REVISITING TOCKS ISLAND DAM – FLOOD RISK MANAGEMENT BENEFITS

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ABSTRACT

Tocks Island Dam was a proposed multipurpose project that was to be located on the Delaware River near the Delaware Water Gap in Pennsylvania and New Jersey. The construction of this dam would have created a reservoir nearly 40 miles long and allowed for the storage of nearly 1 million acre-feet of water for flood control, water supply, power generation, and recreation. Although the construction of Tocks Island Dam was authorized by Congress within the Flood Control Act of 1962, the project was eventually doomed by bureaucracy, a growing environmental movement throughout the United States, and the Vietnam War, amongst other reasons. Tocks Island Dam became one of the most controversial projects ever undertaken by the U.S. Army Corps of Engineers.

Following the official deauthorization of Tocks Island Dam in the early 1990s, several large flood events occurred within the Delaware River watershed. All told, the flood events of January 1996, September 2004, March-April 2005, June 2006, and August-September 2011 caused over $3 billion dollars in damage to population centers located downstream of the proposed construction site like Trenton, NJ and Philadelphia, PA.

New tools developed by the Hydrologic Engineering Center (HEC) were used to quantify discharge, stage, and consequences at locations downstream of Tocks Island Dam for the five previously mentioned flood events with and without the dam. Using these new tools, $700 million in economic damages were predicted to have been avoidable if Tocks Island Dam were constructed and operated according to the latest regulation schedule.

INTRODUCTION

The Delaware River watershed is home to over seven million people and is used as a source of water for over 15 million people. Due to its location in the northeastern part of the country, the watershed is also subjected to complex weather patterns and sometimes significant amounts of atmospheric moisture leading to the possibility of flooding year-round. Multi-year drought conditions have also arisen leading to water supply shortages in Philadelphia, PA and saltwater intrusion from the Atlantic Ocean. Finally, the watershed is also home to world class fisheries and significant populations of striped bass, multiple species of trout, and American shad.

Numerous water resources projects have been constructed throughout this multifaceted watershed for the purposes of flood control, water supply, hydropower, and fish passage, amongst others. Many other projects have been proposed but never constructed. The

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largest and most controversial of these proposed projects was Tocks Island Dam. This project aimed to deliver flood control, water supply, power generation, and recreation benefits to the inhabitants of the Delaware River watershed and beyond. However, significant opposition to this project by residents of the watershed that would have been inundated, environmentalists, and others eventually led to its official deauthorization in 1992.

Since that time, the Delaware River downstream of the proposed project has been subjected to costly flooding. No less than five significant floods, which resulted in hundreds of deaths and billions of dollars of damage, have occurred since 1996. Numerous studies have exhaustively presented and debated the negative consequences of the Tocks Island Dam project (Environmental Defense Fund, 1972; Albert, 1987; Bloodworth, 2005). However, no evaluation of the proposed flood control benefits from recent floods has ever been developed. This study aims to present an updated look at the hydrology and hydraulics of the proposed Tocks Island Dam project and how its operations could have positively benefited the Delaware River watershed.

DELAWARE RIVER WATERSHED

Description

The Delaware River originates in the Catskill Mountains in New York and flows for nearly 330 miles before reaching the Delaware Bay and, eventually, the Atlantic Ocean. The West and East Branches of the Delaware River combine at Hancock, NY to form the mainstem Delaware River. The Delaware River then flows south to form the boundary between New Jersey and Pennsylvania. Major tributaries to the Delaware River include the Lackawaxen, Lehigh, and Schuylkill Rivers. In total, there are approximately 10,000 freshwater stream miles within the watershed, as shown within Figure 1.

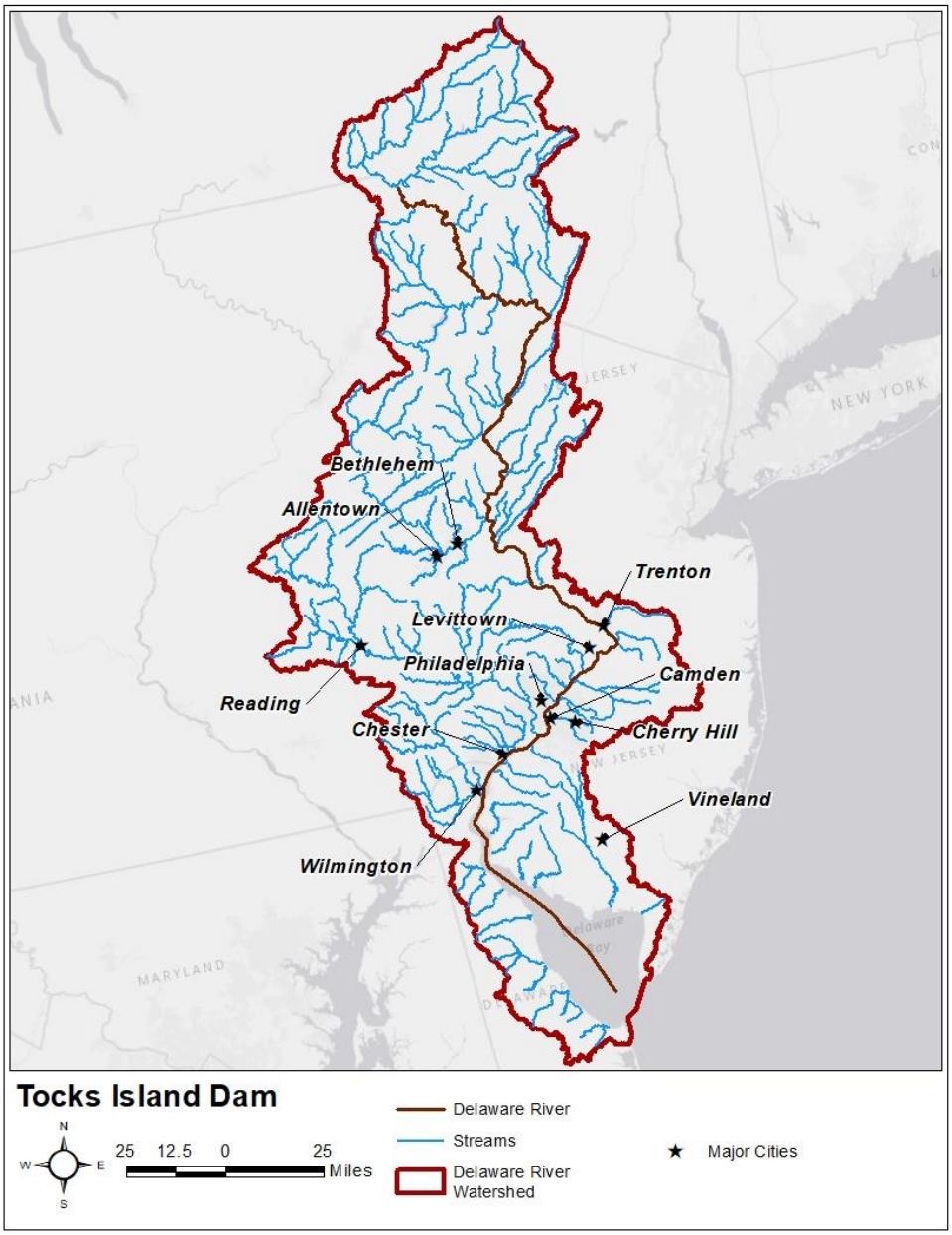

Figure 1. Delaware River Watershed

The Delaware River is the longest river east of the Mississippi River that does not have a dam on its mainstem. However, the watershed does contain hundreds of large dams on various tributaries (U.S. Army Corps of Engineers, 2022). Five large flood control dams are owned and operated by the U.S. Army Corps of Engineers throughout the watershed (Jadwin, Prompton, F.E. Walter, Beltzville, and Blue Marsh).

The combined drainage area of the West and East Branches is approximately 1,500 sq. mi. The drainage area of the Delaware River at Trenton, New Jersey is approximately 6,780 square miles. In total, the Delaware River watershed encompasses approximately 13,500 sq. mi.

Approximately 7.3 million people live within the Delaware River watershed (U.S. Census Bureau, 2022). Major population centers include Allentown, PA, Bethlehem, PA, Trenton, NJ, Levittown, PA, Philadelphia, PA, Camden, NJ, Chester, PA, and Wilmington, DE. However, approximately 15 million people, or roughly 5 percent of the nation's population, relies upon water originating within the Delaware River watershed for various uses.

A 1954 Supreme Court Decree allowed the state of New York to divert up to 800 million gallons per day from the Delaware River watershed for consumptive uses (U.S. Geological Survey, 2022). Following this decree, the Delaware River Basin Commission (DRBC) was created to perform an equitable allocation of waters throughout the basin (Delaware River Basin Commission, 2022). Approximately half of New York City's drinking water supply now comes from 3 reservoirs in the upper Delaware River watershed (Cannonsville, Pepacton, and Neversink).

Flooding

The Delaware River Basin is situated within the Mid-Atlantic temperate zone and is influenced by two major North American weather systems. Low pressure cells originating in the south move along the coast bringing substantial rainfalls and Canadian high pressure systems bring heavy snowfall and cold temperatures to the upper northwest portions of the basin. Cold temperatures are modified in the south and east by coastal influences. Average annual precipitation within the watershed ranges from 42 inches in southern New Jersey to about 50 inches in the Catskill Mountains of southern New York. Annual snowfall ranges from 13 inches in southern New Jersey to about 80 inches in the Catskill Mountains. Generally, precipitation is evenly distributed throughout the year. However, the highest monthly rainfall generally occurs in July or August and comprises approximately 10 percent of the annual total (U.S. Army Corps of Engineers, 2017).

