Research Article

Reservoir Operations & Water Allocation Model: New York City Delaware River Basin Reservoirs

Rezervuar Operasyonları & Su Tahsisi Modeli: New York Şehri Delaware Nehir Havzası Rezervuarları

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Abstract

The New York City (NYC) reservoirs in the Delaware River Basin are essential sources for goods and services, such as drinking water supply, recreation, power generation, and a host of ecosystem services. The reservoirs are located at the headwaters of the Delaware River, which supply water to New York, New Jersey, Pennsylvania and Delaware. However, the river is vulnerable to water shortages under changing climate conditions and needs to be managed wisely. This study developed a hydrologic model within the Stella modeling software for the NYC reservoirs to determine how historical reservoir management policies perform at meeting water demands in the basin and out-of-basin. The model provides information to better understand the interconnected effects of demands from water use sectors under different climate conditions, and to help addressing water shortages under water-stressed conditions. The model simulates reservoir releases based on inflows to reservoirs, water demand by sectors and historical reservoir management policies. The model predictions were compared with historical data to assure that the model was operating in the designed manner. The impact of this study extends directly to decision makers for water resources management, and stakeholders who rely on water resources in the basin.

Keywords*: water resources management, water allocation, stella modelling*

Öz

Delaware Nehir Havzası'nda bulunan ve New York şehrine içme ve kullanma suyu sağlayan rezervuarlar aynı zamanda enerji, ekosistem ve rekreasyon gibi sektörler için de önemli su kaynaklarıdır. Bu rezervuarlar Delaware Nehri'nin üst kısmında bulunmakta ve New York, New Jersey, Pennsylvania ve Delaware gibi önemli eyaletlere su temin etmektedir. Ancak, değişen iklim koşulları sebebi ile nehir susuzluk tehdidi altında kalmakta ve bu nedenle akıllıca yönetilmesi gerekmektedir. Bu çalışmada, Stella isimli bir yazılım programı kullanılarak New York rezervuarları için hidrolojik bir model geliştirilmiştir. Bu model sayesinde, rezervuar işletim kuralları Stella programına matematiksel denklemler kullanılarak girilmiş ve havza içi ve dışı su ihtiyacı belirlenmiştir. Ayrıca, farklı iklim koşullarında, havzadaki su kullanımının, sektörler üzerine etkileri daha iyi anlaşılmış ve olası kuraklık durumunda havzadaki su kıtlığı gibi problemler ele alınmıştır. Çalışılan modelde, rezervuarlara giren su miktarı ve her bir sektörün su ihtiyacı ile rezervuar işletim kuralları baz alınarak, günlük deşarj edilen su miktarı belirlenmiş ve sahada ölçülen veri ile karşılaştırılmıştır. Bu çalışmanın etkisi su kaynaklarının yönetiminde karar vericiler ile havzadaki su kaynaklarına ihtiyaç duyan paydaşlara kadar uzanır.

Anahtar sözcükler: *su kaynakları yönetimi, su tahsisi, stella modeli*

Introduction

The Delaware River Basin (DRB) is located in New York, New Jersey, Pennsylvania, and Delaware, and it comprises an area of nearly 13,600 square miles (Figure 1). Most of the basin is forested and contains important ecological lands and water bodies that are vital for people and nature. The mainstream of the river begins in Hancock, NY, and flows 330 miles to the mouth of the Delaware River Bay where it enters to the Atlantic Ocean (TNC, 2011).

Figure 1. Delaware River Basin. Adapted from “Delaware River Basin Commission (DRBC) website” by DRBC, 1996 – 2018.

The priority of the reservoirs is water supply to NYC. The reservoirs are also essential source for goods and services to the DRB, and thus they provide water for downstream requirements, and to protect the environment and wildlife. Therefore, operation of the reservoirs includes daily decisions on how much water to deliver, release, and spill from each reservoir, as well as how much water to divert between reservoirs. These decisions are complicated sometimes due to a variety of competing demands, including municipal water supply demand, downstream ecological and human demands, flood control, and drought prevention (Mandarano et. al, 2013).

Moreover, climate change along with population growth and economic development has important effects on water resources, especially to the DRB rivers because the reservoirs in the DRB supply approximately half of the city's municipal water supply (Klipsch et. al, 2010). In addition, the flow in the Delaware affects the position of a fresh water and salt-water interface in the lower basin. Low flow in the river during summer and drought conditions can result in the migration of salt fronts to the upstream and thereby affects fresh water intakes used for water supply for Philadelphia and Mid-Hudson areas (Burns et. al., 2017). Furthermore, flow alterations are threatening the survival of freshwater animals, such as mussels, amphibians and crayfish. Therefore, under changing conditions, it is important to better understand the interconnected effects of watershed characteristics, streamflow, climate and sectoral water demand on water resources to implement an integrated and adaptive framework for more sustainable and effective water management. To do this, there is a significant requirement for system-level modeling tools to address water management challenges.

During this study, the Stella (ISEE, 2017) simulation platform was used for the stakeholder-focused Shared Vision Planning process since it allows both stakeholders and technical participants to understand how decisions in one part of the system affect other parts of the system in water resources management puzzle (Leitman et. al, 2015; Creighton, 2010). Stella is an object-oriented graphical modeling environment and provides a high level of user accessibility and simplifies maintenance for complex systems. It also offers the option to prevent a stock from becoming a negative. This option is important for water resources models that non-negativity option never be used (Palmer, 2010).

In this study, a system-oriented approach is developed to evaluate demands of the various water use sectors in the river, and their interactions. A hydraulic model is developed within the Stella modeling software to determine how historical reservoir management policies perform at meeting water demands in the basin and out-of-basin for the years of 1980-2005. The model also helps to better understand the interconnected effects of the water use sectors under different climate conditions, and addresses water shortages under water stressed conditions.

Method

Basin Description and Water Use Sectors

The DRB encompasses four states and 42 counties, and its population is approximately 7.3 million people (USGS, 2017). However, over 15 million people including NYC and northern New Jersey depend on the DRB resources even though they are not located in the basin. Three upstream reservoirs in the DRB, Cannonsville, Pepacton and Neversink, supply drinking water to NYC from the Catskill Mountains located in southeastern New York State. New Jersey also is a water importer from the basin through the Delaware and Raritan Canal (Mandarano et. al, 2013).

Although the Delaware River is the longest undammed river in the east of the Mississippi, total permanent storage capacity of the tributary reservoirs is over 400 billion gallons. Therefore, reservoir releases affect the flow in the main stem of the Delaware River and the largest tributaries. Reservoir storage and releases are used for water supply, flood control, hydropower generation, water quality management, recreational fishing and boating, and support of aquatic habitat (HydroLogics, 2004).

Total withdrawals in the DRB for 2010 were divided into four major sectors: drinking water sector, including public supply and self-supplied domestic use, power generation sector, including thermoelectric power withdrawals, industrial sector, including mining and commercial water use, and agricultural sector, including irrigation, livestock, and aquacultural water use (Figure 2).

Power generation sector is further categorized into thermoelectric and hydroelectric generation power sectors. Based on a United States Geological Survey report, water withdrawals for thermoelectric power generation are considered offstream withdrawals, and therefore included in the calculation of total water withdrawal (Hutson et al., 2010). However, water used for hydroelectric power is not considered a withdrawal because water flowing through a dam is considered as an instream use (Ludlow et al., 2000).

