Final Report

Calculation of vertical tidal datums for the tidal Hudson River north of Yonkers, New York

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and
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By

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Abstract
New Mean Higher High Water (MHHW), Mean Lower Low Water (MLLW), and Mean Sea (River) Level (MSL) datums were calculated for the tidal Hudson River north of Yonkers, NY and south of the Federal Dam at Troy, NY. The work used a previously existing numerical hydrodynamic model created at Stevens Institute of Technology in Hoboken, NJ. The curvilinear model grid is approximately 70 meters horizontal resolution, with 10 vertical sigma layers. The hydrodynamic model was forced by year-2010 observed water levels at the Battery, NY, and observation-based river and point source discharges from the Upper Hudson and Mohawk Rivers north of Troy, NY, and its tributaries along the Hudson River's main stem. Simulated water levels from the Stevens Hudson River model were extracted at each of 77,452 grid cell locations and for every half hour. Standard harmonic analysis was used to calculate the 37 standard NOS tidal harmonic constituents at each cell based on the local simulated time series. The harmonic constituents were used to recreate tidal time series at each cell location for a 19 year tidal epoch. The reconstructed time series were used to calculate preliminary MHHW, MLLW, and MSL datums. Observed water level records from 13 in situ stations along the tidal Hudson were subjected to the same analysis, and were used to debias the numerical model results. Three available NOS tidal benchmark stations were also considered in the debiasing analysis. As in the NOS benchmark analyses for the Hudson River, the long-term primary station at the Battery, NY was used as control to convert the model-simulated and secondary-stations-observed MSL to the National Tidal Datum Epoch of 1983-2001. The mean absolute error (MAE) in the raw model's MHHW values against observed data at the stations was 2.4cm. The MAE for MLLW was 4.9cm. The MAE for MSL NTDE 1983-2001 was 4.1cm, with the highest deviation at 10.9cm found at the port of Albany, NY station. Based on the differences between observation-based datums and model-based datums at the observation stations, three bias fields were calculated and used to debias the tidal datums of the Hudson River model so that they pass through the observed datums: bias of model-based MHHW (referenced to MSL), bias of model-based MLLW (referenced to MSL), and bias of model-based MSL (NTDE 1983-2011, referenced to NAVD88). Interpolation of these biases from the station locations to the Hudson grid was done through the use of ESRI© ArcGIS spline interpolation with boundaries at a regular 0.0001 degree (approximately 11 meter) grid. No smoothing was applied. The three interpolated bias fields were added to the respective model-based datum surfaces. Thus, all new Hudson River datums passed exactly through the observed datums. The resulting tidal datum surfaces have been delivered as geo-referenced raster grids, with metadata. Results compared favorably to preexisting NOAA VDATUM surfaces for the tidal Hudson south of Kingston, NY. Thus, an expansion of this work is suggested to generate all the tidal datums for the Hudson and replace the existing VDATUM.
Introduction

Stevens Institute of Technology has been running an operational forecast model, called NYHOPS since 2006 (www.stevens.edu/NYHOPS), forecasting water levels, 3D currents, waves, and CDOM for the coastal waters of 7 US states 72hrs into the future. The numerical model is based on the sECOM code, a Princeton Ocean Model variant that solves the physical Navier-Stokes equations on a curvilinear grid. The operational model grid’s horizontal resolution includes the NY/NJ Harbor Estuary, as well as the tidal waters of the Hudson River 240km north of Manhattan to the Federal Dam at Troy. The model, built and maintained at Stevens, after a rigorous NOAA-OFS-metrics-based validation process, is operationally used by NWS for storm surge warnings, USCG for SAR operations, OR&R for fate and transport, and is the operational model component of the NOAA IOOS for the NY/NJ Harbor and surrounding waters. The model’s forecasting accuracy had been documented to be the best in the region (DiLiberto et al 2011).