Significant floods within the watershed have occurred due to summer thunderstorms (e.g. June 2006 event), heavy rains associated with the passage of tropical storm remnants (e.g. August 1955 event; Hurricanes Connie and Diane), combinations of snow and rainfall (e.g. March – April 2005 event), ice jams, and storm surge. Events can be localized in scale and primarily affect tributaries or regional in scale and affect the entire Delaware River watershed (e.g. August – September 2011 events) (Bartles, 2014). Additionally, due to the large population dependent upon Delaware River water, droughts are also a concern.

March 1936 Flood

From March 9 – 22, 1936, two extreme storm systems impacted an exceptionally large area extending from the upper Ohio River watershed in Pennsylvania to the state of Maine. During the passage of these storms, the vast majority of precipitation fell as rain. At the time of the first storm event, there was a large accumulation of snow over much of

the affected area. The associated warm front and temperatures that accompanied these storm systems caused the rapid melting of the accumulated snow. When combined with the excessive precipitation, this resulted in the formation of approximately 10 to 30 inches of runoff throughout the Delaware River watershed over the month of March. Over 100 fatalities resulted from this flood event (Grover, 1937). The damage that was wrought by this flood event all but ensured the passage of the Flood Control Act of 1936.

August 1955 Flood

The remnants of two tropical storm systems moved through the northeastern U.S. in August 1955 and caused widespread flooding from Pennsylvania to Massachusetts. The first tropical storm system, Connie, moved through the affected areas from August 12 – 13 and caused between six and eight inches of rain to accumulated within the Lackawaxen River watershed. The second tropical storm system, Diane, moved through the affected areas from August 17 – 20 and deposited an additional six to twelve inches of precipitation (Bogart, 1960). Flooding within the Delaware River watershed was severe. By some accounts, the resultant flow rates within the affected areas were higher than any other that have been recorded since European settlers first arrived in North America. This event represents the largest recorded discharge at the U.S. Geological Survey (USGS) Delaware River at Trenton, NJ stream gage (01463500). Nearly 100 fatalities were caused by this flood event within the Delaware River watershed.

January 1996 Flood

Heavy rain combined with an extremely large snowpack led to widespread flooding throughout several northeastern states in January 1996. Over a 24-hour period on January 18 – 19, between two and four inches of rain fell as a warm front moved through the area. This storm system brought sustained high temperatures and wind speeds. Recorded temperatures at Hawley, PA indicate that temperatures continuously exceeded 32 degrees Fahrenheit (deg F) for approximately 72 hours with maximum temperatures in excess of 50 deg F. These factors led to rapid melting of the available snowpack and voluminous runoff (Lumia, 1998). Large amounts of runoff were realized within the Delaware River. Over 20 deaths and approximately $1 billion in damages were due to this flood event within PA alone (Yarnal, Johnson, Frakes, Bowles, & Pascale, 1997).

September 2004 Flood

The remnants of Tropical Storm Ivan interacted with a passing cold front in mid-September 2004. Precipitation was very heavy throughout the entire Delaware River watershed with upwards of six inches falling within a 24-hour period over large parts of NY (Brooks, 2005). Nearly $1 billion in total damages were realized within PA and NJ due to this flood event.

March-April 2005 Flood

Six months after the September 2004 flood, the Delaware River watershed was again subjected to significant flooding. Frequent precipitation from December 2004 through March 2005 saturated soils within the Upper Delaware River watershed while a particularly cold winter froze some of the saturated soils and left a significant snowpack at higher elevations. From March 28 - 29, two to three inches of precipitation fell within the Delaware River watershed. When combined with high temperatures, the accumulated snowpack began to rapidly melt. Approximately four days later on April 2 – 3, an additional three to five inches of precipitation fell on already saturated soils (Reed & Protz, 2007). The resultant flooding was severe throughout the entire Delaware River watershed and over $200 million in damages were caused within PA, NY, and NJ.

June 2006 Flood

Fifteen months after the March – April 2005 flood events, another massive flood event occurred within the area of interest. The June 2006 event represents the largest basin-wide flood event that has affected the Delaware River since the August 1955 flood event. A stalled frontal system caused tropical moisture to move northward into the Delaware River watershed in late-June 2006. Four-day precipitation accumulations within the watershed ranged from six to fifteen inches (Suro, Firda, & Szabo, 2009). Resultant streamflows were exceptionally large throughout the entirety of the watershed and led to 16 fatalities within MD, PA, NJ, and NY. Over $225 million in damages were caused by this flood event within PA, NY, and NJ.

August – September 2011 Flood

In August and September of 2011, two tropical storm systems moved through the Delaware River watershed. The remnants of Tropical Storm Irene deposited between 7 and 18 inches of precipitation throughout the Delaware River watershed on August 28. Approximately one week later, the remnants of Tropical Storm Lee deposited an additional four to ten inches of rain over a 72-hour period from September 5 – 8 (Lumia, Firda, & Smith, 2014). Basin-wide flooding occurred throughout the Delaware River watershed. Nearly $1 billion in damages were caused by this flood event within PA, NY, and NJ (National Oceanic and Atmospheric Administration, 2012).

TOCKS ISLAND DAM

Delaware River Basin Comprehensive Plan

The Delaware River Basin Comprehensive Plan, which was presented to Congress by the U.S. Army Corps of Engineers Philadelphia District (NAP) in 1934, was the first comprehensive water resources plan to be developed for the watershed. This plan recommended the construction of 34 dams throughout the Delaware River (U.S. Army

Corps of Engineers, 1934). The cornerstone of this plan was Tocks Island Dam which was proposed to be sited along the mainstem Delaware River near Stroudsburg, PA and envisioned to form a reservoir approximately 40 miles long. For the most part, this comprehensive plan was shelved for many years. However, following the devastating August 1955 flood, the plan was resurfaced and several of the proposed projects, including Tocks Island Dam, were reevaluated.

Authorization

In 1959, NAP released a study that detailed an updated proposal for Tocks Island Dam. The proposed construction site was moved to a new location on the Delaware River in Monroe County, PA and Warren County, NJ, about five miles upstream of the Delaware Water Gap and seven miles northeast of Stroudsburg, PA. Also, a new earth and rockfill embankment design was presented. This new proposal was officially proposed for construction in 1962 and estimated to cost $146 million (HD 522, 87th Congress, 2nd Session, 1962). Congress officially authorized the Tocks Island Dam project within the Flood Control Act of 1962 (Public Law 87-874, 1962). The authorized purposes included flood control, water supply, recreation, and conventional hydroelectric power generation. Shortly after its official authorization, the DRBC became the nonfederal sponsor in 1965 (Godfrey, Pollarine, & Sadin, 2012).

Physical Features

The proposed Tocks Island Dam project would have consisted of numerous appurtenant features including an embankment, spillway, powerhouse, and fish ladder, amongst others. The main embankment was intended to span 3200 feet (ft) across the Delaware River between PA on the downstream right side and NJ on the downstream left side. The planned maximum height of the embankment was approximately 160 ft.

The outlet works intakes, spillway, powerhouse, stilling basin, and fish ladder would have been located on the NJ side and required extensive excavation into rock. Two 24-foot diameter conduits, each 1,300 ft long, were planned to deliver water to the river outlet works and powerhouse. The river outlet works were designed to pass a peak of 33,000 cubic feet per second (cfs) during the spillway design flood (SDF). The powerhouse was meant to contain two Kaplan turbines, each generating 35 Megawatts (MW) for a total nameplate capacity of 70 MW. The spillway was designed to consist of six 53.5 foot wide by 40-foot tall tainter gates. Once opened, the gates would release floodwaters through a 376-foot-wide ogee weir with a peak design discharge capacity of 452,000 cfs during the SDF. A fish ladder was included in the design for passage of American shad and other aquatic species. It was anticipated that over 1,000,000 adult shad would move through the fish passage facilities on an annual basis (U.S. Army Corps of Engineers, 1972).

Protective works for Port Jervis, NY and Matamoras, PA were also included. These protective works consisted of levees, floodwalls, pumping stations, and channel improvements and were meant to protect upstream populated areas within the planned

reservoir footprint. A summarization of the features of Tocks Island Dam is contained in Table 1. A depiction of the dam and several of the appurtenant features is shown within Figure 2.