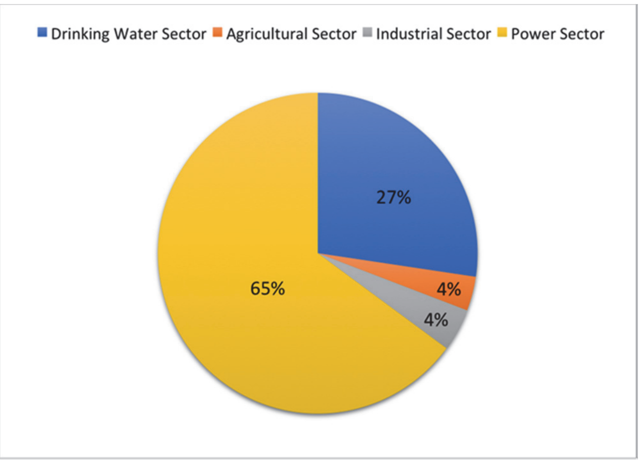

Figure 2. Sectoral water allocation in the Delaware River Basin for 2010.

History of Water Management Policies in the Basin

There have been conflicts over the management of the Delaware River for hundreds of years. One of the most important treaties was signed in 1783 between New Jersey and Pennsylvania. Based on this treaty, these two states agreed that there would be no dams on the Delaware main stem. During the 1900s, the basin states decided to focus on multiple approaches to resolve securing water allocation for growing population. To allocate water resources equitably, New York, Pennsylvania and New Jersey appointed commissioners to negotiate a compact in 1924. However, they weren't able to reach an agreement. Eventually NYC received a permit to export water out of the basin for drinking water supply; The US Supreme Court decree of 1931 affirmed the diversion of 440 mgd water to NYC (Mandarano et. al., 2013), and permitted the City to build two dams, Pepacton and Neversink. The location of the dams is shown in Figure 1. However, there were no environmental interests or specified provisions for ecological flows in the 1931 decree (Ravindranath et. al, 2016).

After the 1931 decree, NYC and New York State petitioned the Court to increase its diversion from the Delaware River Basin for water supply purposes. Pennsylvania joined New Jersey to protest the case. An amended decree was issued on June 7, 1954 that increased NYC's diversion to 800 mgd upon the construction of the Cannonsville Reservoir located in the Delaware's West Branch. New Jersey was also allowed to allocate 100 mgd water through the Delaware and Raritan Canal. In addition to diverting water for drinking water requirements of states, the decree obligated NYC to make reservoir releases (as needed) to maintain a minimum flow requirement of 1,750 cfs at the USGS gauge station at Montague, NY or 3,400 cfs at Trenton, NJ. Furthermore, the decree required that NYC release into the Delaware River an excess release quantity (ERQ), which was estimated to be 83% of the volumetric difference between the City's total safe yield and its forecasting annual water consumption. Based on the amount calculated in the decree, an excess release bank (ERB) was established. The aim of the ERB is to assist lower basin drought. The releases from the bank are become effective at Montague on June 15 until the following March 15, or until the combined storage is equal to or lower than the drought warning line, or until the cumulative releases from the excess release bank becomes equal to seasonal quantity, whichever occurs first. However, in case of emergency, the Delaware River Basin Commission (DRBC) might use water from the ERB for thermal releases to support downstream fisheries or lower basin water demand without considering above conditions (DRBC, 1977; U.S., 1954; Mandarano et. al, 2013; Ravindranath et. al, 2016).

Recognizing that litigation through the Supreme Court is not an effective way to manage water resources in the basin, the basin states agreed on forming a commission, which negotiates a compact to guide water resources management. As a result, the DRBC was created in 1961 and the governance of the basin unified in one body. The DRBC consists of the governors of the four states and a federal commissioner appointed by the president (Mandarano et. al., 2013).

After a historical drought between 1961 and 1967, it was obvious that there was a need for conservation release rules to protect downstream fisheries from low flows or excessive water temperatures. The inadequacy of conservation releases resulted in New York State's Environmental Conservation Law in 1976, which includes augmented conservation releases from the Cannonsville, Pepacton and Neversink reservoirs (experimental release program). With this law, temperature targets of 75 °F as a daily maximum and 72 °F as a daily average at USGS gages at Callicoon, Harvard, Woodbourne, and Hale Eddy located downstream of the Cannonsville, Pepacton and Neversink reservoirs were also set. New York State Department of Environmental Conservation (NYSDEC) also specified a thermal stress bank of 6,000 cfs-day to meet these targets by cold-water releases from reservoirs. The thermal stress bank was created to ensure that enough water was actually in the reservoir for fishery protection (Ravindranath et. al., 2016). The following studies by NYSDEC and experiences showed the benefit of these releases on ecosystem; as a result, docket D-77-20 CP was approved by DRBC (Mandarano et. al., 2013). The combined total of the augmented releases and thermal releases could not exceed the excess release bank water quantity based on the docket D-77-20 CP. However, this rule did not take part in the first revision of the docket in 1983. After approval of the docket in 1983, instead of limiting the augmented conservation releases with the amount of water in the excess release bank, the drought operation rule curve was used to regulate the conservation releases depending on the combined storage of the reservoirs.

In 1983, the decree parties unanimously approved Interstate Water Management Recommendations of the Parties of the Supreme Court Decree of 1954 to the Delaware River Basin Commission Pursuant to Commission Regulation 78-20. This is generally known as the 1983 Good Faith Agreement (GFA). Under the GFA, the experimental release program, which was established in the original 1977 docket, became permanent and releases were limited based on drought operation curves, which are the main component of the GFA. Drought operation curves set a criterion that separates the levels of drought as drought warning and drought emergency based on the combined storage of the three NYC Delaware Basin Reservoirs (Figure 3). It is important to note that in 1999, DRBC approved Revision 4 which implemented to raise the drought warning line by 4 billion gallons (DRBC, 2017).

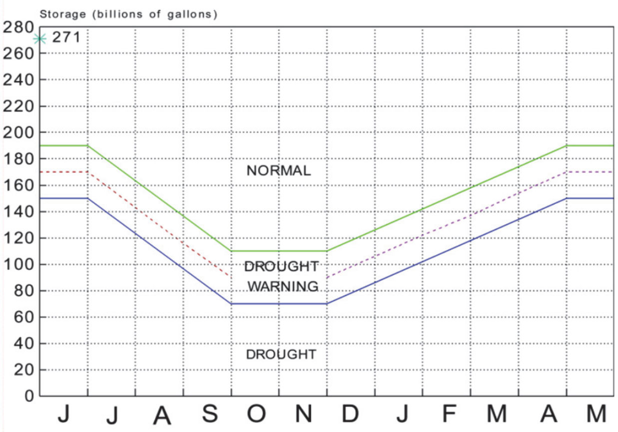

Figure 3. Drought Operation curve for Cannonsville, Pepacton and Neversink Reservoirs. Adapted from “Delaware River Basin Commission (DRBC) website” by DRBC, 2008.

Using these drought definitions as a framework, Table 1 shows an adaptive allocation and flow objective schedule established in the GFA. In Table 1, the drought warning line was separated into two categories which are illustrated by the red dashed line in Figure 2: the upper half, and the lower half. The upper half of the drought warning level were limited between the normal conditions line and drought warning line while the lower half was restricted between the drought warning and drought line. Based on combined storage of the NYC Reservoirs, the GFA sets target flows for out of basin allocations, as well as, Montague and Trenton. During drought conditions, the

GFA calls for a reduction of releases out of basin, and sets a specific release schedule depending on the four predetermined salt front river mile locations for Montague and Trenton (Table 2). Drought conditions' operations are mandated by the GFA when the combined reservoir levels decrease below the drought-operating curve for 5 consecutive days (U.S., 1954; DRBC, 1982a).