Beginning in 2011, a new, higher resolution numerical model grid for the Hudson has been constructed at Stevens Institute of Technology (Figure 1). The new grid has 68m average resolution for the Hudson waters from Yonkers, NY to Troy, NY. It resolves to a very good extend all of the Hudson’s waters to the Hudson River NYSDEC GIS Clearinghouse coastline as well as the river’s tributaries to their head of tide. Model bathymetry is based on the most recent available bathymetric and topographic surveys of the area, and uses geodetic NAVD88 as the bathymetric datum. The new tidal Hudson model was set up and ran in the year 2010, providing output every half an hour at each of 77,452 locations. It was forced with observed 6-minute total water levels at the River’s southern mouth, observed watershed-area-adjusted 15-minute locally distributed river inflows from the Hudson and its tributaries north of the Troy Dam and at tributary heads-of-tide along its tidal coastline, monthly estimates of distributed water treatment plant effluents at main outfall locations, monthly estimates of distributed power plant inflow and outflow at locations of intakes and outfalls, and meteorological analysis surface winds and barometric pressure forcing. The model run was validated against observed water levels at 5 real-time stations with observations in 2010 with a mean total water level (tidal and surge) RMSE of 8cm (Georgas 2012b).

Stevens Institute of Technology was tasked to extract and use the new Hudson model’s water level data from the 2010 model run, debias the model based on available observations, and calculate the Mean Higher High Water (MHHW) and Mean Lower Low Water (MLLW) tidal datum surfaces in the Hudson River north of the City of Yonkers, NY up to the Troy Dam, referenced to NAVD88.

Stevens was also tasked to compare the new MHHW and MLLW surfaces it created to a preexisting NOAA VDATUM product for the River. The preexisting VDATUM surfaces were created for the Hudson River, as
part of a Great-South-Bay- (Long Island)-focused project, with an older 2D model (ADCIRC) that simulated astronomical-tide-only dynamics in the New York Bight and New York Harbor area. Figure 2 summarizes that report’s process for creating the VDATUM for the area that includes the lower Hudson up to Kingston, NY: a long water level time series for NTDE(1983-2001) was reconstructed for calculating datums based on a 40-day ADCIRC run, and corrected (de-biased) by observations, of which very few were available on the Hudson.

The project started on August 20th 2013 and was completed on December 20th 2013.

**Methods**

We first extracted the year 2010 Hudson River model water level time series at each of 77,452 locations and for every half hour. We then applied and run the software and calculated preliminary (before debiasing) model-based MHHW and MLLW datums at all model cells. In order to produce as accurate a tidal datum as possible, we needed to account for the whole synodic 19 year tidal epoch. We used the methodology of the original work for the Hudson River VDATUM (NOAA 2010, Figure 2, but for our NYHOPS sECOM model, not ADCIRC) to do just that, by first calculating the standard NOS tidal constituents at every model cell based on the simulated water level time series from the 2010 Hudson numerical model run, reconstructing the astronomical tide time series based on the calculated standard NOS constituents for a 19 year tidal epoch at each cell, and finally calculating the MHHW, MSL, and MLLW at each cell from these 19 year time series. These values are all referenced to NAVD88, the model’s datum (Figure 3). We then subtracted the computed MSL from the MHHW and MLLW values, to reference MHHW and MLLW to MSL, the negative of the Topography of the “Sea” Surface (in this case, River Surface). The MHHW and MLLW surfaces referenced to MSL could be, and were, then directly compared to the corresponding surfaces from NOAA’s VDATUM which are also referenced to MSL (Figures 4-5). Note that the published NOAA VDATUM surfaces did not include all of the Hudson, but stopped near Kingston, NY. The published NOAA VDATUM surfaces are also modeled-based (using ADCIRC), but also debiased with observations. However, observations in the Hudson were very scarce during the original VDATUM study (NOAA 2010). It will be shown that this lack of stations to debias the ADCIRC model with created a problem with the preexisting VDATUM dataset.

