Appendix 8-B: Thermal Analysis

B&B Engineers & Geologists
of new york, p.c.
an affiliate of Geosyntec Consultants

10777 Westheimer Rd., Suite 900
Houston, TX 77042
PH 281 920 4601
www.geosyntec.com

Memorandum

Date:	December 10, 2024
To:	Neil Henderson and Casey Sengstaken – CHPE LLC | TDI-USA Holdings LLC
Copies to:	Rudy Bonaparte, Ph.D., P.E. (NY) and Jared Brisman, P.E. (NY) – B&B Engineers & Geologists of New York, P.C.
From:	Jeff Rominger, Ph.D., John Kondziolka, M.S., and Logan Brant, Ph.D., P.E. (NY) – B&B Engineers & Geologists of New York, P.C.
Subject:	Thermal Analysis for the Champlain Hudson Power Express® Transmission Project: Harlem Riverbed Installation Case for the 1,250 MW DC Transmission Cables
B&B Project No.	GHZ3285/600

EXECUTIVE SUMMARY

This memorandum summarizes the thermal analysis performed by B&B Engineers & Geologists of New York, P.C. (B&B), an affiliate of Geosyntec Consultants, Inc., in support of the submarine installation of high voltage direct current (HVDC) cables for the Champlain Hudson Power Express® (CHPE) directly on the riverbed of the Harlem River. The objective of this thermal analysis was to determine whether the heat generated by the normal operation of the HVDC cables satisfies the New York State requirements for thermal discharges to water bodies in 6 NYCRR, Part 704.2 (NYSDEC, 2023). For this analysis, increases in Harlem River water temperatures above pre-CHPE conditions were calculated at all water depths for a modeled cross section of the river following the installation of the CHPE HVDC cables. Based on this thermal analysis, B&B concluded that installation of the CHPE HVDC cables directly on the bed of the Harlem River will comply with the New York State requirements that govern thermal discharges to water bodies in 6 NYCRR part 704.2 (NYSDEC, 2023).

INTRODUCTION

The CHPE is being developed by Transmission Developers, Inc. USA Holdings LLC (TDI-USA). The power transmission project will deliver renewable electric power to New York from hydroelectric sources in Quebec, Canada, through a pair of nominal 5-inch diameter buried HVDC power cables. The buried cables will extend from the United States-Canada border to a converter station in Astoria, Queens. For the 6.2-mile segment of the Project through the Harlem River, the cable bundle will be installed directly on the riverbed (*i.e.*, unburied installation).

B&B was retained by TDI-USA to provide geotechnical engineering, thermal modeling, and electric and magnetic field (EMF) modeling services for the segment within the Harlem River where the CHPE HVDC cables will be placed on top of the sediment at the bottom of the river (referred to below as "riverbed installation" of the HVDC cables). This memorandum summarizes B&B's thermal analysis for the riverbed installation of the HVDC cables, as requested by the New York State Department of State (NYS DOS).

ENVIRONMENTAL CONDITIONS AND SELECTED PROPERTIES PERTINENT TO THERMAL ANALYSIS

The CHPE HVDC cables will be placed on top of the sediment at the bottom of the Harlem River. During normal operation of the CHPE HVDC cables, electricity passing through the cables will generate heat that will dissipate through the surrounding environment, including through the riverbed sediment, as well as through the Harlem River water and into the air. While dissipating through the surrounding Harlem River water, this heat has the potential to increase the water temperature in the vicinity of the cable. Figure 1 shows the modeled infrastructure and environment.