Table 1. Pertinent Features of Tocks Island Dam

Embankment	
Type	Earth and rockfill embankment with central impervious core
Length	2600 ft (NGVD29)
Crest Elevation	455 ft (NGVD29)
Maximum Height	160 ft (NGVD29)
Spillway	
Type	Concrete lined chute with gated crest in left abutment
Crest Elevation	392 ft (NGVD29)
Crest Type	Gated ogee weir
Crest Gates	6 - 53.5 ft (width) x 40 ft (height) tainter
Width	376 ft
Design Capacity	452,000 cfs at 445 ft (NGVD29)
Outlet Works and Power Facilities	
Tunnels	2 - 24' diameter bifurcated tunnels
Length	1,300 ft
Design Capacity	66,000 cfs at 444.4 ft (NGVD29)
Turbines	2 - Kaplan 55,600 HP
Generators	2 - 35 MW

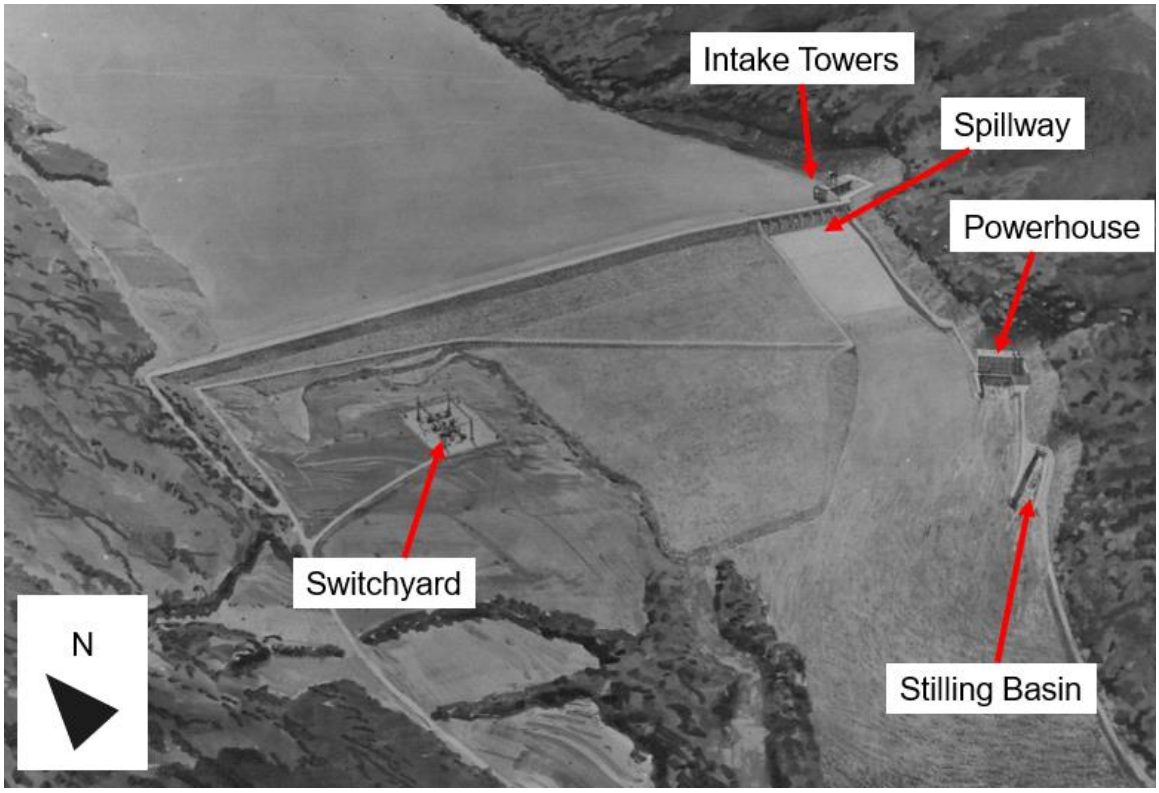

Figure 2. Tocks Island Dam and Appurtenant Features

At normal pool, Tocks Island Dam would have formed a 37-mile-long reservoir inundating portions of the Delaware River in Pennsylvania, New Jersey, and New York, as shown within Figure 3. At the top of dam, this reservoir would have contained approximately 1.3 million acre-feet (ac-ft) of water. A summarization of pertinent features of Tocks Island Reservoir is contained in Table 2 and depicted within Figure 4.

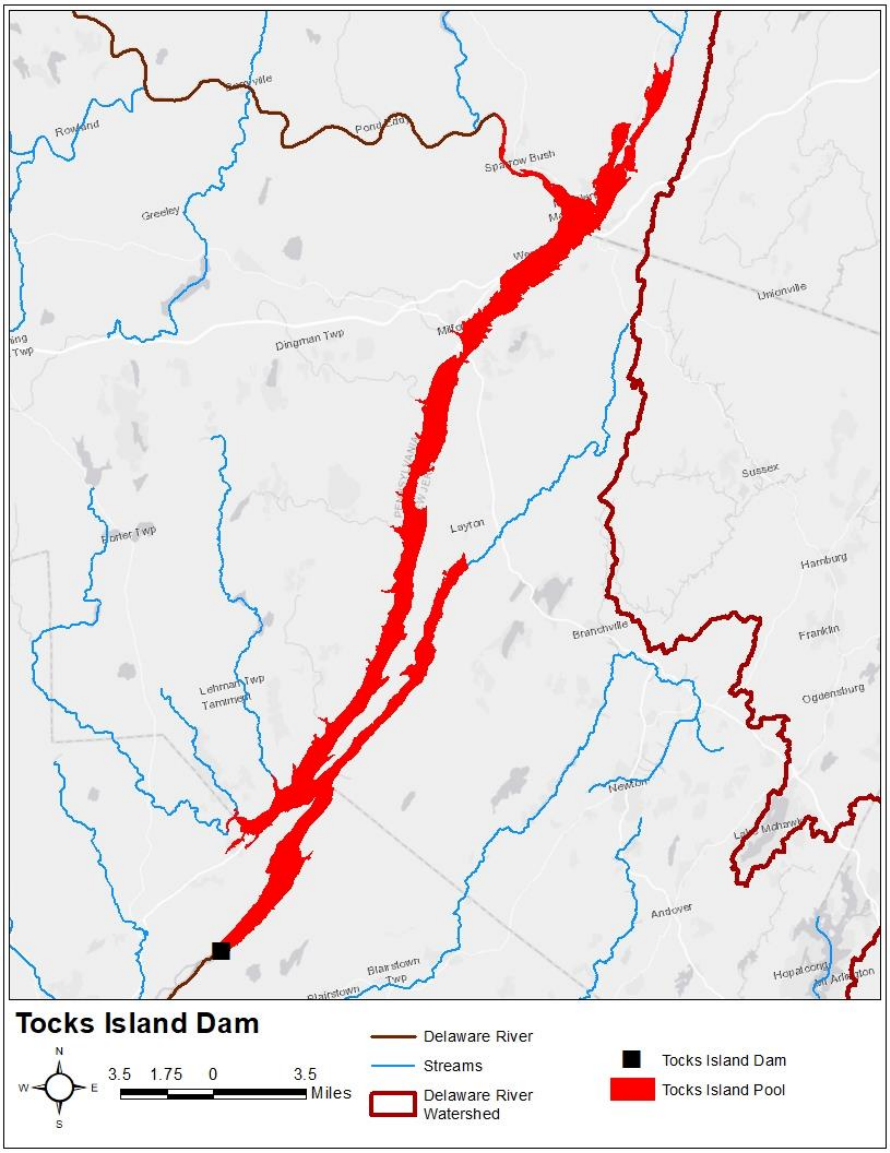

Figure 3. Location of Tocks Island Dam and Reservoir

Table 2. Pertinent Features of Tocks Island Reservoir

Pool	Elevation Range (ft, NGVD29)	Surface Area (acres)	Storage (ac-ft)	
			Incremental	Cumulative
Inactive	295 - 356	4,170	96,300	96,300
Joint Use	356 - 410	12,425	425,600	521,900
Flood Control	410 - 432	17,230	323,500	845,400
Surcharge	432 - 455	21,590	460,200	1,305,600

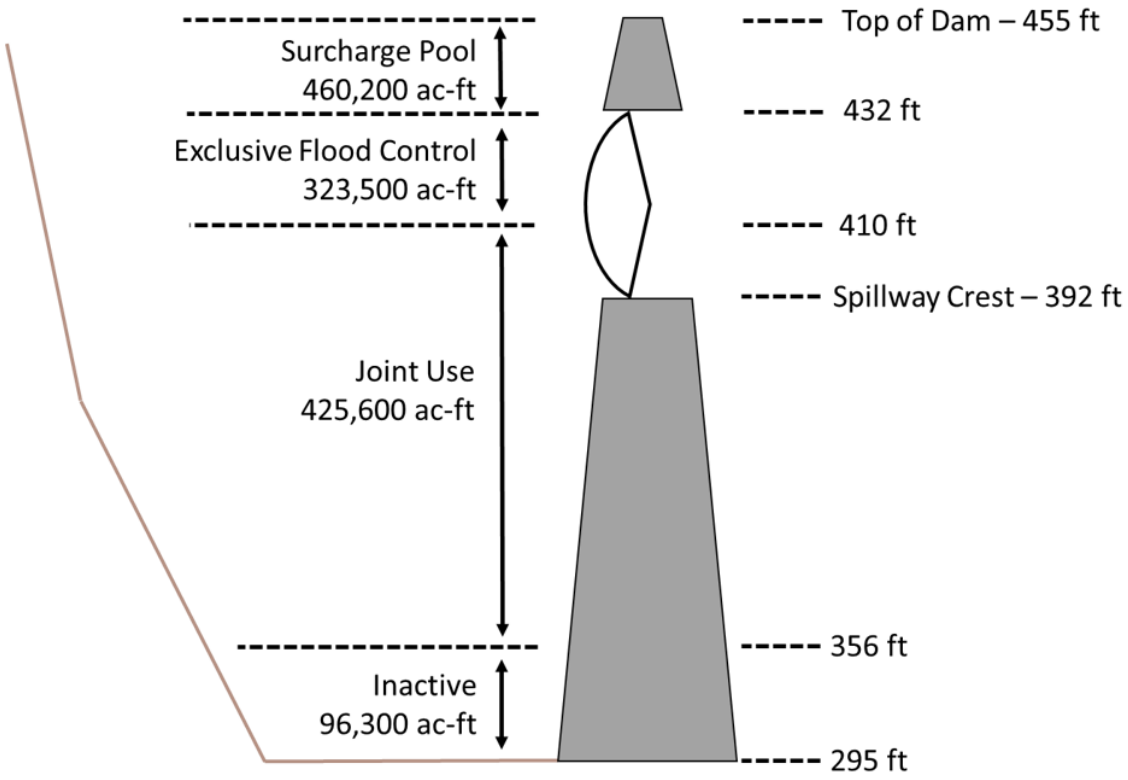

Figure 4. Tocks Island Dam and Reservoir Features

Plan of Reservoir Regulation

The proposed Schedule of Regulation presented within Design Memoranda 2 incorporated the requirements for reservoir operation for all project purposes. This combined operation is judged as the most advantageous for the realization of all project benefits with a minimum of detrimental effects to specific purposes (U.S. Army Corps of Engineers, 1965). Releases were intended to be made so that the reservoir elevation was contained within two rule curves (termed "Upper" and "Lower"), as depicted within Figure 5. The target elevation ranges encompassed by these rule curves varied throughout the year to balance storage for hydropower, recreation, and water supply purposes alongside flood control and minimum downstream release requirements.