To debias our NYHOPS sECOM model, and provide an independent level of comparison to the preexisting VDATUM surface, we collected time series of observed water level records along the Hudson River from the in-house NYHOPS databases for 2010, expanded their time span backwards through official, verified, USGS and NOS web services, and calculated the same datums [MSL referenced to NAVD88 (the negative
equivalent of VDATUM’s TSS surface), MHHW referenced to MSL, and MLLW referenced to MSL] based on these observations at 13 locations along the tidal Hudson River (Figure 6 and Table 1). We looked for data from the following agencies/networks: NOAA/NOS, USGS, HRECOS (Hudson River Environmental Conditions Observing System), all with Quality Assurance Plans, and REON (River and Estuary Observatory Network). We were successful in gathering water level data from NOAA NOS (www.tidesandcurrents.noaa.gov), USGS (http://waterdata.usgs.gov/usa/nwis/rt), and HRECOS (http://www.hrecos.org/joomla/) stations (Table 1). In situ water level observations at these stations were originally reported to us as either referenced to NAVD88 or NGVD29. For the stations referenced to NGVD29 we used the VertCon tool of the National Geodetic Survey (NGS) to convert to NAVD88 (http://www.ngs.noaa.gov/TOOLS/Vertcon/vertcon.html). The observed time series of water levels referenced to NAVD88 at these stations were also used to calculate tidal constituents, reconstruct a 19 year tidal epoch time series, and, from that, calculate MHHW, MSL, and MLLW values referenced to NAVD88 at these stations. We also downloaded and compared the various datasets with the three available published NOS benchmark datums in the Hudson for the latest NTDE of 1983-2011 (Albany, Haverstraw, and the Battery; e.g. http://tidesandcurrents.noaa.gov/benchmarks.html?id=8518995).

We compared the preliminary (Figure 3) and observed MHHW and MLLW datums at the locations of gages with data. After QA/QC, analysis at 11 stations and 2 benchmarks were used for MHHW and MLLW. In order to use the maximum number of available observations for our analysis, and at the same time check the robustness of the observations record and our method, we performed the same calculation a second time after filling gaps larger than 6 hours in the observation record with the reconstructed astronomical tide series at each station. (The standard method that NOS uses to fill in shorter gaps is linear interpolation for up to 2hrs, and Single Value Decomposition for up to 6 hours). Through this analysis it was deduced that some calculated datums from 3 out of 13 stations varied significantly within the observation record. After significant effort was spent to try and retain the record of the station showing the largest inconsistency in the observed record, Tivoli Bays South (up to 35cm), we concluded that that record was unsuitable for the tidal epoch reconstruction within the time frame allotted to this project. Thus, we did not consider that station further; a nearby station, Tivoli Bays North, did not exhibit the same problem. The MSL values (referenced to NAVD88) of two other stations, George Washington Bridge and Schodack Island were also considered questionable: MSL values before and after gap filling were considerably different, 7.5cm at Schodack, and 16.1cm at George Washington Bridge (GWB). MSL, MHHW, and MLLW datum differences were within 2cm after gap filling for all other stations. Since the accuracy criterion for the study is 9cm, we decided to exclude GWB MSL in our comparisons (perhaps due to inconsistent
leveling within the observation record, or other reasons), and include Schodack Island as noted. MSL at NAVD88 for all other stations were within 2cm before and after gap filling (average discrepancy 9mm). Tidal reconstruction (at MSL) at the two stations with MSL problems was found sufficiently reliable to be used for MHHW and MLLW calculations referenced to MSL. All 12 remaining station records for MHHW and MLLW were accurate within 4.5cm, (average 1.4cm, 1.7cm, resp.) after manual QAQC and elimination of obvious non-event outliers in their records.