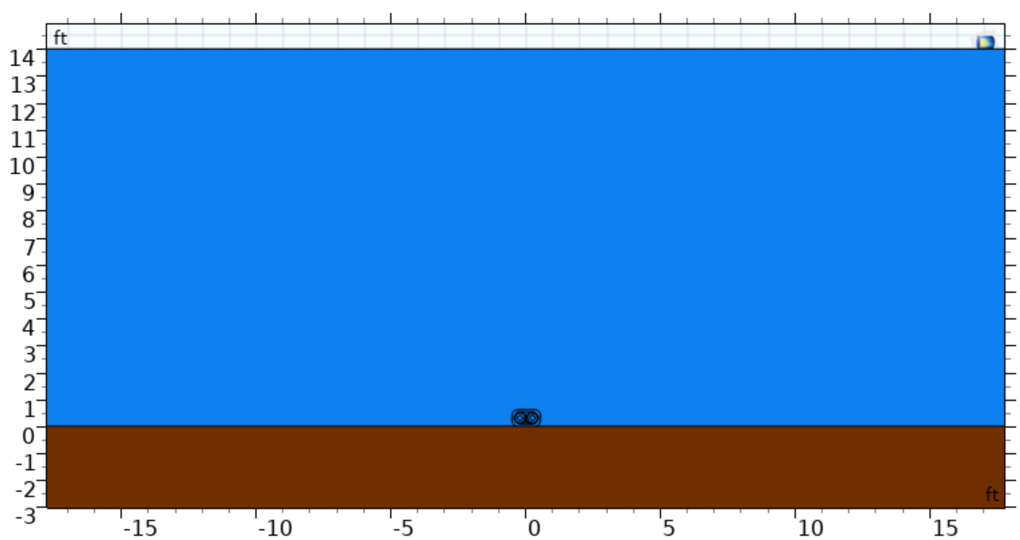

Figure 1. Model Geometry for Harlem River Cross Section with CHPE Infrastructure. CHPE = Champlain Hudson Power Express®. Blue indicates

free-flowing water; brown indicates the existing river bottom sediments. The CHPE infrastructure resting on the sediment is outlined in black.

Historical Harlem River water temperatures have been measured by multiple agencies, including the New York City Department of Environmental Protection (NYCDEP) and United States Environmental Protection Agency (US EPA) (USGS, 2016). Harlem River water temperatures have generally been measured between 34- and 81-degrees Fahrenheit for measurements from 1985 to 2012 (USGS, 2016). For the thermal analysis, an upper-bound water temperature of 81 degrees Fahrenheit was conservatively applied to the entire depth of the Harlem River as the pre-CHPE water temperature.

The thermal conductivities/resistivities, heat capacities, and densities of the local environmental media control the distribution of heat surrounding the CHPE HVDC cables. The thermal properties modeled are shown in Table 1. Heat capacities and densities for air and water were assigned from the material library associated with the computer software program used for the thermal analysis, COMSOL® (COMSOL - Software for Multiphysics Simulation). COMSOL is a multiphysics modeling system that has been "subject to extensive verification and validation" (US EPA, 2010, p. 118) and is routinely used for modeling thermal impacts from utility infrastructure (*e.g.*, OWC *et al.*, 2023). The thermal resistivity of the existing sediment was assigned an upper-bound value for cohesionless Harlem River material per agreement with TDI-USA. An effective thermal conductivity (the inverse of the effective thermal resistivity) of the Harlem River water was calculated using a combination of the thermal properties of water and the flow properties of the Harlem River.[1] Flowing water will have a higher effective thermal conductivity (lower resistivity) than static water due to the turbulent mixing and resultant transport of heat that occur when water is flowing.

The water depth in the Harlem River varies, with a reported minimum depth of approximately 14 ft (HDR Engineering, Inc., 2012, p. 38). For the purpose of evaluating maximum potential thermal impacts, we selected the shallowest water depth as the basis for the thermal analysis.

[1] An effective thermal conductivity of flowing Harlem River water was calculated using a conservatively low characteristic velocity of 10 cm/s. From this, a friction velocity (u^*) and surface water slope were calculated *via* Manning's Equation using a roughness factor 0.035 (for "natural streams – major rivers") and the depth (d) and width of the Harlem River. The turbulent diffusivity of the river was modeled using $\varepsilon_v = 0.067du^*$ (Fischer *et al.*, 1979). By equating the turbulent thermal diffusivity of flowing water to the thermal diffusivity in the heat equation, an effective thermal conductivity of flowing water ($K_{effective}$) can be calculated by $K_{effective} = \varepsilon_v c_p \rho$, where c_p is the heat capacity of water and ρ is the density of water.