There were 9 revisions from the DRBC's first release policy, Docket D-77-20 CP of May 1977 until the adoption of Flexible Flow Management Plan (FFMP) in September 2007. Until 2007, the adjustments of conservation releases, thermal targets and thermal protection banks were minor, except the Revision 1 in November 1983, the Revision 7 in May of 2004, and the Revision 9 of September 2006 (Ravindranath et. al, 2016).

With implementation of the GFA to the Revision 1 of 1983, there was an important modification that resulted in reduction of conservation releases to basic releases during drought warning and drought emergency conditions, and it would only be returned to the augmented levels after the combined storage reached to 25 BG above the drought warning level and remained at there for 15 consecutive days (DRBC, 2017). It is important to note that Revision 1 was the last revision approved with any expiration date. Therefore, if the decree parties cannot reach an agreement on the subsequent revisions or extensions in the future, they could fallback on the release policy defined in Revision 1 (Ravindranath et. al, 2016).

Table 1

Allocation and Flow Objective Schedule

Storage condition	NYC allocation (mgd)	NJ allocation (mgd)	Montague flow objective (cfs)	Trenton flow objective (cfs)
Normal	800	100	1750	3000
Upper half – Drought warning	680	85	1655	2700
Lower half – Drought warning	560	70	1550	2700
Drought	520	65	1100 – 1650*	2500 – 2900*
Severe Drought	To be negotiated based on conditions			

*Varies with time of year and location of salt front as shown on Table 2.

In 2002, Revision 5 was amended. Based on the amended Revision 5, using the habitat bank to augment flows at Hale Eddy, Harvard, and Bridgeville below the NYC reservoirs was required. Also, during drought conditions, the allowance was made to use the habitat bank as the summer baseline release levels to augment conservation releases. In addition, the total quantity of the thermal release bank is defined explicitly (9,200 cfs-days) in the amended Revision 5. In 2003, after the approval of the Revision 6, this amount was reduced to 4567 cfs-days (DRBC, 2017).

Table 2

Flow Objectives for Salinity Control during Drought Periods

Seven-day Average Location of 'Salt Front' River – mile (R.M.)	Flow objective, Cubic Feet Per Second At:					
	Montague, N.J.			Trenton, N.J.		
	Dec - Apr	May - Aug	Sept - Nov	Dec - Apr	May - Aug	Sept - Nov
Upstream of R.M. 92.5	1600	1650	1650	2700	2900	2900
Between R.M. 87.0 and R.M. 92.5	1350	1600	1500	2700	2700	2700
Between R.M. 82.9 and R.M. 87.0	1350	1600	1500	2500	2500	2500
Downstream of R.M. 82.9	1100	1100	1100	2500	2500	2500

Revision 7 of 2004, made a number of adjustments. There were now three different banks and all of them were interrelated in a complex fashion each other. These banks were an ERB, a thermal release bank (TRB), and a supplemental release bank, which constituted a habitat bank. The aim of the habitat bank is to support tailwaters of the reservoirs. It also established a new concept by setting minimum flow targets at Hale Eddy on the West Branch of the Delaware River, at Harvard on the East Branch of the Delaware River, and at Bridgeville on the Neversink. These flow targets were subject to water availability in the habitat bank (DRBC, 2004). The conservation release rules were becoming increasingly complex with Revision 7. Consequently, The Decree Parties stated their intention to develop a long-term program. The basis of the program was considered to be based on sustainable sources of water, while releasing water based upon the overall needs in the tail waters below the reservoirs, as well as in the main stem and in the bay (Ravindranath et. al, 2016).

The intention for Revision 7 was to endure until May 31, 2017. However, due to severe floods in 2005 and 2006, Revision 9 was approved in 2006 resulting from political pressure of the public and the governors of New Jersey and Pennsylvania. The revision established a spill mitigation program, which aimed to increase releases from the reservoirs to achieve an 80% of reservoir void from September 1 to February 1. NYC reservoirs in the Delaware River Basin are not designed for flood mitigation; therefore the DRBC is named the program as spill mitigation rather than flood mitigation (Ravindranath et. al, 2016).

A fundamental change to the conservation release program was made with the approval of the FFMP in 2007, which established an adaptive release schedule. The adaptive release schedule included releases for habitat protection and the new discharge mitigation program. The FFMP was designed to provide a more natural flow regime. It was also more adaptive than the previous operating schedules for controlling releases and diversions from NYC reservoirs. The aim of the FFMP was to address competing demands in the basin, as well as drought management, flood mitigation, protection of cold-water fishery, diverse array of habitat requirements in the main stem river, estuary and bay, and salinity repulsion (DRBC, 2011).

The initial implementation cycle of the FFMP was from 2007 to 2011. The 2011 FFMP is a set of principles, rules and procedures for the management of storage, water supply, conservation releases, diversions, flow targets relating to the allocation of water from the DRB (DRBC, 2011).

The latest FFMP, called Flexible Flow Management Program - Operational Support Tool (FFMP-OST), is effective until May 31, 2017. It holds the promise of further improving the ecological health of the upper Delaware River while using water more carefully (DRBC, 2017).

Structure and Operation of the NYC-DRB Stella Model

The NYC-DRB Stella model uses daily time step and simulates twenty-four years of historical policy decisions for the NYC Delaware River Basin Reservoir System which consists of three large reservoirs; Cannonsville, Pepacton and Neversink. The main portion of the model consists of mapped water balance, which shows the inflows and withdrawals of the system. The releases from Cannonsville and Pepacton reservoirs meet at the Delaware River above Port Jervis, NJ. Then, they join with releases from the Neversink Reservoir at Port Jervis, NJ (Figure 4).

The basic concept of a mass balance is the change in storage, which equals to sum of the inflows minus the sum of the outflows as illustrated in *Equation 1*.

$$\text{Change in storage} = \left[\sum inflows\right] - \left[\sum outflows\right] \qquad (1)$$

Looking in detail at the mass balance for the NYC reservoirs, *Equation 2* incorporates all the components into the hydrological system of the reservoir.

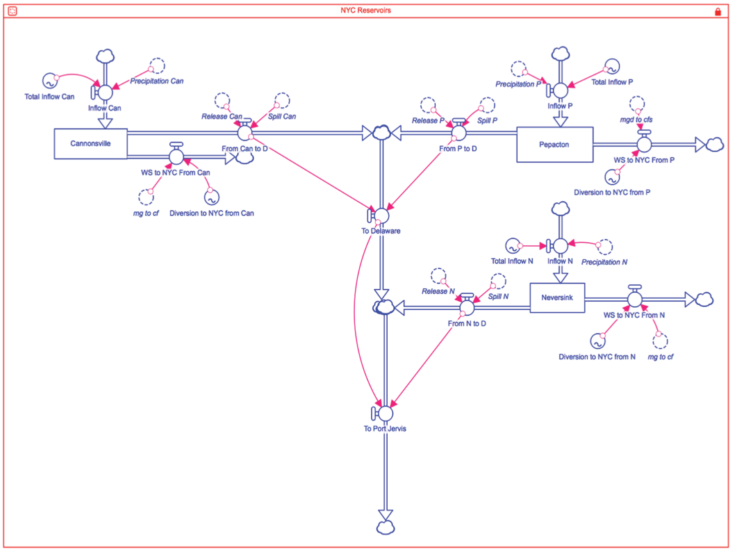

Figure 4. The Stella model of the NYC reservoirs in the Delaware River Basin.