We also calculated a similarly model-based, observation-debiased, new MSL layer, referenced to NAVD88, for the Hudson River to Troy, NY. This is in fact required for conversion of the datum surfaces to NAVD88, so that results could correctly be debiased and referenced to NTDE 1983-2001, and it was found not to be available north of Kingston, NY: The VDATUM TSS (which is the negative of the MSL) stops there. Since the time span of the observation records available to us varied from station to station, a technique based on the standard tidal datum method for semidiurnal tide (NOAA 2003) was used to convert monthly averaged sea levels at each station to the (latest official) 1983-2001 NTDE MSL values by using the Battery as the primary control station. This also enabled direct comparison of the results of our analysis at these stations with the two published NOS benchmarks (tidal datums, including MHHW, MLLW, MSL, and NAVD88 elevations) collected and downloaded from the NOAA database at Albany and the Battery, and a mid-Hudson benchmark at Haverstraw Bay. As in our adopted methodology, the published NOS benchmark datums at Albany and Haverstraw are also reported on the NOAA website to have used the Battery as the control station.

We finally de-biased the preliminary surfaces, and created the MHHW, MLLW, and MSL datums through the use of the ESRI© ArcGIS spline interpolation with boundaries. No smoothing was applied. The biases of the model to the observations at stations were mapped, interpolated, and the interpolated field was added to the modeled datum surfaces. Thus, all new datums passed exactly through the observed datums. Quality control of the final product against the observations used in the analysis showed differences less than 0.001m. The raster datasets were created in ArcGIS 10.2 and we included metadata in FGDC format.
Results

Comparisons of raw-model-derived datums to observation-derived datums

Comparisons of the results of our analysis at locations with multiple datasets are tabulated in Table 2 and are shown in Figure 7. Based on these comparisons the calculated MHHW and MLLW values from the raw Hudson sECOM model compare very well with the observation based values. Differences between model-based MHHW and MLLW values to observation-based values were small and for the most part within the stated uncertainty around LiDAR datasets, 9cm, that was agreed as a metric for acceptance without a need to de-bias. The mean absolute error (MAE) in the model’s MHHW values across the 12 stations was 2.3cm, while the MAE for MLLW was 5.3cm. Model-based MHHW for all stations was within 9cm of observed. MLLW was also within 9cm of observed, except at two stations: Tivoli Bays North (10.9cm) and Norrie Point (10.5cm). Therefore de-biasing of the new model with observed data was required.

Comparisons of raw-model-derived datums to preexisting VDATUM

VDATUM’s northern extend is at Kingston, NY. Figures 4-5 show the differences between the downloaded NOAA VDATUM MHHW and MLLW surfaces (“VDATUM”) minus the new raw model-based MHHW and MLLW surfaces. In both cases, negative differences mean that the new model surfaces are above the VDATUM surfaces for both MLLW and MHHW. As also seen in Table 2 and Figure 2 against data, the existing VDATUM MHHW surface appears to be low by some 20cm in the middle of the domain. For the 8 stations south of Kingston, NY, where VDATUM results were available, the respective Hudson model errors are 2.5cm and 4.3cm, respectively. Comparing these values with the VDATUM MAE of 5.6cm and 2.5cm, respectively, it can be said that the raw-model-based datums before debiasing are overall comparable or better than the already debiased published VDATUM surfaces. The debiased VDATUM compares better for MLLW, and worse for MHHW. The opposite is true for the model. In fact, the MHHW error of the debiased VDATUM reaches -13.7cm at the Marist College Pump Station. The Hudson model’s worst performance (before debiasing) is also in the middle region of the tidal Hudson (10.9cm, Tivoli Bays North).