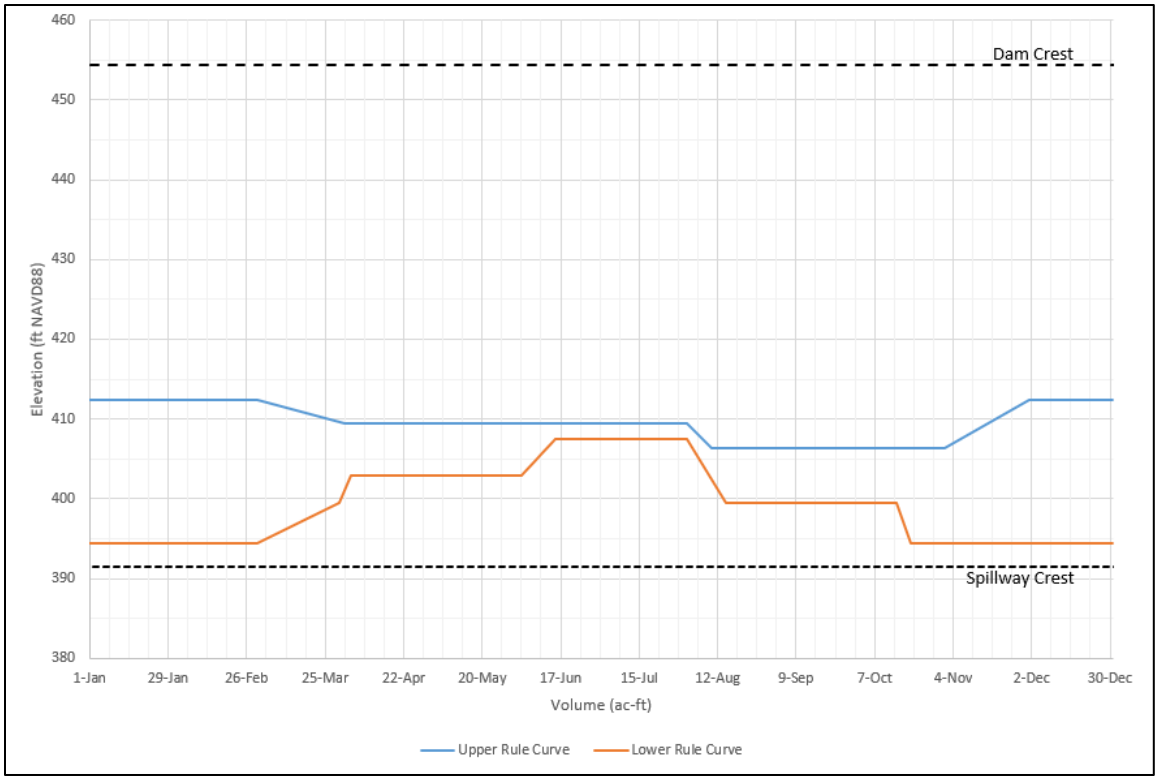

Figure 5. Tocks Island Dam Operational Rule Curves

Three locations downstream of the proposed Tocks Island Dam, Belvidere, Riegelsville, and Trenton, NJ, were meant to be used as control locations. Operations at Tocks Island Dam were intended to maintain water surface elevations (WSEL) at these three locations below flood stage while also reserving additional flood control storage for future floods. These locations, along with their flood stages and corresponding discharges (using the latest stage-discharge relationships maintained by the USGS), are detailed in Figure 6.

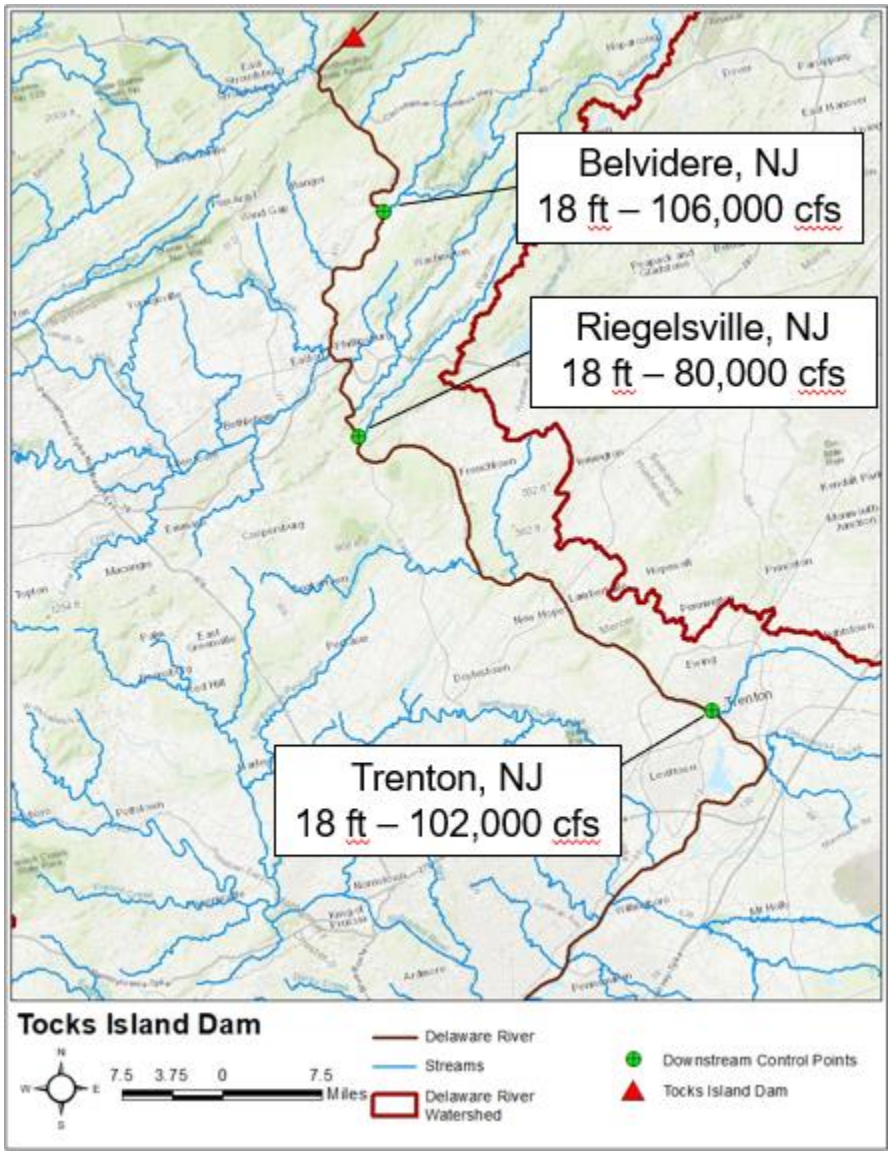

Figure 6. Downstream Control Locations

Controversy

The Tocks Island Dam project was embroiled in controversy throughout its lifetime. These controversies included real estate acquisition practices, anticipated increases in tourism, estimated construction costs, and potential eutrophication.

In 1965, Congress established the Delaware Water Gap National Recreation Area (Public Law 89-158, 1965). The 46,000-acre recreation area was intended to surround the reservoir created by Tocks Island Dam and enhance recreation. Administration of the recreation area was overseen by the National Park Service. NAP began acquiring real estate in 1966 within the recreation area in addition to other areas surrounding the proposed project. In all, nearly 72,000 acres of land was to be acquired for construction

and operation of the project. Due to opposition from local inhabitants, real estate was often acquired through eminent domain. Over the subsequent five to ten years, over 6,000 properties were acquired and nearly 4,000 people were displaced. To offset some of the costs of the project, NAP rented several of the newly acquired properties. These real estate acquisition practices, along with the rental of their former homes, alienated many of those that had inhabited the areas surrounding the project. This led to sometimes violent clashes between inhabitants, protesters, and the Federal government (Janson, 1975).

Due to its proximity to major cities like New York, Allentown, and Philadelphia, recreation to the Tocks Island Dam project was expected to be large. As many as 10 million visitors per year were expected to recreate in and around the project lands (U.S. Army Corps of Engineers, 1971). The areas surrounding the proposed project were largely rural with minimal amenities and transportation corridors. Significant concerns were raised by the states of NJ and NY regarding the potential for environmental damage due to the anticipated increase in tourism to the area.