Change in storage = Initial storage of the reservoir + (precipitation that falls onto the reservoir + streamflow that runs into the reservoir) – (spill + controlled release + water supply to NYC from the reservoir) (2)

The inflow to each reservoir includes historical rainfall onto the surface of the reservoir, and streamflows that flow into the reservoirs. Streamflow data comes from two different sources. The data available for gauging stations are obtained from the United States Geological Survey (USGS). The data of the ungauged inlets are estimated using the StreamStats online software program and the Delaware River Basin Streamflow Estimator Tool (DRB-SET) established by the USGS (Stuckey and Ulrich, 2016). The basin characteristics are identified for ungauged stream locations in the StreamStats Beta Version 4. Then, daily mean streamflows are computed in the DRB-SET for selected locations in the Delaware River Basin. In addition, direct precipitation onto the NYC reservoirs is considered in the model. Twenty-four years of daily precipitation data for each reservoir were taken from the CLIMOD2 online tool established by the Northeast Regional Climate Center (Center N. R. C., 2015).

The outflows of the reservoirs are the NYC water diversion, controlled releases and spill. To maintain proper operating conditions in the NYC reservoir system, water for NYC demand is transferred from the reservoirs through diversion tunnels. In the model, water diversions were set up before the reservoir outlets. The three diverted outlets, Water Supply to NYC from Cannosville, Water Supply to NYC from Pepacton and, Water Supply to NYC from Neversink, are drawn as flows in the schematic diagram in Figure 3.

The outlets, from reservoirs to the Delaware River (From Cannosville to Delaware, From Pepacton to Delaware, From Neversink to Delaware), consist of the controlled releases and spill. The spill was activated based on the reservoir operation zone. The spillway simply dumps the excess water when reservoir volume is above the operation zone. If the volume was not above the operation zone, the spill equation was set equal to zero. *Equation 3* shows the mathematical definition of the spill for the NYC-DRB Stella Model.

Spill = IF Inflow + Reservoir Storage – Demand – Water Supply to NYC From Reservoir >= Seasonal Reservoir Pool Operation Zone THEN Inflow + Reservoir Storage – Demand–Seasonal Reservoir Pool Operation Zone–Water Supply to NYC From Reservoir ELSE 0 (3)

The controlled releases from the reservoirs were based on total water demand of the basin. The daily water demand for each sector was determined in the basin. In the NYC-DRB Stella model, there are three kinds of water use sectors: Wildlife and Aesthetic (Conservation Releases), Fisheries (Thermal Releases), and Lower Basin Water Demand (Direct Releases for Montague). In addition, habitat bank releases were implemented into the demand equation starting from 2002. *Equation 4* defines the total demand for water use sectors in the basin. The first part of the equation was limited until 1983 due to the commitment defined in the Docket D-77-20 CP. Based on the commitment, the augmented conservation releases and the thermal stress releases were not to exceed the total volume of the excess release bank during any water year. Therefore, the cumulative volume of the thermal releases and the augmented conservation releases were limited to the cumulative volume of the excess release bank, and the conservation releases was defined in first part of the demand equation together with the thermal releases.

Demand = IF TIME >= 0 AND TIME <= 1126 THEN Thermal & Conservation Releases + Direct Releases for Montague ELSE IF TIME > 1126 AND TIME < 7788 THEN Conservation Releases + Thermal Releases + Direct Releases for Montague ELSE Conservation Releases + Thermal Releases + Direct Releases for Montague + Habitat Bank Release (4)

The controlled releases were made to meet water demand of the basin if the volume of the reservoir was above the total volume of the demand. In this case, the total amount of the demand was released from the reservoirs. If it was not above, the total volume of the reservoir and the inflow were released.

There are different types of banks in the NYC-DRB Stella model. The aim of these banks is to store water in the reservoirs for water demands of various sectors in the basin. Excess release bank stores water to maintain the Montague flow target. TRB is used to support fishery habitat in the downstream of the reservoirs, and habitat bank is established to support tailwaters of the reservoirs. The DRBC assigns a certain amount of water to these banks for every year, and the releases based on the basin demand are limited with these banks. In case of drought emergency conditions, the DRBC might establish additional amount of water to use for downstream purposes. No releases are made if excess release bank equals to seasonal quantity for lower basin demand, or if thermal release bank equals to the amount of water that the DRBC established for the fishery protection, or if habitat bank equals to the amount of water that the DRBC established to support tailwaters of reservoirs.

Structure and Operation of Water Use Sectors in the NYC-DRB Stella Model

Conservation release schedules had been established to protect wildlife and aesthetic of the environment at the downstream of the reservoirs. The schedules were revised four times for the Pepacton and the Neversink Reservoirs, and five times for the Cannonsville Reservoir between 1980 and 2005. Each revision was modeled in the model individually based on its schedule. If the combined storage of the NYC reservoirs is above the drought warning line, and maintains 15 billion gallons (BG) above this level for 15 consecutive days, the reservoirs release water depending on the augmented release schedule. If it is below the line and stays 5 consecutive days below or at the drought warning level, then reservoirs release water based on basic release schedule.

To protect trout species downstream of the NYC reservoirs, thermal stress releases are made from each reservoir. Reservoir releases were made whenever the maximum water temperature at designed downstream USGS gaging stations, Harvard (station number: 01417500), Woodbourne (station number: 01436500) or Hale Eddy (station number: 01426500), exceeded a maximum of 75 °F. The temperature data for each station was taken from USGS. However, there is no water temperature data for the Woodbourne station. Thus, the Bridgeville station was used to get daily maximum water temperature data. The Bridgeville station is located 17 miles downstream of the Neversink Reservoir, and 11 miles downstream of the Woodbourne station. The cumulative volume of these releases was restricted to 6,000 cfs-days from all reservoirs, and it was used between May 1st and November 1st. Furthermore, the thermal stress releases were released if the combined storage of the NYC reservoirs was above the drought warning line. However, there were some exceptions in the model. In case of drought emergency conditions, thermal releases made under the drought conditions for fishery production, and additional releases added to 6,000 cfs from the excess release bank.

To ensure that the lower basin gets enough water, the Montague flow target was established by DRBC in 1983 based on the drought operation curves. In the model, direct releases from the NYC-DRB reservoirs were made based on the different flow targets at Montague under normal, drought warning, and drought conditions.

Flows of the Delaware River at Montague are composed of following parts (NYCDEP, 1974):

1. Controlled releases from Lake Wallenpaupack on Wallenpaupack Creek, Pennsylvania for the production of hydroelectric power.
2. Controlled releases from Rio Reservoir on the Mongaup River, New York for the production of hydroelectric power.
3. Uncontrolled runoff above the Montague, New Jersey.
4. Controlled releases from Cannonsville, Pepacton, and Neversink Reservoirs of the City of New York.

The NYC-DRB reservoir releases are necessary to maintain the Montague flow objective. However, determination of the amount of release from each reservoir is complex because there is a time difference between the combined flows from the other sources and required flow at Montague. Therefore, water released from the reservoirs were scheduled in the model to allow for differences in travel times.

In the model, the Stella produced a message warning of a circular connection of the simulated outflow of reservoirs and water use sectors. Therefore, the observed data was used to estimate thermal and lower basin releases instead of simulated outflow data for each reservoir.