Comparisons to NOAA benchmarks

An important comparison is between the observation-based, model-based, and VDATUM-based (where available) datum values against the published datum sheets at the three NOS benchmark stations. First, the comparison between our newly calculated observation-based datums and the published ones at
Albany and the Battery is excellent and maintains that the methods we used to calculate the tidal datums from the observations have little error, well below the required 9cm for this project, and that these datums can be reasonably used for debiasing the model-based surfaces. The MHHW values are within 3mm. The maximum discrepancy is the observation-based MLLW value at Albany, which is 4.4cm higher than published. The published NOS datums at Albany were based on an older 5 year record (July 1982-June 1987). We used a newer 7 year record as can be seen on Table 1. Therefore the results of our tidal datum analysis based on the USGS gage at the Hudson River at Albany were used to debias our model results. The differences between our analysis and the benchmark were: -0.2cm, +4.4cm, and +3.8cm for MLLW @ MSL, MHHW @ MSL, NTDE1983-2001 MSL @ NAVD88. The symbol “@” is used here to mean “referenced to.” It should be noted that the tide at Albany is non-stationary, with periods of freshets coming over the nearby Troy dam as well as periods with winter ice cover, both known to dissipate primary lunar forcing especially at low waters on a non-tidal event-driven basis (Georgas 2012a). The mean sea level (river level) of the upper tidal Hudson at Albany, NY does not always co-vary with the MSL of the primary tidal station used in tidal epoch conversions, at the Battery, NY. The Battery station is at the mouth of the Hudson 150 miles downstream, away from such influences as the dynamic hydraulic head due to the river’s discharge near Albany. This can be seen in Figure 7: The standard deviation of the difference between the monthly averaged water levels at the Battery and 10 observation stations is low (order 3cm) for stations south of Norrie Point, and then increases to order 15cm at Albany.

Second, comparisons of the debiased-VDATUM datums against the two benchmarks within the VDATUM region (Haverstraw and the Battery) are also excellent. The difference for each of the three datums is within 4-7mm at the Battery. The comparison is perfect for MLLW and MHHW at Haverstraw (referenced to MSL); the difference for MSL referenced to NAVD88 is 1.9cm there. These published datums were used to de-bias the ADCIRC-modeled surfaces during the creation of VDATUM, which explains the low remaining bias.

Third, comparisons of the raw model against published NOS benchmark datums also show the same order of difference as comparisons to the new observations in this study: The MHHW difference in the raw model is 2cm at Albany, 4.1cm at Haverstraw, and just 3mm at the Battery. The MLLW error is 4.4cm, 1cm, and 6.4cm, respectively. The MSL difference is 3.5cm, 6.4cm, and 9.3cm, respectively. These are all before any debiasing of the Hudson model. This order of MSL difference is expected, as the model was not run for a 19 year epoch, and MSL has approximately risen by a long term rate of 2.77mm/year*18years=5cm from the middle of the last NOS NTDE (1992) to 2010. (The actual difference between the MSL of the 1983-2001 NTDE and the average of the hourly observed time series at the Battery collected in 2010 is 12.4cm!). We
thus converted the model MSL to NTDE 1983-2001 by using the Battery as our Primary station. After conversion, Table 2 and Figure 7 show that, for the existing-VDATUM region, results between the model and the existing VDATUM are comparable against observations: The MAE of MSL for the model is 2.3cm, while for the debiased VDATUM is 1.4cm. For the Hudson as a whole, the model MAE rises to 4.1cm, with the highest differences again near Albany (9.6cm at Albany, 10.9cm at the Port). The Hudson modeled MSL (-TSS) surface thus required de-biasing from observations.

**Final debiased surfaces and comparisons to preexisting VDATUM product**

The interpolated bias fields from model to observations are seen in Figure 8.

Figures 9-10 show the final deliverable products. We provided the new MHHW and MLLW datum surfaces in a geo-referenced GIS format through Google Drive: https://drive.google.com/file/d/0B2K9CSGfq-W4WENicUZ5bjdhS0E/edit?usp=sharing. The total size of the 5 delivered surfaces is 1.5GB, zipped to 35MB. It should take about 5-10 minutes to download from google drive. The Appendix at the end of this report explains the provided datasets and has instructions for their use.