Table 1. Summary of Modeled Environmental Thermal Properties

Environmental Parameters	Value/Range	Source
Harlem River high-end temperature condition	81 F	High-end value for Harlem River temperature data 1985-2012 (USGS, 2016)
Harlem River minimum water depth	14	HDR Engineering, Inc. (2012, p. 38)
Harlem River water thermal properties		
Effective thermal resistivity of flowing water in Harlem River	8.6E-5 K-m/W	Calculated based on turbulent diffusivity of flowing water at 0.1 m/s
Water heat capacity	4,187 J/kg-K	COMSOL® material library
Water density	1,010 kg/m^3	COMSOL® material library
Sediment and subsurface thermal properties		
Sediment and subsurface thermal resistivity	1.31 K-m/W	Attachment AA of the Engineering, Procurement, and Construction Agreement between CHPE LLC and NKT Inc.
Sediment and subsurface heat capacity	1,632 J/kg-K	COMSOL® material library for saturated sand
Sediment and subsurface density	1,500 kg/m^3	COMSOL® material library

NEW YORK STATE DEPARTMENT OF ENVIRONMENTAL CONSERVATION DIVISION OF WATER RESOURCES CRITERIA GOVERNING THERMAL DISCHARGES

New York State has established criteria that govern thermal discharges to state water bodies (6 NYCRR Part 704.2) (NYSDEC, 2023). These criteria include both general criteria that apply to all state water bodies as well as special criteria that are specific to each type of water body in the state. The general criteria (6 NYCRR Part 704.2(a)) state (NYSDEC, 2023):

> The following criteria shall apply to all waters of the State receiving thermal discharges, except as provided in section 704.6 of the Part:
>
> (1) The natural seasonal cycle shall be retained.
> (2) Annual spring and fall temperature changes shall be gradual.
> (3) Large day-to-day temperature fluctuations due to heat of artificial origin shall be avoided.
> (4) Development or growth of nuisance organisms shall not occur in contravention of water quality standards.
> (5) Discharges which would lower receiving water temperature shall not cause a violation of water quality standards and section 704.3 of this Part.
> (6) For the protection of the aquatic biota from severe temperature changes, routine shut down of an entire thermal discharge at any site shall not be scheduled during the period from December through March.

The special criteria that apply to the Harlem River, an estuarine water body, are (6 NYCRR Part 704.2(b)(5)) (NYSDEC, 2023):

(i) The water temperature at the surface of an estuary shall not be raised to more than 90 degrees Fahrenheit at any point.

(ii) At least 50 percent of the cross sectional area and/or volume of the flow of the estuary including a minimum of one-third of the surface as measured from water edge to water edge at any stage of tide, shall not be raised to more than four Fahrenheit degrees over the temperature that existed before the addition of heat of artificial origin or a maximum of 83 degrees Fahrenheit whichever is less.

(iii) From July through September, if the water temperature at the surface of an estuary before the addition of heat of artificial origin is more than 83 degrees Fahrenheit an increase in temperature not to exceed 1.5 Fahrenheit degrees at any point of the estuarine passageway as delineated above, may be permitted.

(iv) At least 50 percent of the cross sectional area and/or volume of the flow of the estuary including a minimum of one-third of the surface as measured from water edge to water edge at any stage of tide, shall not be lowered more than four degrees from the temperature that existed immediately prior to such lowering.

CHPE HVDC CABLE BUNDLE PROPERTIES

B&B modeled the CHPE HVDC cables using cable bundle specifications and electrical properties provided by TDI-USA. The geometry of the CHPE HVDC cable bundle was interpreted from Lankhorst (2024) (Figure 2). As illustrated in Figure 2, the HVDC cable bundle will consist of two single-core submarine cables – one positively charged and the other negatively charged – bundled together in a horizontal arrangement (*i.e.*, touching side-by-side during installation, with a separation distance of 138 mm for the conductor centers). The single-core cables will consist of a copper conductor that is surrounded by a number of different layers that include insulation, metal sheath, metal armor, and an outer covering consisting of two layers of black polypropylene yarn with the inner layer impregnated with bitumen (NKT HV Cables AB, 2022). As compared to the total external cable diameter of 138 mm, the conductors will have an outer diameter of 57.8 mm. The submarine cables will be encased by the UraGUARD Cable Protection System (CPS), which will have a nominal thickness of 25 mm. Under the installation conditions, the HVDC cables have a rated continuous current of 1,638 amps. Table 2 summarizes these cable dimensions and thermal properties used for the thermal modeling analysis.