The NYC-DRB Stella model runs for 15 years of record (1980 – 1995) to simulate reservoir releases from the outlet of each reservoir. The reason why the model runs until 1995 is because of the data availability for the Rio Reservoir. The reservoir release data, which are used to calculate the uncontrolled streamflow above Montague are only available until 1995. The model outputs were compared with historical data to ensure that the model operates in the designed manner.

Seasonal Reservoir Pool Operation Zone

Each reservoir has been modeled based on a seasonal reservoir operation zone, which is a function of time and volume of the reservoir. The reservoir operation zone was implemented into the model to regulate the spill from the reservoirs depending on the available volume of water. Long-term median storage was computed on the basis of 23 years of reservoir volume records to calculate the daily seasonal reservoir operation zones (Figure 5). Based on the operation zone, when the total volume of reservoir and inflow is higher than the volume of the pool zone at the specific time steps, excess water from the reservoir is spilled. The daily reservoir storage data was gathered from Delaware River Master Report for the period of between 1980 and 2005 (ODRM, 2016).

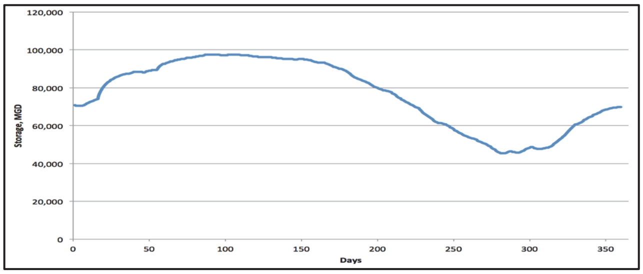

Figure 5. Seasonal pool operation zone for Cannonsville Reservoir.

Results

The historical streamflow and precipitation, and reservoirs operation parameters were employed to generate results with the NYC-DRB Stella model. The generated and actual historical outflow and storage for each reservoir were compared and verified for accuracy. As an example, Figure 6 shows observed and simulated outflows for a fifteen-year simulation (1980 – 1995) for the Cannonsville reservoir.

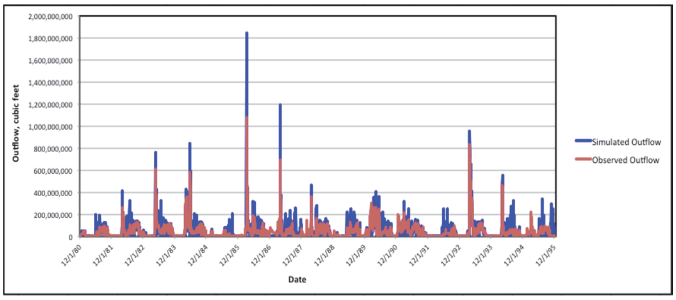

Figure 6. Observed versus simulated outflow for Cannonsville Reservoir.

Figure 7 indicates the years that drought emergency in the basin was declared by the DRBC. Throughout fifteen years, only four states of emergency were declared due to drought in the Delaware River Basin. As seen from Figure 6, during the drought emergency, releases from each reservoir were made for minimum conservation purposes based on the basic release schedule. The releases were returned to the augmented levels after the combined storage reached 25 BG above the drought warning level and remained at these levels for 15 consecutive days. Inflows to the reservoirs generally exceeded draft rates during the December through May, and thereby increased the reservoir's storage (Figure 8).

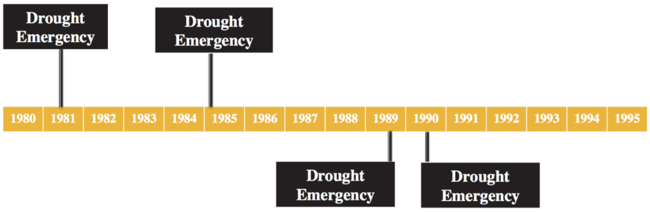

Figure 7. Drought emergency conditions for the Delaware River Basin between the years of 1985 and 1995.

In 1982, the precipitation in April was the greatest for the month in the record, thus all three reservoirs spilled before the month ended. In 1986, the capacity of the combined storage was increased during the winter months, and thus all three reservoirs spilled. Throughout August and September 1993, the amount of precipitation decreased significantly, therefore the storage continued to decline above normal rates (Figure 8).

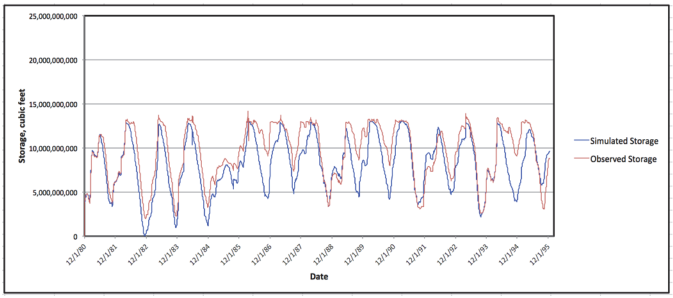

Figure 8. Observed versus simulated storage for Cannonsville Reservoir.

Even though the model followed a similar trend for the storage of the each reservoir, the model projects more spills compared to actual data. This might be the result of large inflows into the reservoirs. Therefore, estimated inflow through DRB-

SET and recorded data by USGS along with the precipitation was compared with actual inflow by calculating it via mass balance. To calculate the inflow, the daily actual storage data was subtracted from the outflow (reservoir releases and NYC diversion) for each reservoir. Figure 9 illustrates the comparison of estimated inflow by using DRB-SET tool and calculated inflow by using actual data for Cannonsville Reservoir. Based on the figure, the inflow data trend used in the model was very close to the actual inflow data calculated through mass balance.

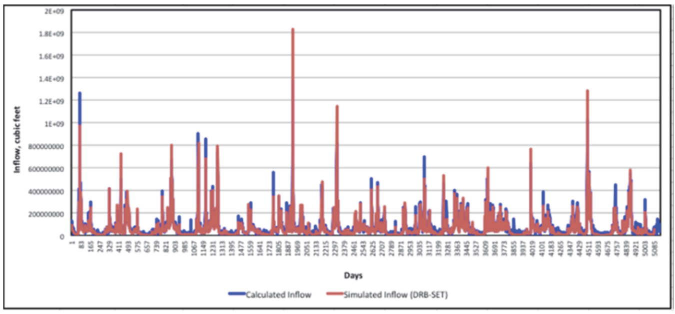

Figure 9. Estimated versus calculated inflow for Cannonsville Reservoir.

The seasonal reservoir operation zone, which determines the spill from the reservoirs depending on the volume of water inside the reservoir was calculated based on the long-term median storage on the basis of 23 years of reservoir storage records. To determine the reason why reservoirs spill more water than actual state, the observed daily storage records were compared with the long-term median storage for each reservoir. As an example, Figure 10 shows the comparison of actual daily storage and long-term median storage data for Cannonsville Reservoir. According to the figure, on some days reservoirs do not spill although actual reservoir storage is above the long-term median storage. However, the model spills if the storage is higher than the long-term median.