Figure 11 shows the comparison of these new de-biased datums against the existing VDATUM. Within the common river stretch, differences exist that can be as high as 15.9cm MHHW near Poughkeepsie, NY where the existing MHHW VDATUM is found to be low as also seen in Figure 7. Interestingly, comparison of Figure 8 to Figure 11 shows that the biases shown in Figure 8 for the raw Hudson model were comparable, if not smaller, than the errors discovered in the processed VDATUM product south of Kingston, NY.

With regard to the south and north boundaries of the common domain in Figure 11, at Yonkers (just south of Tarrytown) and Kingston, respectively, absolute differences are smaller: Less than 0.5cm for NTDE 83-01 MSL, less than 3.1cm for MHHW, and less than 6.1cm for MLLW. The mean difference between our new product and the existing VDATUM, and the standard deviation of that difference, at the southern boundary of our new products at Yonkers can be found in Table 3.

**Conclusions and recommendations for future work**

Based on the above analysis, we find the existing NOAA VDATUM surfaces reasonable, but considerably inaccurate, especially at MHHW. We recommend a follow-up study to replace NOAA VDATUM with guidance from our new Hudson model and an extended methodology based on what we learned in this project.
The published datums compared very well with the various datasets considered, with the largest deviation (order 5cm) being against the NOS benchmark at Albany, NY (Figure 7). The reason for that deviation is that the mean sea level (river level) of the upper tidal Hudson at Albany, NY does not always co-vary with the MSL of the primary tidal station used in tidal epoch conversions, at the Battery, NY. The Battery station is at the mouth of the Hudson 150 miles downstream, away from such influences as the dynamic hydraulic head due to the river’s discharge near Albany. The standard deviation of the difference between the monthly averaged water levels at the Battery and 10 observation stations is low (order 3cm) for stations south of Norrie Point, and then increases to order 15cm at Albany. It would therefore be interesting to test a methodology that assigns either Albany or the Battery as the control station to a secondary station, based on the covariance of monthly-averaged statistics.

Finally, further sECOM model development is ongoing, including direct assimilation of observed time series directly within the model’s dynamic simulation. Improved accuracy of the raw model datums could result from such a run, and it could be tested against independent, unassimilated, observations.
References


Acknowledgements

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Referenced Tables and Figures follow
Table 1. Hudson River water level stations considered in this study for tidal datum calculation.

<table>
<thead>
<tr>
<th>Source</th>
<th>Station name</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Data freq.</th>
<th>Downloaded time span</th>
<th>Data gaps</th>
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<td>NOAA</td>
<td>The Battery, NY</td>
<td>40.700000°N</td>
<td>74.013333°W</td>
<td>6 mins</td>
<td>1995-11-29 / 2013-08-31</td>
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<td>USGS</td>
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<td>42.646111°N</td>
<td>73.747500°W</td>
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<td>2007-10-01 / 2013-09-08</td>
<td>Yes</td>
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<td>USGS</td>
<td>Hudson River at Piermont, NY</td>
<td>41.043194°N</td>
<td>73.896056°W</td>
<td>15 mins</td>
<td>2010-11-03 / 2013-09-08</td>
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<td>USGS</td>
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<td>USGS</td>
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<td>41.650833°N</td>
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<td>73.942139°W</td>
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<td>HRECOS</td>
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<td>HRECOS</td>
<td>Pump Station at Marist College, NY</td>
<td>41.720583°N</td>
<td>73.938778°W</td>
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<td>HRECOS</td>
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<td>42.499611°N</td>
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<td>2011-10-03 / 2013-09-04</td>
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Table 2. Calculated datums for water level stations, m.

Based on the observation periods in Table 1 converted to NTDE 1983-2001. The Battery and Hudson at Haverstraw show published benchmark datums.