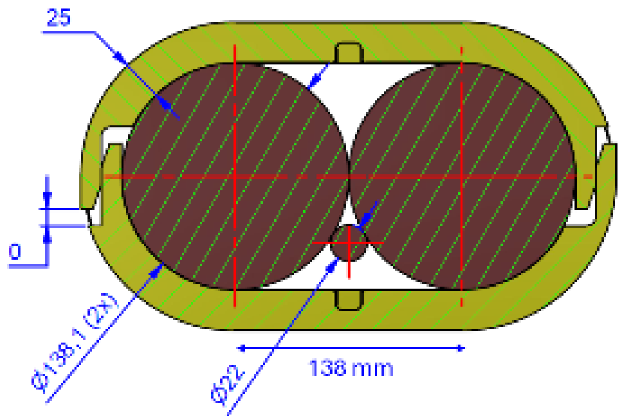

Figure 2. UraGUARD CPS Cross Section (dimensions in mm) (Lankhorst, 2024). CPS = Cable Protection System. Note that the cross section does not show the different cable components discussed above. As discussed above and indicated in Table 2, the copper conductors will have a diameter of 57.8 mm, as compared to the total external cable diameter of 138 mm.

Table 2. Summary of CHPE HVDC Cable Bundle Material Properties and Thicknesses

Cable Parameters	Value/Range	Source
Maximum operating temperature of CHPE cable	70 C (158 F)	NKT HV Cables AB (2022)
Complete cable density	3,618 kg/m^3	NKT HV Cables AB (2022)
External cable diameter	138.1 mm	NKT HV Cables AB (2022)
Copper wire		
Thermal resistivity of the conductor wire (copper)	0.0025 K*m/W	COMSOL® material library for copper
Density of the conductor wire (copper)	8,960 kg/m^3	COMSOL® material library for copper
Heat capacity at constant pressure of the conductor wire (copper)	385 J/kg-K	COMSOL® material library for copper
Conductor outer diameter	57.8 mm	NKT HV Cables AB (2022)
Layer T1		
Thermal resistivity between conductor and sheath, T1	3.62 K*m/W	NKT HV Cables AB (2022)
Heat capacity between conductor and sheath, T1	1,750 J/kg-K	COMSOL® material library for polymer
Density between conductor and sheath, T1	1,000 kg/m^3	COMSOL® material library for polymer
Diameter over conductor insulation	108.6 mm	NKT HV Cables AB (2022)
Layer T2		
Thermal resistivity between sheath and armor, T2	3.72 K*m/W	NKT HV Cables AB (2022)
Heat capacity between sheath and armor, T2	1,700 J/kg-K	COMSOL® material library for polypropylene
Density between sheath and armor, T2	905 kg/m^3	COMSOL® material library for polypropylene
Diameter over metallic sheath	114.6 mm	NKT HV Cables AB (2022)
Diameter over inner sheath	120.1 mm	NKT HV Cables AB (2022)
Layer T3[a]		
Thermal resistivity of outer armor, T3	6.0 K*m/W	NKT HV Cables AB (2022)
Heat capacity of outer armor, T3	1,700 J/kg-K	COMSOL® material library for polypropylene
Density of outer armor, T3	905 kg/m^3	COMSOL® material library for polypropylene
Diameter over armor	130.1 mm	NKT HV Cables AB (2022)
UraGUARD Cable Protection System (CPS)[b]		
UraGUARD thickness	25 mm	Lankhorst (2024)
Thermal resistivity of UraGUARD CPS	4.21 K*m/W	Lankhorst data tables received Sep. 24, 2024
Heat capacity of UraGUARD CPS	1,000 J/kg-K	COMSOL® material library for PVC with 40% plasticizer
Density of UraGUARD CPS	250 kg/m^3	COMSOL® material library for PVC with 40% plasticizer

Notes:
CHPE: Champlain Hudson Power Express®
CPS: Cable Protection System
HVDC: High voltage direct current
PVC: Polyvinyl chloride
(a) Layers "T2" and "T3" were combined into a single layer in the model for the purposes of the thermal impacts analysis due to the similarity in layer material and thermal properties.
(b) UraGUARD material properties and dimensions may change upon receipt of additional or updated information from Lankhorst.

THERMAL ANALYSIS

The thermal impacts of the CHPE cable bundle on the surrounding Harlem River water were analyzed using the Heat Transfer module within the COMSOL® Multiphysics software environment (version 6.2). This software allows users to model heat transfer and the resulting material temperatures in both transient and steady-state scenarios.

To evaluate the temperature distribution in the Harlem River at a 14-foot water depth cross section, a steady-state temperature model was created with the CHPE HVDC cables conservatively set at their maximum rated operating temperature of 158 degrees Fahrenheit. The resulting water temperature in the Harlem River and any potential increase above pre-CHPE conditions were both analyzed.