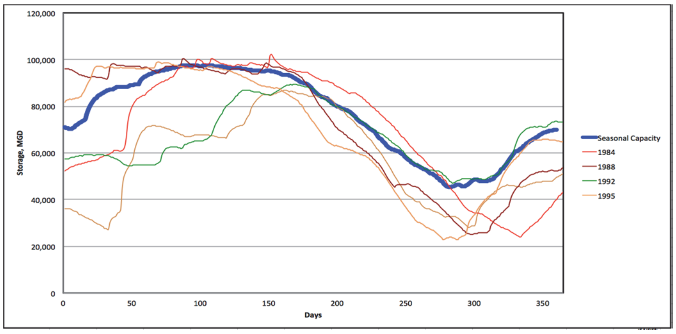

Figure 10. Actual daily storage versus long-term median storage for Cannonsville Reservoir.

To determine statistically significant differences between each year and the long-term median seasonal capacity, a non-parametric statistical analysis was performed with 95% confidence limits. Table 3 summarizes the results for three reservoirs. The difference between actual storage data and the long-term median of seasonal capacity for each reservoir was not statistically significant. Therefore, the seasonal operation zone approach was used in the model to represent an amount of seasonal storage in the reservoirs. This approach provides a guidance to determine the amount of storage available for both downstream purposes and recreational use of the reservoirs.

Table 3

Comparison of Actual Storage Data For Each Year and The Long-Term Median Seasonal Capacity For Three Reservoirs

Years	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
								Significance							
Cannosville	0.15	0.17	0.22	0.16	0.27	0.17	0.21	0.18	0.14	0.19	0.18	0.26	0.14	0.43	0.17
Pepacton	0.17	0.17	0.20	0.17	0.18	0.18	0.18	0.15	0.26	0.20	0.17	0.21	0.16	0.20	0.18
Neversink	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32

Furthermore, the actual and simulated outflow data was compared for each reservoir by using mean squared error to test the model accuracy. Table 4 shows the results for each reservoir. According to the table, the results indicate that the deviation of the actual data and simulated data is not large.

Table 4

Comparison of Actual and Simulated Outflow by Using Mean Squared Error for Each Reservoir

Reservoirs	Mean Squared Error (%)
Cannosville	2
Pepacton	7
Neversink	6

Discussion and Conclusion

The Delaware River Basin has been home to contentious debates over water allocation and management in the Eastern United States. The four states in the basin, New York, Pennsylvania, New Jersey and Delaware, have been negotiating on water allocation agreements since the early years of the republic. Extensive hydrological modeling approaches have proceeded from the negotiations. The model described in this study included the development of the NYC reservoirs model, which predicts reservoir releases based on inflows to reservoirs, water demand by sector and historical reservoir management policies. The impact of this study extends directly to decision makers and stakeholders who rely on water resources in the Delaware River Basin.

The Stella model is developed for NYC reservoirs operation to better understand cumulative effects of water withdrawals on water resources and reservoir operations under different climatic conditions. Moreover, running the simulation over the period of fifteen years and analyzing the main droughts in the basin shows how different operations manage drought over the historical record. These simulations enable to compare the various operations for future scenarios.

Through the use of non-parametric statistical technique, the difference between actual daily storage data for each reservoir and the long-term median were compared. The analysis showed that there are no significant differences between datasets. Therefore, the seasonal operation zone approach was accepted to use in the model. With this approach, the available storage was determined in each reservoir for downstream purposes and recreational use of the reservoirs. In addition, the mean squared error was estimated to compare simulated and actual outflow data for each reservoir. The results show that the error between the actual and simulated data was not large. In other words, the model predicts the outflow of each reservoir close to the actual outflow data.

However, some limitations still exist in this developed model. For instance, the Stella model produces a message warning of a circular connection of the simulated outflow and water use sectors such as fish and lower basin demand sectors. Therefore, an observed data is used to calculate water demand for fish and lower basin. Furthermore, the future climate scenarios have not been covered in the model. To determine their effects on river characteristics, the current reservoir operation techniques will be implemented into the model, and then it will be run under climate projections.

References

Burns, D. A., Klaus, J., & McHale, M. R. (2007). Recent climate trends and implications for water resources in the Catskill Mountain region, New York, USA. *Journal of Hydrology, 336*(1), 155-170.

Center, N. R. C. (2015). *Climate information for management and operational decisions (CLIMOD 2)*. Retrieved from: http://climod.nrcc.cornell.edu/

Creighton, J. (2010). *How to conduct a shared vision planning process* (In IWR Report 10-R-6). Alexandria, VA: US Army Institute for Water Resources.

Delaware River Basin Commission (DRBC). (1977). *Docket D-77-20 CP*. Retrieved from http://www.state.nj.us/drbc/library/documents/Res2004-3.pdf West Trenton, NJ:

Delaware River Basin Commission (DRBC). (1979). Resolution No.79-8. Retrieved from http://www.state.nj.us/drbc/library/documents/Reservoir_NYC/Res1979-08.pdf West Trenton, NJ.

Delaware River Basin Commission (DRBC). (1980). Resolution No.80-16, Resolution No.80-19, Resolution No.80-26. Retrieved from http://www.state.nj.us/drbc/programs/flow/ resolutions.html West Trenton, NJ.

Delaware River Basin Commission (DRBC). (1981). Resolution No.81-12, Resolution No.81-25. Retrieved from http://www.state.nj.us/drbc/programs/flow/resolutions.html West Trenton, NJ.

Delaware River Basin Commission (DRBC). (1982a). Interstate Water Management Recommendations of the Parties to the U.S. Supreme Court Decree of 1954 to the Delaware River Basin Commission Pursuant to Commission Resolution 78-20.

Delaware River Basin Commission (DRBC). (1982b). Resolution No.82-7, Resolution No.81-25. Retrieved from http://www.state.nj.us/drbc/programs/flow/resolutions.html West Trenton, NJ.

Delaware River Basin Commission (DRBC). (1983). Docket D-77-20 CP (Revised). Retrieved from http://www.state.nj.us/drbc/programs/flow/resolutions.html West Trenton, NJ.

Delaware River Basin Commission (DRBC). (1984). Resolution No.84-22. Retrieved from http://www.state.nj.us/drbc/programs/flow/resolutions.html West Trenton, NJ.

Delaware River Basin Commission (DRBC). (1985). Resolution No.85-30, Conservation Order no. 7. Retrieved from http://www.state.nj.us/drbc/programs/flow/resolutions.html West Trenton, NJ.

Delaware River Basin Commission (DRBC). (1987). Resolution No.87-20. Retrieved from http://www.state.nj.us/drbc/programs/flow/resolutions.html West Trenton, NJ.

Delaware River Basin Commission (DRBC). (1990). Resolution No.90-12. Retrieved from http://www.state.nj.us/drbc/programs/flow/resolutions.html West Trenton, NJ.

Delaware River Basin Commission (DRBC). (1993). Docket D-77-20 CP (Revision 2). Retrieved from http://www.state.nj.us/drbc/programs/flow/resolutions.html West Trenton, NJ.

Delaware River Basin Commission (DRBC). (1996). Resolution No.96-5. Retrieved from http://www.state.nj.us/drbc/programs/flow/resolutions.html West Trenton, NJ.

Delaware River Basin Commission (DRBC). (1997). Docket D-77-20 CP (Revision 3). Retrieved from http://www.state.nj.us/drbc/programs/flow/resolutions.html West Trenton, NJ.

Delaware River Basin Commission (DRBC). (1999). Docket D-77-20 CP (Revision 4). Retrieved from http://www.state.nj.us/drbc/programs/flow/resolutions.html West Trenton, NJ.

Delaware River Basin Commission (DRBC). (2000). Resolution No.2000-14, Temporary Modification of Special Thermal Releases. Retrieved from http://www.state.nj.us/drbc/programs/flow/resolutions.html West Trenton, NJ.