<table>
<thead>
<tr>
<th>Station</th>
<th>ID</th>
<th>MHHW, m above MSL</th>
<th>MSL for NTDE 1983-2001, m above NAVD88</th>
<th>MLLW, m above MSL</th>
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<td>Hudson River at Albany, NY (1)</td>
<td>ALB</td>
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<td>-0.825</td>
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<td>PAL</td>
<td>0.848</td>
<td>0.355</td>
<td>-0.839</td>
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<td>Schodack Island, NY</td>
<td>SCI</td>
<td>0.824</td>
<td>0.266</td>
<td>-0.785</td>
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<td>Tivoli Bays North, NY</td>
<td>TIN</td>
<td>0.644</td>
<td>0.102</td>
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<td>Norrie Point, NY</td>
<td>NOP</td>
<td>0.630</td>
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</tr>
<tr>
<td>Hudson River at South Dock at West Point, NY</td>
<td>WPT</td>
<td>0.551</td>
<td>0.014</td>
<td>-0.526</td>
</tr>
<tr>
<td>Hudson River at Haverstraw, NY</td>
<td>HAV</td>
<td>0.570</td>
<td>0.050</td>
<td>-0.550</td>
</tr>
<tr>
<td>Hudson River at Piermont, NY</td>
<td>PIE</td>
<td>0.623</td>
<td>0.037</td>
<td>-0.586</td>
</tr>
<tr>
<td>Hastings-on-Hudson, NY</td>
<td>HAS</td>
<td>0.607</td>
<td>0.025</td>
<td>-0.586</td>
</tr>
<tr>
<td>George Washington Bridge, NJ</td>
<td>GWB</td>
<td>0.653</td>
<td>-0.037</td>
<td>-0.678</td>
</tr>
<tr>
<td>Battery, NY</td>
<td>BAT</td>
<td>0.755</td>
<td>-0.063</td>
<td>-0.766</td>
</tr>
</tbody>
</table>

(1) The results of our tidal datum analysis based on the USGS gage at the Hudson River at Albany, tabulated here, were used to debias our model results. We did not use the published NOS benchmark datasheet at Albany, as it was found to be based on an older and smaller time period of analysis (5 years) than ours (almost 7 years, Table 1). The differences between our analysis and the benchmark were: -0.2cm, +4.4cm, and +3.8cm for MLLW @ MSL, MHHW @ MSL, NTDE1983-2001 MSL @ NAVD88. @ here means “referenced to.” For further discussion on this apparent discrepancy, please see text.
### Table 3. Differences (meters) between NOAA VDATUM and the new (De-biased) surfaces at the southern edge of the latter near Yonkers, NY

<table>
<thead>
<tr>
<th>Datum</th>
<th>Mean difference</th>
<th>STD of difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>MHHW (@MSL)</td>
<td>-0.0222</td>
<td>0.0006</td>
</tr>
<tr>
<td>MLLW (@MSL)</td>
<td>+0.0037</td>
<td>0.0006</td>
</tr>
<tr>
<td>TSS (@MSL) (1)</td>
<td>-0.0028</td>
<td>0.0005</td>
</tr>
</tbody>
</table>