To increase confidence in the reliability of this modeling for calculating maximum potential temperature rise conditions in the Harlem River, a number of conservative assumptions and parameterizations were built into the model that serve to over-estimate the potential thermal impacts to the Harlem River.

- An upper-bound ambient water temperature was applied as the pre-CHPE condition to the entire water column (including the water at the sediment interface, which is typically at a much lower temperature);
- The finite rate of heat transfer through water was modeled explicitly for a conservatively low river water velocity (0.10 m/s);
- Convection within the Harlem River water column, a process that would increase the rate of heat dissipation from CHPE and reduce the thermal impacts to the river, was ignored;
- The CHPE cable bundle was modeled to be at its maximum allowable operating temperature (158 degrees Fahrenheit) at all times; and
- An upper-bound thermal resistivity for inorganic/cohesionless sediment was used to model heat transfer through the entirety of the sediment thickness.

Heat maps of the modeled temperature distribution in the Harlem River with the CHPE HVDC cables operating at maximum temperature are shown in Figures 3-5. Figure 3 shows a heat map in the CHPE cable bundle, with the conductors operating at the maximum of 158 degrees Fahrenheit. Figure 4 shows a heat map of the temperature distribution in the Harlem River water immediately surrounding the CHPE cable bundle. Figure 5 shows a heat map with labeled temperature contour lines of the temperature distribution throughout the modeled depth of the Harlem River. The modeled temperature rise in the Harlem River water is less than approximately 0.1 degrees Fahrenheit in the immediate vicinity of the CHPE HVDC cables and less than that further away from the cables. These findings, combined with the additional layers of conservatism built into the analysis, demonstrate that the riverbed installation of the CHPE HVDC cables has negligible impact on the Harlem River water temperatures, even under worst-case scenarios. These results are also consistent with a thermal analysis performed on a CHPE crossing location in the Hudson River in which the maximum temperature rise in the river water was also found to be less than a degree Fahrenheit (Exponent 2014). Therefore, the riverbed installation of the CHPE HVDC cables complies with the specific thermal criteria in 6 NYCRR Part 704.2(b)(5) (NYSDEC, 2023) as well as the general thermal criteria in 6 NYCRR Part 704.2(a) (NYSDEC, 2023).

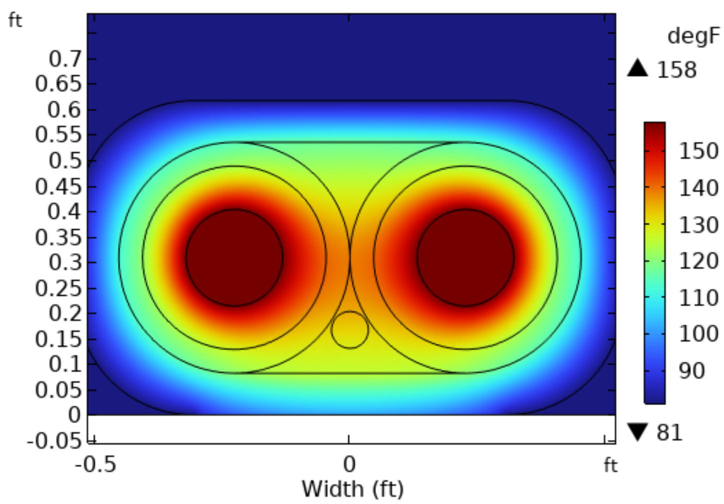

Figure 3. Heat Map Within CHPE Infrastructure.
CHPE = Champlain Hudson Power Express®.

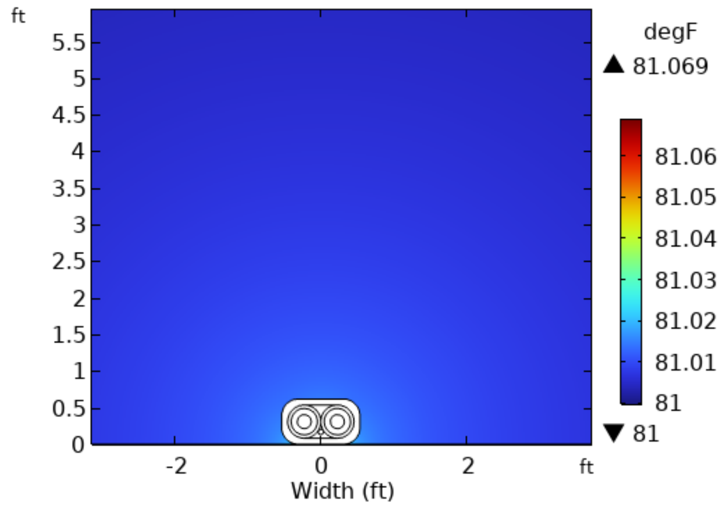

Figure 4. Heat Map of Harlem River Water near CHPE Infrastructure. CHPE = Champlain Hudson Power Express®.

