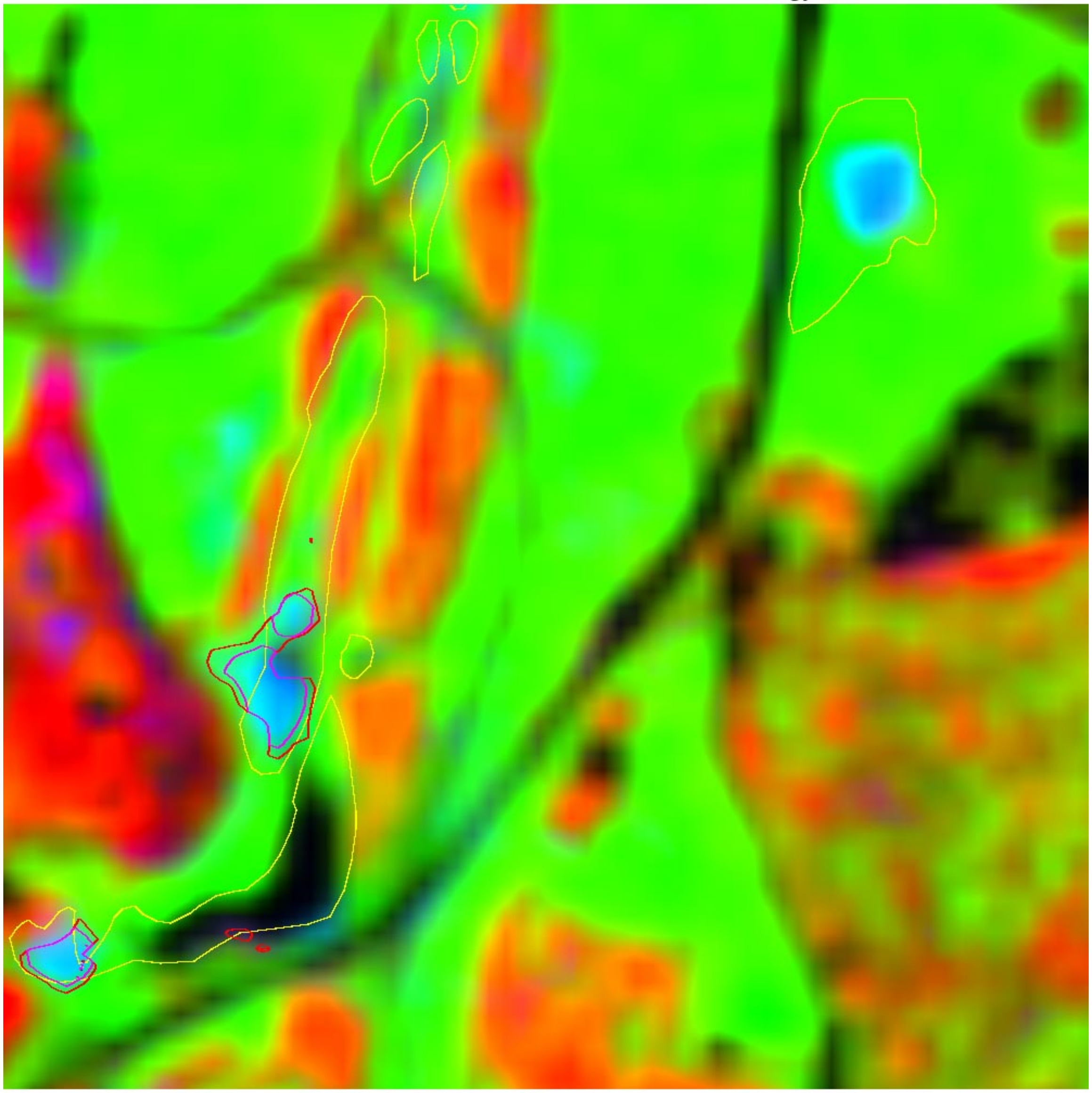


Figure 14b Wetland extents from NYSDEC boundaries and DRM bounding extents superimposed on Landsat-derived phenology map in Fig. 4.. NYSDEC freshwater (yellow) boundaries capture forested wetlands missed by the DRM exents (magenta=Min, red=Max). The conspicuous patch of late greening vegetation (upper right) is excluded from the DRM by the elevation constraint. Incorporating a Lidar-derived elevation model could resolve this problem.

Alley Pond Park   Queens   4/23/2010

Figure 15a Wetland extents from NYSDEC and DRM bounding extents superimposed on visible-infrared WorldView-2 image from April 23, 2010. NYSDEC tidal (white) appear to underestimate the extent in many areas while freshwater (yellow) etents also do not extend into the darker soils. In oontrast, the DRM exents (magenta=Min, red=Max).extends well into the partially forested area.