During the lifespan of the project, construction cost estimates increased. At the time of its authorization, the total project construction cost was estimated to be $146 million (HD 522, 87th Congress, 2nd Session, 1962). By 1969, this estimate increased to $214 million (Godfrey, Pollarine, & Sadin, 2012). At the same time, the Vietnam War was also causing economic strains within the Federal government. As such, funding allocations for actual construction were limited, which led to construction delays.

Finally, water quality concerns within the reservoir formed by Tocks Island Dam were raised beginning in the late 1960s. Due to the propensity of non-point source pollution from upstream farms, eutrophication within the proposed reservoir was identified as a possibility. To combat the potential for eutrophication, the DRBC planned on constructing a large wastewater treatment facility in the area (U.S. Army Corps of Engineers, 1971). However, this did not alleviate all concerns.

Deauthorization

Due to environmental concerns, the prevailing political climate, and funding issues, DRBC removed support for the Tocks Island Dam project in 1975. By 1976, USACE had spent $63.5 million on studies, investigations/surveys, construction, and real estate acquisition. Also, NAP estimated that approximately 553 years of manpower had been spent designing and constructing the project at that time (Godfrey, Pollarine, & Sadin, 2012).

Congress passed the National Parks and Recreation Act of 1978 which added the areas within the Tocks Island Dam project footprint to the National Wild and Scenic Rivers System (H.R.12536, 1977-1978). This designation entailed that the Delaware River was to be “preserved in a free-flowing condition, and that they and their immediate environments shall be protected for the benefit and enjoyment of present and future generations.” The land already acquired by the Federal government was handed over in

its entirety to the National Park Service for stewardship. The Delaware Water Gap National Recreation Area thus became a 70,000-acre park. The Tocks Island Dam project was officially de-authorized in 1992.

MODELING PURPOSE

Since the official deauthorization of Tocks Island Dam, the Delaware River downstream of the proposed project has been subjected to no less than five significant floods, which resulted in hundreds of deaths and billions of dollars of damage. The annual maximum series of peak discharge at the USGS Delaware River at Trenton, NJ stream gage (01463500) is shown in Figure 7. The five recent flood events (January 1996, September 2004, March-April 2005, June 2006, and August-September 2011), which were previously described, are highlighted. The Flood Stage (20 ft, orange line), Moderate Flood Stage (23 ft, red line), and Major Flood Stage (25 ft, purple line), as demarcated by the National Weather Service, are also shown (National Weather Service, 2022).

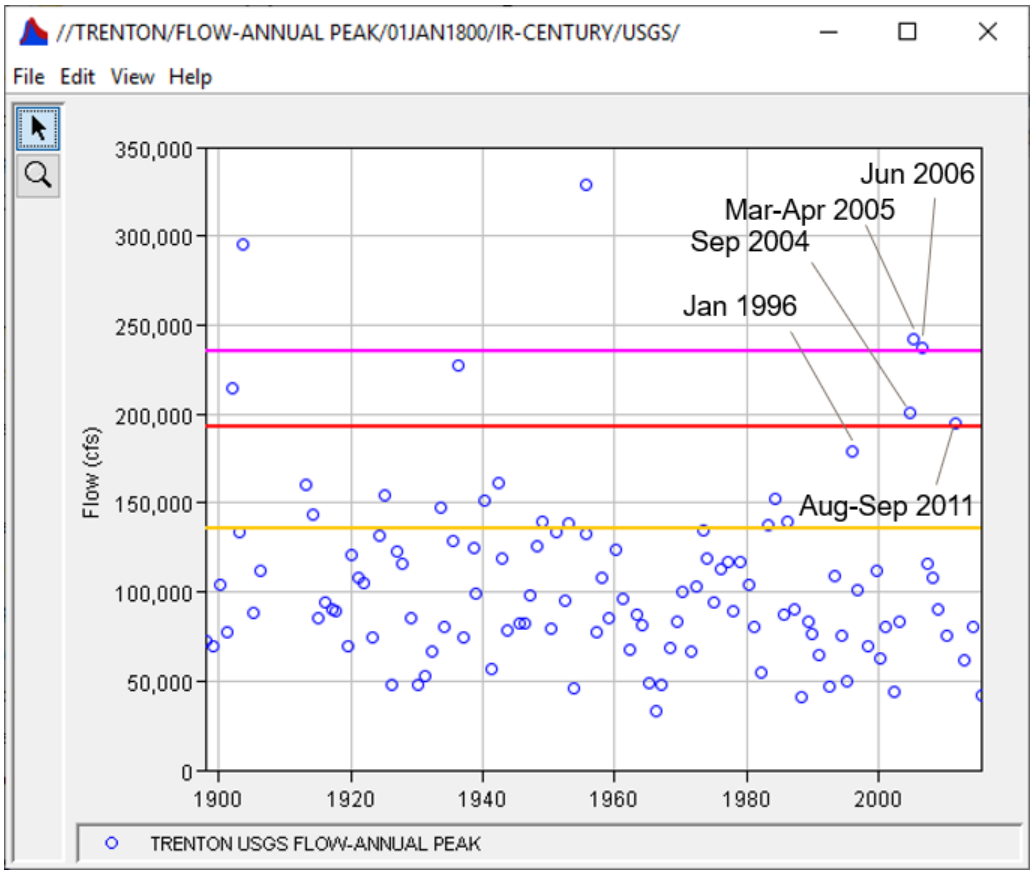

Figure 7. Recent Flood Events in Question

This study aims to present an updated look at the hydrology and hydraulics of the proposed Tocks Island Dam project and how its operations could have positively benefited the portions of Delaware River located downstream. In essence, this study proposes the following question:

Had Tocks Island Dam been built and operated according to the latest schedule of regulation, how much flood damage could have been prevented?

To answer this question, hydrologic, reservoir operations, hydraulic, and consequences models were built, calibrated, validated, and used to quantify the damages with and without the proposed Tocks Island Dam project.

HYDROLOGIC MODELING

The Hydrologic Engineering Center's (HEC) Hydrologic Modeling System (HEC-HMS) version 4.10 was used to simulate the precipitation runoff process throughout the Delaware River watershed (U.S. Army Corps of Engineers, 2022). An existing HEC-HMS model, which was built as part of a Corps Water Management System (CWMS) implementation, was used within this modeling effort.

The HEC-HMS model encompassed the entirety of the Delaware River watershed. The previously mentioned flood events were used to calibrate and validate the HEC-HMS model during the CWMS implementation (U.S. Army Corps of Engineers, 2017). Multiple statistical metrics, including Nash-Sutcliffe Efficiency (NSE), Ratio of the Root Mean Square Error to the Standard Deviation Ratio (RSR), and Percent Bias (PBIAS), were used to gauge model performance. An example of the NSE achieved when simulating the June 2006 flood event is shown in Figure 8.

Since this model was calibrated, validated, and previously used to simulate all necessary flood events, no major modifications were necessary for this modeling effort. However, the model was updated to use the latest version, the existing calibration and validation events were recomputed, and new outputs were generated for use.

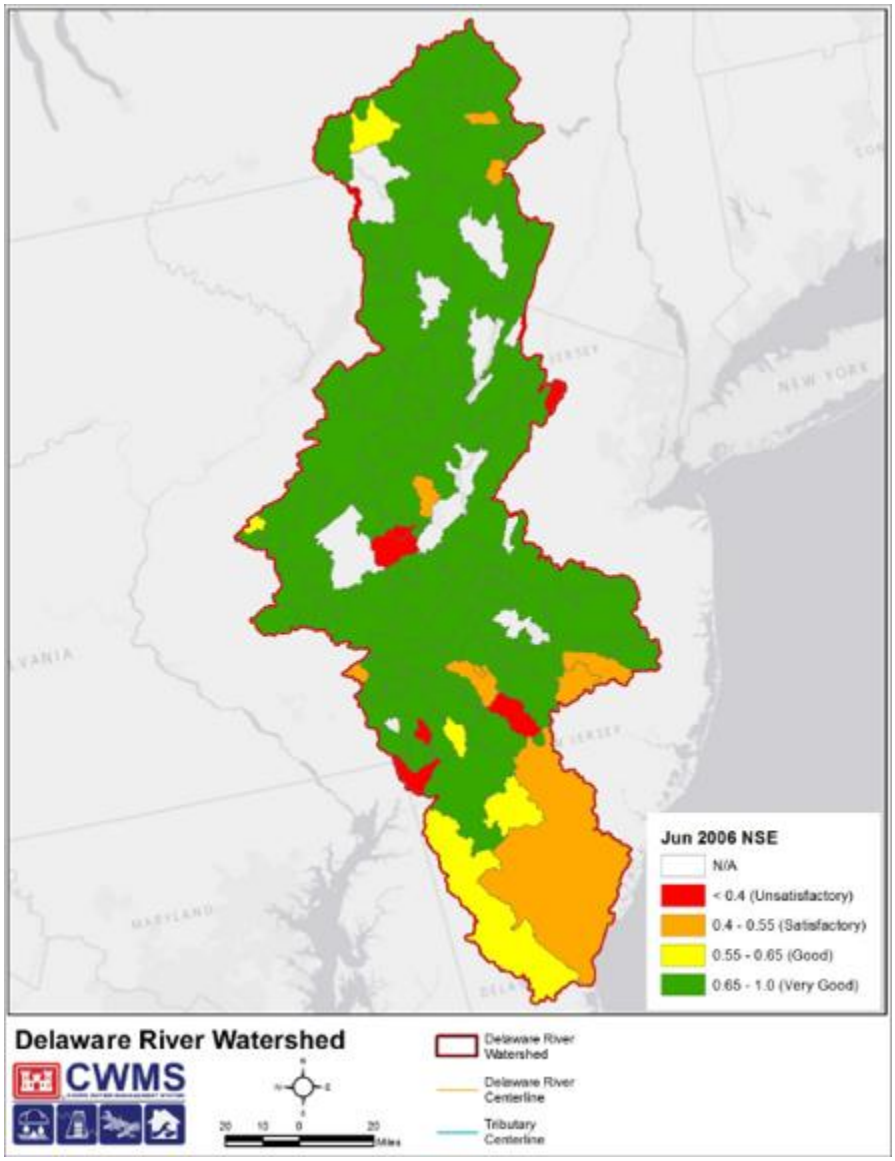

Figure 8. NSE Results for the June 2006 Flood, adopted from (U.S. Army Corps of Engineers, 2017)

RESERVOIR SIMULATION

The HEC Reservoir System Simulation (HEC-ResSim) version 3.3 was used to simulate reservoir operations of the proposed Tocks Island Dam project in addition to downstream flow rates (U.S. Army Corps of Engineers, 2021). Similar to the HEC-HMS model, an existing HEC-ResSim model from the Delaware River CWMS implementation was used.