(1) The Topography of the Sea Surface (TSS) is the difference between NAVD88 and MSL. Thus, the MLS@NAVD88 surface calculated in this study is directly comparable to the negative of TSS. Both are referenced to the NTDE of 1983-2001.
**Figure 1.** A zoom of the Hudson River numerical hydrodynamic model around Norrie Point, NY. The model was set up and run in calendar year 2010.
Figure 2. Process for creating VDATUM.
Figure 3. Geo-referenced tidal datum surfaces (m above NAVD88) for the tidal Hudson River based on the year-2010 numerical-model-simulated water level time series, converted to the 1983-2001 NTDE.
Figure 4. Differences (m) between MHHW based on VDATUM minus MHHW based on the model.
Figure 5. Differences (m) between MLLW based on VDATUM minus MHHW based on the model.
Figure 6. In situ water level observation stations considered for Hudson River tidal datum calculation and comparison to numerical model results and the existing VDATUM for this project. Legend lists respective agencies/networks. The primary NOS station for the Hudson is the Battery, NY. The Battery, Hudson River at Haverstraw and Hudson River at Albany have published NOS Benchmarks for the 1983-2001NTDE.
Figure 7. Datum comparisons at observations stations between observation-based and model-based results from this study. Existing-VDATUM-based datums and published NOS benchmarks are also shown. MHHW and MLLW are referenced to MSL. MSL converted to NTDE 83-01 referenced to NAVD88. Also shown is the standard deviation of the difference between monthly-averaged sea level at the Battery against concurrent data at other stations. Model results are raw here (not de-biased).
**Figure 8.** Bias corrections applied to Hudson-model-derived fields so that the modeled datums pass through the observed. From left to right: MSL, MHHW, and MLLW bias, meters. These fields were created with ArcGIS spline interpolation (with barriers) of the difference between the modeled and the observed field at the station locations. They were added to the respective model results to debias them so that they can pass through the observed values.
Figure 9. Project Deliverable Products 1-2: Observation-de-biased modeled surfaces referenced to MSL, meters.
Figure 10. Project Deliverable Products 3-5: Observation-de-biased modeled surfaces referenced to NAVD88, meters. MSL is the negative equivalent of VDATUM’s TSS (NTDE 83-01).
Figure 11. Comparison between the newly created vertical tidal datums for the Hudson River (model-based, de-biased by observations) to the existing NOAA VDATUM to the latter’s northern extent at Kingston, NY. Differences are new datum minus VDATUM, in meters. Positive values indicate VDATUM is biased low, negative values indicate VDATUM is biased high. From left to right: MSL NTDE 1983-2001 referenced to NAVD88, MHHW referenced to MSL, MLLW referenced to MSL.
APPENDIX

How to display the raster datasets and associated metadata on ArcGIS or other GIS software:

First download and unzip the Final_Products_With_Metadata.zip file. The zip software will unzip the
directory “Final_Products_With_Metadata” that contains the 5 surfaces (the georeferenced “datasets”).

Although there will be many files and subfolders in the “Final_Products_With_Metadata” folder, these
only comprise 5 raster datasets, each with its own metadata. As always with GIS data, a dataset comprises
multiple binary files and, in the case of a raster, folders.

Each of the dataset and its metadata can be viewed in ESRI ArcMap, for example, (or other GIS software,
including free Arc Explorer, and open-source qGIS), by opening that software, clicking on “import data”
(“+” button in ArcMap), navigating to the directory “Final_Products_With_Metadata” and selecting any of
the five new raster datasets that are available:

1. “mhhw-msl”: The MHHW surface referenced to Mean Sea Level (MSL),
2. “mllw-msl”: The MLLW surface referenced to MSL,
3. “msl-navd88”: The MSL surface referenced to NAVD88, (the negative recalculation of
   VDATUM’s Topography of the Sea Surface (TSS) based on new observations referenced to
   the latest 1983-2001 NOS National Tidal Datum Epoch)
4. “mhhw-navd88”: The MHHW surface referenced to NAVD88 (from 1 and 3 above), and
5. “mllw-navd88”: The MLLW surface referenced to NAVD88 (from 2 and 3 above).

Note that some software will also show files such as mhhw-msl.ovr, etc. These files are just overview files,
not the real datasets.

To view the metadata, you can either navigate to the subfolder for each dataset and click to load the .xml
file there, or you can use ArcGIS:

E.g in ArcGIS 9, right-click on the dataset after you import it, then “data” then “view metadata”, and select
stylesheet “XML” or “ISO”. Since the metadata were created with ArcGIS 10, they are best viewed in
ArcGIS 10.

Once loaded onto a GIS package, you can get the specific datum at every mapped location by selecting the
“identify” (i) button and clicking on that location on the map.