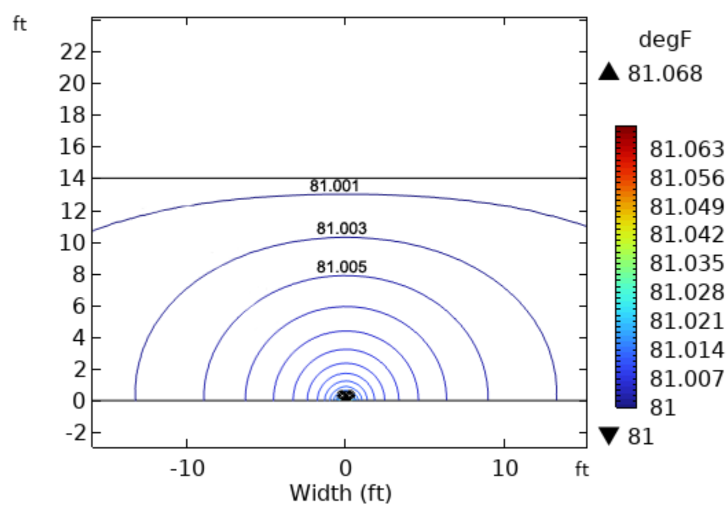

Figure 5. Heat Map of Harlem River Water.

CONCLUSIONS

Based on the thermal analysis presented herein, B&B concluded that water temperature in the Harlem River with the CHPE HVDC cables installed directly on the riverbed and operating at their maximum allowable temperature will comply with the New York State Department of Environmental Conservation criteria for thermal discharges.

REFERENCES

Exponent. 2014. "Memorandum from K. Hosseini [Exponent] to S. Murphy and S. Dave re: Champlain Hudson Direct Current Cable Thermal Analysis [Project: 1003651.EX0]." 17p., April 29.

Fischer, HB; List, EJ; Koh, RCY; Imberger, J; Brooks, NH. 1979. *Mixing in Inland and Coastal Waters*. Academic Press, Inc., San Diego, CA. 483p.

HDR Engineering, Inc. 2012. "Champlain Hudson Power Express Project: Project Description and Purpose." Report to Champlain Hudson Power Express Inc.; CHPE Properties Inc. Submitted to US Army Corps of Engineers (USACE), New York District. 74p.

Lankhorst. 2024. "Con Edison - Harlem River HA-28B Crossing Proposal." 2p., August 22.

New York State Dept. of Environmental Conservation (NYSDEC). 2023. "Classifications and standards of quality and purity: Criteria governing thermal discharges." 6 NYCRR 704.2. Accessed on December 5, 2024 at https://govt.westlaw.com/nycrr/Browse/Home/NewYork/UnofficialNewYorkCodesRulesandRegulations?guid=I06666980b5a111dda0a4e17826ebc834&originationContext=documenttoc&transitionType=Default&contextData=(sc.Default)

NKT HV Cables AB. 2022. "Design Report Submarine Cable." Report to Champlain Hudson Power Express (CHPE). 1AA0529714. 32p., July 28.

OWC; ITPEnergised; Power Advisory LLC; Prospect Hill Consulting; Continuum Associates LLC. 2023. "Shared Landfall and Cable Route Infrastructure Feasibility Study Final Report (Revision B)." Report to New York State Energy Research and Development Authority (NYSERDA). Submitted to National OSW Research and Development Consortium. NOWRDC Report 4476-D6.3 Rev. B, 165p., December.

US EPA. 2010. "State-of-the-Science Report on Predictive Models and Modeling Approaches for Characterizing and Evaluating Exposure to Nanomaterials." Office of Research and Development (ORD), EPA/600/R-10/129., 165p., September.

US Geological Survey (USGS). 2016. "Historical Water-Quality Data From the Harlem River, New York." doi: 10.3133/sir20165044. USGS Scientific Investigations Report 2016-5044. 33p.