The HEC-ResSim model encompassed the entirety of the Delaware River watershed. The existing HEC-ResSim model included several large, constructed projects throughout the Delaware River watershed including Cannonsville, Pepacton, Neversink, Prompton, Jadwin, Wallenpaupack, Toronto, Cliff, Swingbridge, Rio, F.E. Walter, Beltzville, Wild

Creek, Penn Forest, Nockamixon, Blue Marsh, and Ontelaunee. However, modifications were required to add the proposed Tocks Island Dam project. Specifically, the physical system components (e.g. elevation-storage of the reservoir and elevation-discharge relationships of the various outlets) in addition to operational logic for the proposed Tocks Island Dam project were entered.

The outputs from the previously mentioned HEC-HMS model were used as boundary conditions within the HEC-ResSim model. Simulations with and without Tocks Island Dam were computed. Tocks Island Dam operations for each simulation were reviewed and release logic was modified to produce realistic operations. An example of the inflow, outflow, and resultant pool elevation at the proposed Tocks Island Dam for the June 2006 flood is shown in Figure 9.

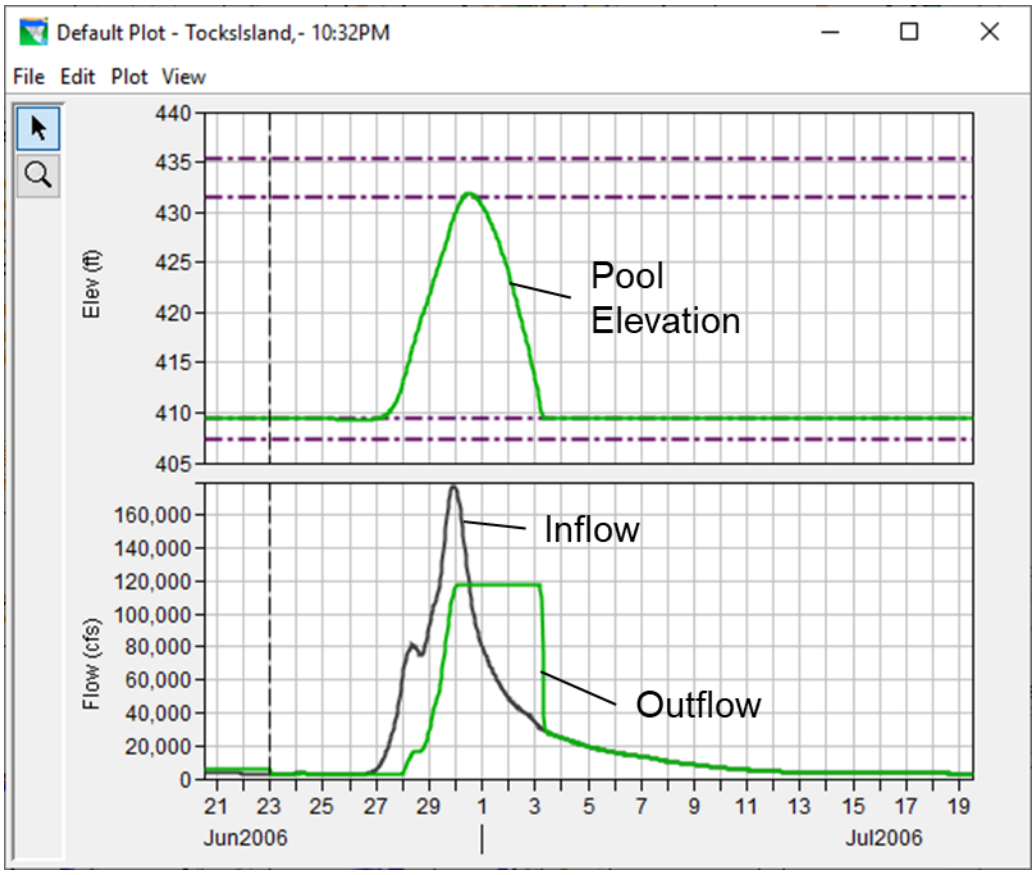

Figure 9. Tocks Island Dam Inflow, Outflow, and Pool Elevation During the June 2006 Flood

The differences in flow between with and without the proposed Tocks Island Dam project were reviewed at downstream locations. An example of the reductions in discharge afforded by the proposed Tocks Island Dam project at the Trenton, NJ stream gage for the June 2006 flood is shown in Figure 10.

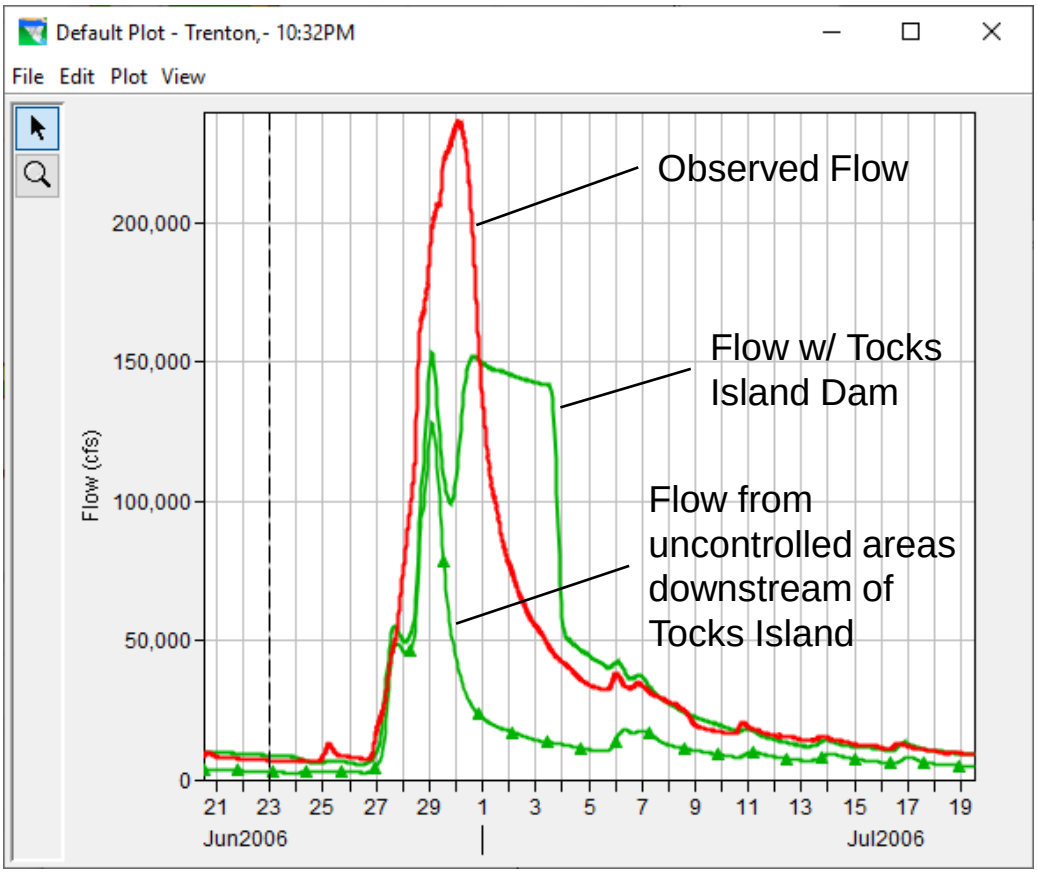

Figure 10. Observed Flow and Flow with Tocks Island Dam at Trenton, NJ During the June 2006 Flood

HYDRAULIC MODELING

The HEC River Analysis System (HEC-RAS) version 6.3.1 was used to simulate the flow, depth, and velocity of water downstream of the proposed Tocks Island Dam project (U.S. Army Corps of Engineers, 2022). Similar to the HEC-HMS and HEC-ResSim models, an existing HEC-RAS model from the Delaware River CWMS implementation was used as part of this effort.