Alley Pond Park Queens Phenology

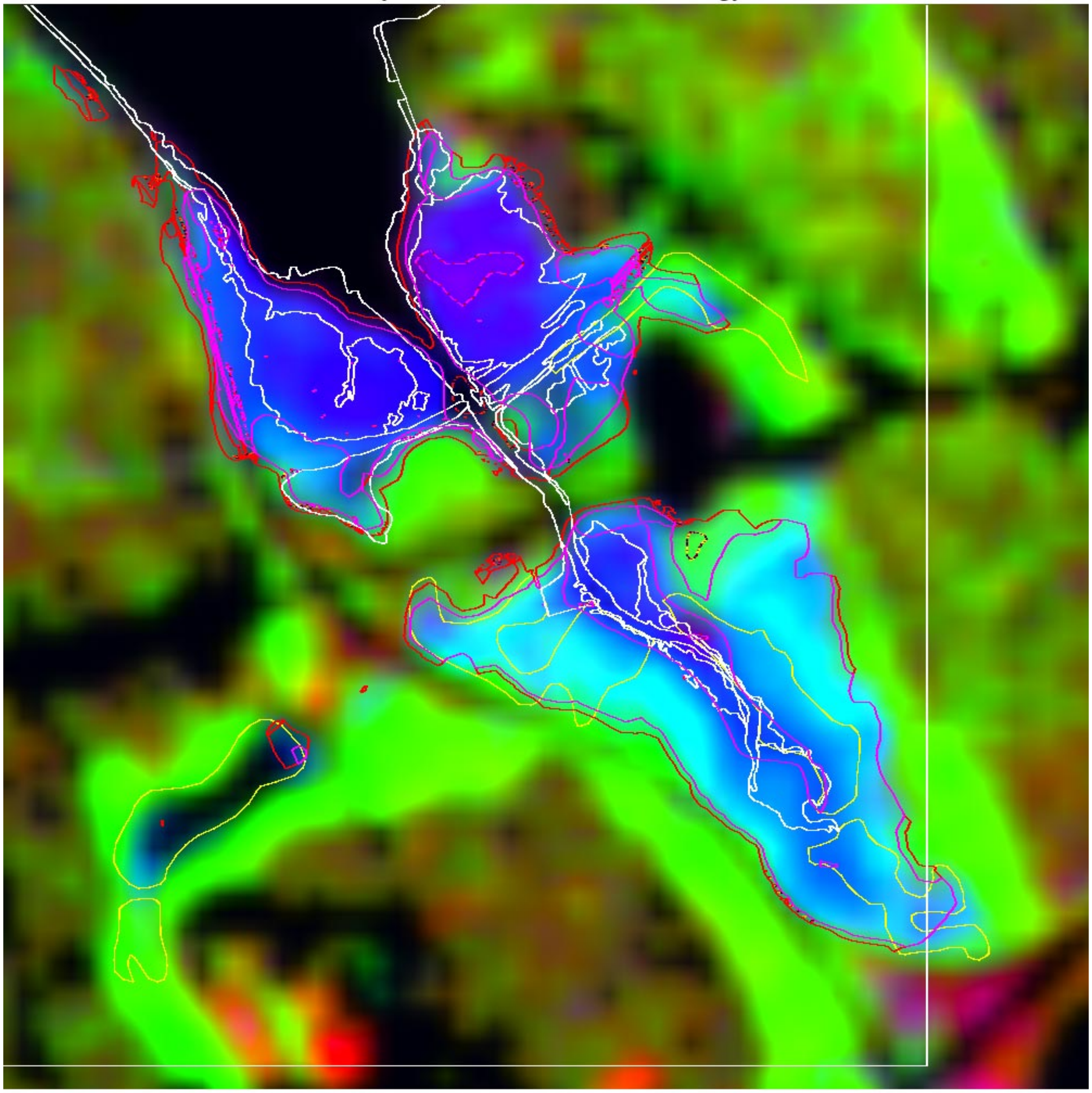


Figure 15b Wetland extents from NYSDEC boundaries and DRM bounding extents superimposed on Landsat-derived phenology map in Fig. 4.. NYSDEC freshwater (yellow) boundaries capture less of the upland forest than DRM exents (magenta=Min, red=Max)..

Mayor's Office of Long-Term Planning and Sustainability
City Hall
New York, NY 10007
www.nyc.gov/PlaNYC2030