Delaware River Basin Commission (DRBC). (2001). Resolution No.2001-5, Extension of D-77-20 CP (Revision 4). Retrieved from http://www.state.nj.us/drbc/programs/flow/resolutions.html West Trenton, NJ.

Delaware River Basin Commission (DRBC). (2001). Resolution No.2001-33. Retrieved from http://www.state.nj.us/drbc/programs/flow/resolutions.html West Trenton, NJ.

Delaware River Basin Commission (DRBC). (2002a). Resolution 2002-6, Docket D-77-20 CP (Revision 5). Retrieved from http://www.state.nj.us/drbc/programs/flow/resolutions.html West Trenton, NJ.

Delaware River Basin Commission (DRBC). (2002b). Resolution 2002-21, Docket D-77-20 CP (Revision 5, amended). Retrieved from http://www.state.nj.us/drbc/programs/flow/resolutions.html West Trenton, NJ.

Delaware River Basin Commission (DRBC). (2002c). Resolution No.2002-33. Retrieved from http://www.state.nj.us/drbc/programs/flow/resolutions.html West Trenton, NJ.

Delaware River Basin Commission (DRBC). (2002d). Resolution 2003-4, Docket D-77-20 CP (Revision 6). Retrieved from http://www.state.nj.us/drbc/programs/flow/resolutions.html West Trenton, NJ.

Delaware River Basin Commission (DRBC). (2003). Resolution No.2003-26. Retrieved from http://www.state.nj.us/drbc/programs/flow/resolutions.html West Trenton, NJ.

Delaware River Basin Commission (DRBC). (2004a). Resolution 2004-3, Docket D-77-20 CP (Revision 7). Retrieved from http://www.state.nj.us/drbc/programs/flow/resolutions.html West Trenton, NJ.

Delaware River Basin Commission (DRBC). (2004b). Resolution 2004-9, Docket D-77-20 CP (Revision 8). Retrieved from http://www.state.nj.us/drbc/programs/flow/resolutions.html West Trenton, NJ.

Delaware River Basin Commission (DRBC). (2008). Delaware River Basin Water Code, with Amendments Through July16, 2008, 18 CFR Part 410, DRBC, West Trenton, NJ, 182 p.

Delaware River Basin Commission (DRBC). (2011). Flexible Flow Management Plan. Retrieved from: https://water.usgs.gov/osw/odrm/ffmp/index.html

Delaware River Basin Commission (DRBC). (2013). *Brochure on State of Delaware River Basin*. Retrieved from http://nj.gov/drbc/library/documents/SOTB/2013brochure.pdf

Delaware River Basin Commission (DRBC). (2014). *Salt Line*. Retrieved from https://www.nrc.gov/docs/ML1408/ML14086A553.pdf

Delaware River Basin Commission (DRBC). (2016). *History of the Reservoir Releases Program in the Upper Delaware River Basin*. Retrieved from http://nj.gov/drbc/programs/basinwide/sotb2013/water_quantity.html

Delaware River Basin Commission (DRBC). (2017a). *History of the Reservoir Releases Program in the Upper Delaware River Basin*. Retrieved from https://water.usgs.gov/osw/odrm/releases.html

Delaware River Basin Commission (DRBC). (2017b). *History of the Reservoir Releases Program in the Upper Delaware River Basin*. Retrieved from http://nj.gov/drbc/basin/

Hoffman, J.L. (2004). *DGS04-8 Summary of Flows in the Delaware River at Trenton and Montague with Major Upstream Diversions, 1913-2002*. Retrieved from http://www.state.nj.us/dep/njgs/geodata/dgs04-8.htm

Hutson, S.S., Linsey, K.S., Ludlow, R.A., Reyes, Betzaida, and Shourds, J.L. (2016). *Estimated use of water in the Delaware River Basin in Delaware, New Jersey, New York, and Pennsylvania, 2010: U.S. Geological Survey Scientific Investigations Report 2015–5142*. Retrieved from http://dx.doi.org/10.3133/sir20155142.

HydroLogics, Inc. STV, Inc., ATS, Inc., the Greeley-Polhemus Group, & the DRBC staff. (2004). *Strategy for Resolution of Interstate Flow Management Issues In the Delaware River Basin*. Retrieved from http://www.state.nj.us/drbc/library/documents/04flowreport/entire.pdf

ISEE Systems. (2017). *System thinking for education and research*. Retrieved from https://www.iseesystems.com/store/products/stella-architect.aspx

Institute for Water Resources (IWR). (2014). *Aspects of governing water allocation in the U.S.* Retrieved from http://www.iwr.usace.army.mil/Portals/70/docs/iwrreports/2014-R-4_Aspects_of_Governing_Water_Allocations_in_the_US.pdf

Klipsch J, Hurst M., & Fleming M. (2010). *Delaware River Basin flood analysis model, reservoir operations and streamflow routing component*. Retrieved from http://www.hec.usace.army.mil/publications/ProjectReports/PR-73.pdf Leitman, S., & Kiker, G. A. (2015). Development and comparison of integrated river/reservoir models in the Apalachicola–Chattahoochee–Flint basin, USA. *Environment Systems and Decisions, 35*(3), 410-423.

Ludlow, R. A., & Gast, W. A. (2000). Estimated water withdrawals and use in Pennsylvania, 1995 (No. 174-99). Retrieved from https://pubs.usgs.gov/fs/1999/0174/fs19990174.pdf

Mandarano, L. A., & Mason, R. J. (2013). Adaptive management and governance of Delaware River water resources. *Water Policy, 15*(3), 364-385.

Miller, R. L., Bradford, W. L., & Peters, N. E. (1988). *Specific conductance: theoretical considerations and application to analytical quality control*. Retrieved from https://pubs.usgs.gov/wsp/2311/report.pdf.

New Jersey Water Supply Advisory Council Department (NJDEP). (2014). *Managing the Delaware River. The 1954 Supreme Court Decree, the Good Faith Agreement, and the Flexible Flow Management Program. The New Jersey Perspective, Part 1.* Retrieved from http://www.nj.gov/dep/workgroups/docs/wsc-managing-delaware-river-part-1.pdf

New Jersey Water Supply Advisory Council Department (NJDEP). (2014). *Managing the Delaware River. The 1954 Supreme Court Decree, the Good Faith Agreement, and the Flexible Flow Management Program. The New Jersey Perspective, Part 2*. Retrieved from http://www.nj.gov/dep/workgroups/docs/wsc-managing-delaware-river-part-2.pdf

New York City Department of Environmental Conservation (NYCDEP). (1974). Proposed Alternative Releases from New York City Reservoirs in the Upper Delaware River Basin. Retrieved from https://water.usgs.gov/osw/odrm/documents/1974-Alternative-Releases-part-1-of-2.pdf.Palmer, R. N. (2010). *Basic Introduction to STELLA II*. Seattle, Washington: University of Washington..

Office of Delaware River Master (ODRM). (2015). *Report of the River Master of the Delaware River for the Period of December 1, 1984 – November 30, 1985. U.S. Geological Survey open file report 86-0606*. Retrieved from https://pubs.usgs.gov/of/1986/0606/report.pdf

Office of Delaware River Master (ODRM). (2016). Retrieved from: http://water.usgs.gov/osw/odrm/releases.html.