The original HEC-RAS model geometry was clipped to encompass the mainstem Delaware River from the Mongaup River confluence to the Christina River confluence, the Neversink River below the Godeffroy gage, the Lehigh River downstream of the Little Lehigh River confluence, the Tohickon River downstream of Nockamixon Dam, and the Schuylkill River downstream of Fairmount Dam. An inline structure representing the proposed Tocks Island Dam was also added. The outputs from the previously mentioned HEC-HMS and HEC-ResSim models were used as boundary conditions within the HEC-RAS model. Simulations with and without Tocks Island Dam were computed.

The previously mentioned flood events were used to calibrate and validate the HEC-RAS model during the CWMS implementation (U.S. Army Corps of Engineers, 2017). Multiple statistical metrics, including NSE, RSR, and PBIAS, were used to gauge model performance. Computed stages and inundation extents were found to be in close agreement with observations.

The WSEL and inundation differences between with and without the proposed Tocks Island Dam project were reviewed at downstream locations. An example of the reductions in WSEL afforded by the proposed Tocks Island Dam project at the Trenton, NJ stream gage is shown in Figure 11. An example of the reductions in inundation extents near the Trenton, NJ stream gage is shown in Figure 12.

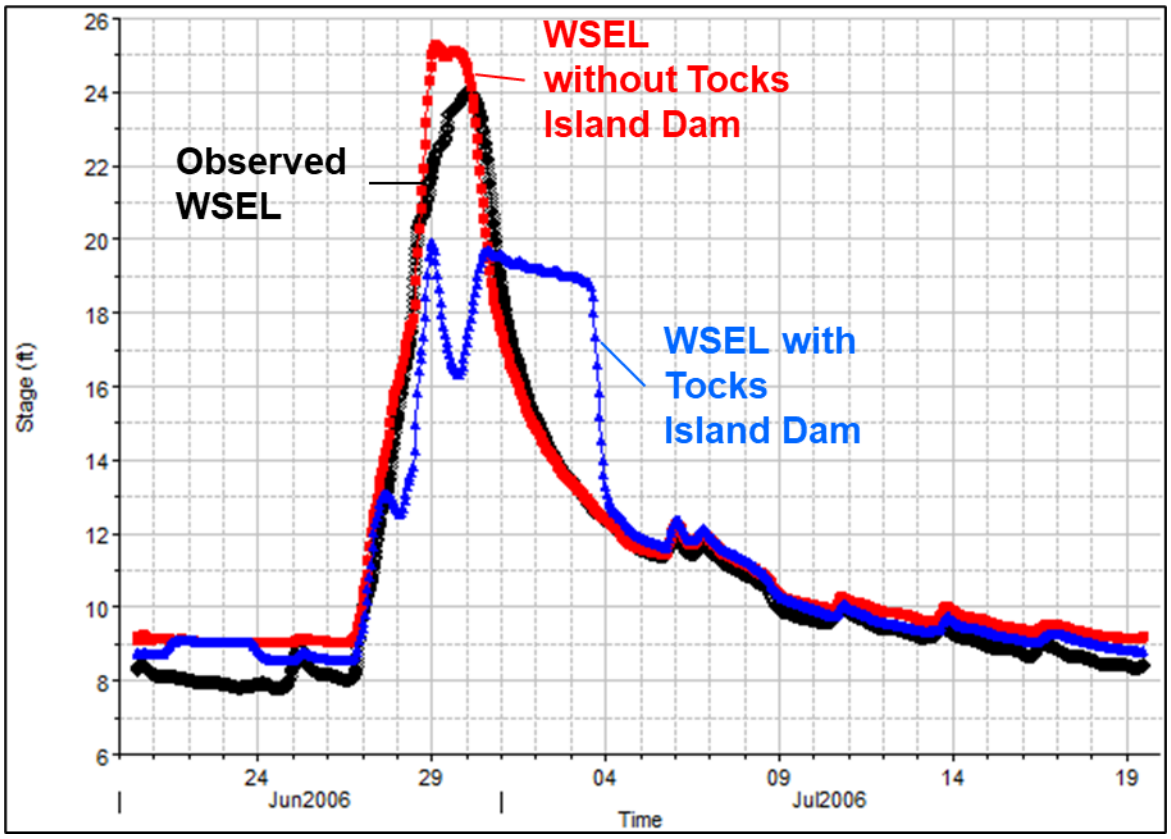

Figure 11. Observed and Computed WSEL With and Without Tocks Island Dam at Trenton, NJ During the June 2006 Flood

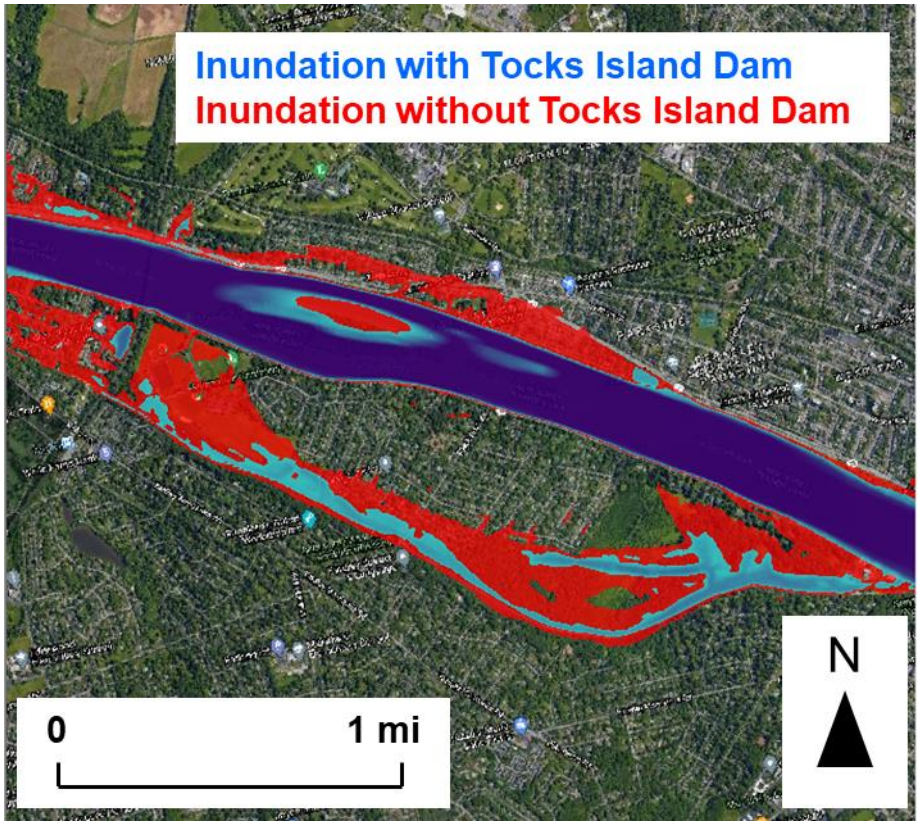

Figure 12. Computed Inundation Extents With and Without Tocks Island Dam near Trenton, NJ During the June 2006 Flood

CONSEQUENCE MODELING

The USACE Life Loss Estimation software (LifeSim) version 2.0 was used to estimate life loss and direct economic damages downstream of the proposed Tocks Island Dam project (U.S. Army Corps of Engineers, 2021).

Unlike the previously mentioned models, no existing LifeSim model was available for use. As such, a new LifeSim model was created for the areas downstream of the proposed Tocks Island Dam. A structure inventory was built using the National Structure Inventory (U.S. Army Corps of Engineers, 2022). This structure inventory encompassed the mainstem Delaware River from the proposed Tocks Island Dam site to the Christina River confluence, the Lehigh River downstream of the Little Lehigh River confluence, the Tohickon River downstream of Nockamixon Dam, and the Schuylkill River downstream of Fairmount Dam, as shown in Figure 13.

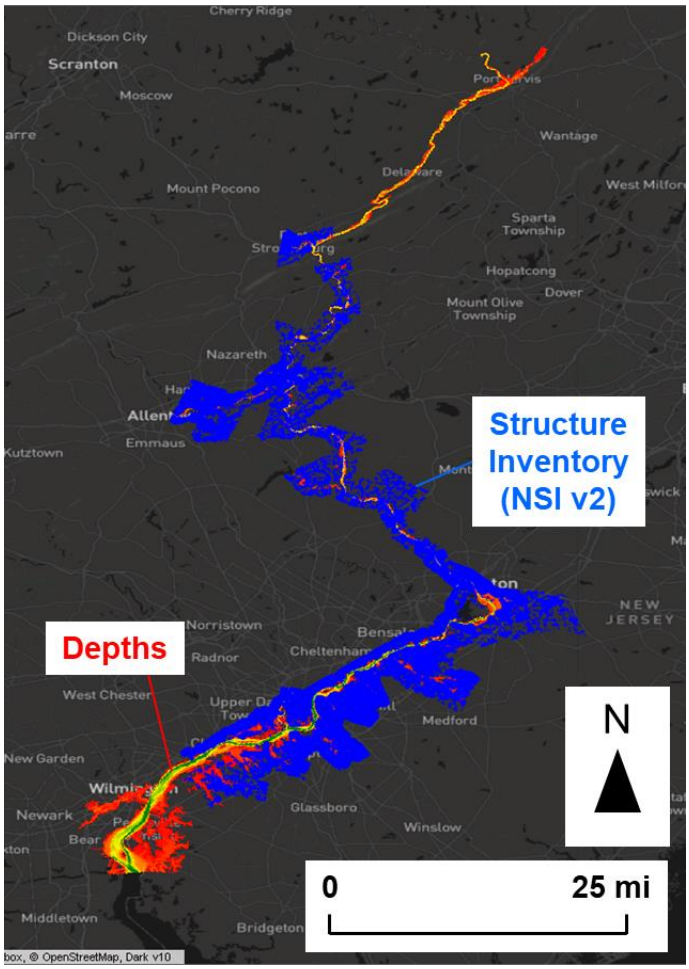

Figure 13. NSI and Computed Inundation for June 2006 Flood Event

The outputs from the previously mentioned HEC-RAS model were used as boundary conditions within the LifeSim model. Simulations with and without Tocks Island Dam were computed. The location, type, and value of each structure was reviewed alongside computed inundation extents. Structures that were erroneously located or misclassified were corrected. Further validation of the LifeSim model was performed using redacted National Flood Insurance Program (NFIP) claims. These claims were cross referenced with Census Tracts in order to geographically locate them and then compared against the LifeSim modeling results for each of the previously mentioned flood events. For the June 2006 flood, the total NFIP claims paid for the area downstream of Tocks Island Dam was approximately $37 million, as shown in Figure 14. For the June 2006 flood, total FEMA Public Assistance and Individual Program funding approved for PA and NJ was approximately $106.5 million (Federal Emergency Management Agency, 2022). The LifeSim model results for the June 2006 flood were approximately $136 million, which compared very well with the reported NFIP and Public Assistance and Individual Program damages.

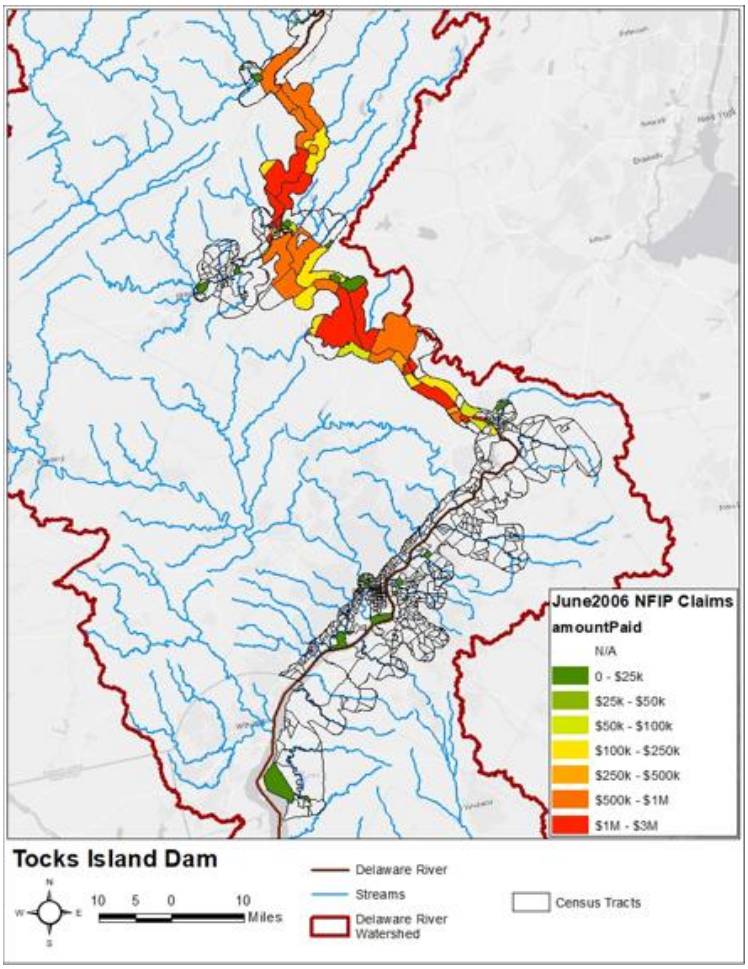

Figure 14. Summary of NFIP Claims for the June 2006 Flood Event

The differences in consequences between with and without the proposed Tocks Island Dam project were reviewed at downstream locations. An example of the reductions in inundation extents and damaged structures near the Trenton, NJ stream gage is shown in Figure 15. An example of the differences in structural, content, and total damages between with and without the proposed Tocks Island Dam project is shown in Figure 16.

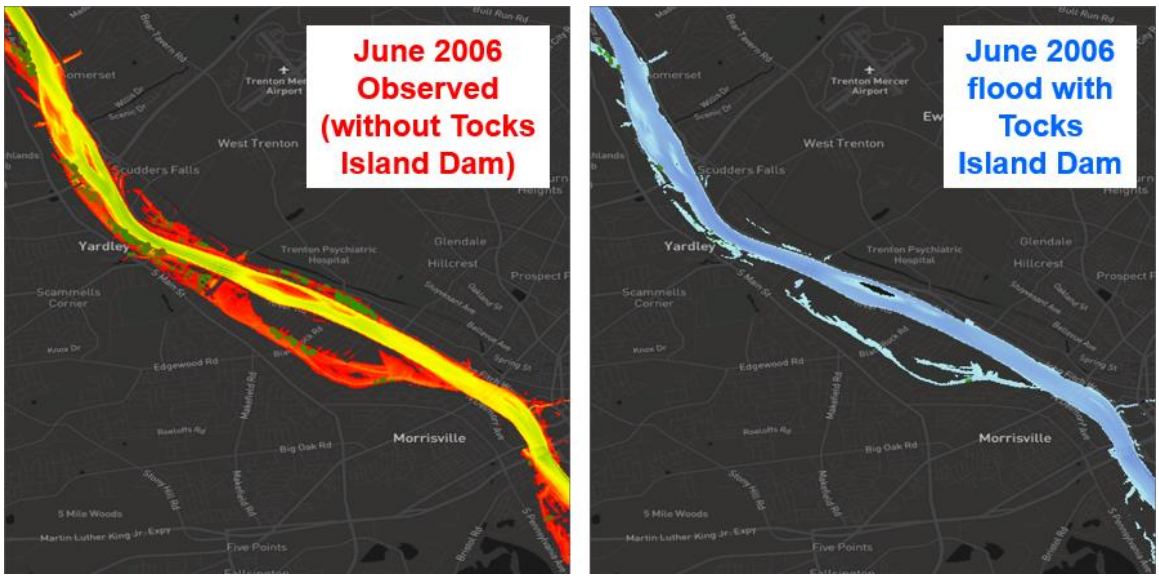

Figure 15. Computed Inundation Extents and Damaged Structures With and Without Tocks Island Dam near Trenton, NJ During the June 2006 Flood

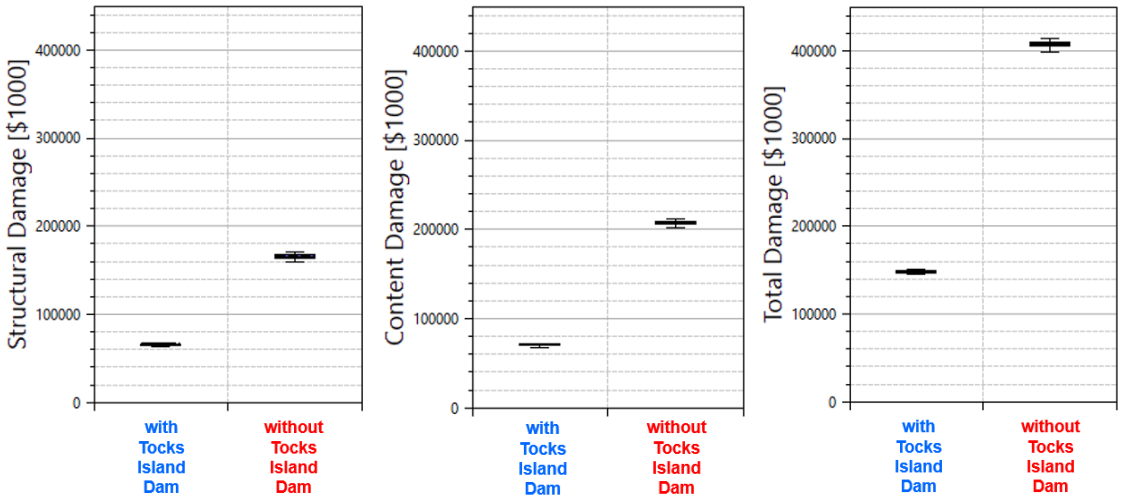

Figure 16. Structural, Content, and Total Damage for the June 2006 Flood

CONCLUSIONS

A summarization of the total estimated flood damages, the percent reduction, and the total reduction in damages due to the operation of the proposed Tocks Island Dam project for the previously mentioned flood events is contained within Table 3. These results indicate that a total of approximately $730 million in damages could have been avoided if Tocks Island Dam were built and operated according to the latest schedule of regulation.

Table 3. Estimated Flood Damages With and Without Tocks Island Dam for Five Large Flood Events

	Total Damage* ($ million)			
Flood	**Without Tocks Island**	**With Tocks Island**	**% Reduction**	**Total Reduction**
Jan 1996	199	143	28.1	56
Sep 2004	330	177	46.5	153
Mar-Apr 2005	459	237	48.4	222
Jun 2006	407	148	63.6	259
Aug-Sep 2011	292	250	14.5	42
SUM	***1,687***	***955***	***43.4***	***732***

**in 2019 dollars*

While the question posed within this study was investigated and damages were quantified for five recent flood events, additional efforts are needed to quantify the benefits from the additional authorized purposes of water supply, recreation, and hydropower. Moreover, additional flood events (e.g. September 2021) should also be analyzed and their corresponding damages estimated in order to provide a more comprehensive estimate of total benefits.

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