Ravindranath, A., Devineni, N., & Kolesar, P. (2016). An environmental perspective on the water management policies of the Upper Delaware River Basin. *Water Policy, 18*(6), 1399-1419.

Santoro, E. D. (2004). *Delaware Estuary Monitoring Report–Covering Monitoring Developments and Data Collected or Reported during 1999–2003*. Retrieved from http://www.state.nj.us/drbc/library/documents/estuary-monitor-rpt_2004.pdf

Stuckey, M. H., & Ulrich, J. E. (2016). *User's guide for the Delaware River Basin Streamflow Estimator Tool (DRB-SET) (No. 2015-1192)*. Retrieved from https://pubs.usgs.gov/of/2015/1192/ofr20151192.pdf

Survey, G. (1982). U.S. Geological Survey Water-supply Paper: U.S. Government Printing Office.

Supreme Court of the United States (U.S.). (1954). Amended Decree, State of New Jersey v. State of New York and City of New York.

The City of New York Environmental Protection (NYCEP). (2017). Retrieved from http://www.nyc.gov/html/dep/html/watershed_protection/neversink.shtml

The City of New York Environmental Protection (NYCEP). (2017a). Retrieved from http://www.nyc.gov/html/dep/html/watershed_protection/pepacton.shtml

The City of New York Environmental Protection (NYCEP). (2017b). *History of New York City's Water Supply System*. Retrieved from http://www.nyc.gov/html/dep/html/drinking_water/history.shtml

The Nature Conservancy (TNC). (2011). *Delaware River Basin Priority Conservation Areas and Recommended Strategies. Final report to the National Fish and Wildlife Foundation*. Retrieved from http://www.state.nj.us/drbc/library/documents/DEbasin-priority-areas_2011NFWF.pdf

Weston, R. T. (1989). The Delaware River Basin: Courts, Compacts and Commissions.

Yagecic. J., R. MaxGillivray, E. Silldorff, & E. Vowinkel. (2012). Chapter 3- Water Quality in the Technical Report for the Delaware Estuary & Basin. *Partnership for the Delaware Estuary Report Ni. 12*(01), 63-106.

Extended Turkish Abstract
(Genişletilmiş Türkçe Özet)

Rezervuar Operasyonları & Su Tahsisi Modeli: New York Şehri Delaware Nehir Havzası Rezervuarları

Nüfus artışı ve sanayileşme ile birlikte su kaynaklarına olan talebin artması, iklim değişikliği sebebi ile yağış ve sıcaklık rejimlerinin değişmesi sonucu su kaynaklarının kullanıcılar arasında adil ve dengeli bir şekilde paylaştırılması her geçen gün daha da önem kazanmaktadır. Bu sebeple, su kaynaklarının daha verimli ve uzun vadede kullanılabilmesi için havza bazında bir su yönetimi planı yapılması gerekmektedir. Böylelikle, hem suyun sürdürülebilir yönetimi hem de koruma – kullanma dengesi sağlanmış olur.

Amerika Birleşik Devletleri'nde havza bazında su kaynaklarının eşit dağılımını sağlamak ve oluşacak problemleri en aza indirgeyebilmek amacıyla havzadaki su kaynaklarının tek bir kurum üzerinden yönetilmesi için havza komisyonları oluşturulmuştur. Bu komisyonlar sayesinde her bir havzadaki suların yönetiminden sorumlu kişiler tek bir çatı altında toplanmış, geçmişteki koordinasyonlardan kaynaklı problemler en aza indirilmiştir.

New York, Pennsylvania, New Jersey ve Delaware eyaletleri sınırları içerisinde yer alan Delaware Nehir Havzası'ndan sorumlu Delaware Nehir Havzası Komisyonu havzanın problemlerine bütüncül bir yaklaşım ile çözümler üretmektedir. Delaware Nehir Havzası Komisyonu, Amerika Birleşik Devletleri'nde kurulan federal hükümetinde içerisinde olduğu ve eyaletler arası iş birliği özelliği taşıyan ilk komisyondur.

Delaware Nehir Havzası 13,600 mil kare büyüklüğündedir ve havzanın %15'i imarlı alan, %49'u ormanlık alan, %26'sı tarım alanı, %10'u ise sulak araziden oluşmaktadır (DRBC, 2013). Ormanlık alanlar genellikle havzanın üst kısmında, tarım alanları ise alt kısımlarda yoğunluklu bulunmaktadır. Amerika Birleşik Devletleri'nin populasyonunun yaklaşık %5'i havzanın su kaynaklarından yararlanmaktadır, ancak havzanın mevcut ve gelecekte ki yaklaşık su potansiyeli dikkate alındığında, havzada sürdürülebilir bir su yönetiminin uygulanmasının gerekliliği kaçınılmazdır. Havza da bulunan rezervuarların toplam su tutma kapasitesi 400 milyar galonun üzerindedir ve bu rezervuarlardan deşarj edilen sular, içme – kullanma, taşkın kontrol, hidroelektrik enerji üretimi, tuzluluk kontrolü ve çevresel ihtiyaç için kullanılmaktadır (HydroLogics, 2004).

Delaware Nehir Havzası Komisyonu'nun sorumluluğundaki New York'a içme ve kullanma suyu sağlayan, aynı zamanda alt havzalar için önemli bir su kaynağı olan, Cannonsville, Pepacton ve Neversink rezervuarları havzanın kuzeyinde yer almaktadır. Önceliği New York şehrine tüneller yardımı ile su sağlamak olan bu rezervuarlar, aynı zamanda çevresel akış ve alt havzada bulunan şehirlerin su ihtiyacı açsından da önemli bir yere sahiptir. Ayrıca, kurak dönemlerde tuzlu okyanus sularının Delaware Koyu'ndan havzaya girişi ile içme ve kullanma suyunun kalitesinin bozulması gibi problemler oluşmuş, bu sebeple rezervuarlardan yapılan kontrollü deşarjlar önem arz etmiştir.

Kontrollü deşarjlar havzada belirlenen sektörlerin su ihtiyacına bağlı olarak Cannonsville, Pepacton ve Neversink'in toplam hacmine göre yapılmaktadır. Bu sebeple, Delaware Nehir Havzası Komisyonu tarafından rezervuarların toplam hacmi dört ayrı aşamaya ayrılmış ve her bir rezervuardan deşarj edilen

su miktarı kuraklık dönemlerine ve aylara göre sınırlandırılmıştır. Örneğin, üç rezervuarın ölçülen toplam hacmi 220 milyar galon ise, rezervuarlardan yapılan deşarjlar normal şartlar için belirlenen debilere bağlı yapılır. Ancak kurak dönemlerde, toplam hacim 60 milyar galona düşerse, deşarjlar kurak dönem için belirlenmiş debilere bağlı olarak yapılır. Ayrıca, kurak dönemlerde artan tuzluluk konsantrasyonunu önlemek amaçlı havzada belirlenen noktalarda istenen debinin sağlanması amacıyla da rezervuarlardan kontrollü deşarjlar yapılmaktadır.

Bu çalışmada, çoğunluğu Delaware Nehir Havzası Komisyonu tarafından yürürlüğe sokulmuş olan kanunlar derlenip, Stella isimli bir yazılım programına girilmiş ve New York Şehri Delaware Nehir Havzası (NYC-DRB) rezervuarları için hidrolik bir model geliştirilmiştir. Bu model ile birlikte, havza içi ve dışı içme suyu ihtiyacı belirlenmiş ve iklim değişikliğinin etkisi ile havzadaki su kullanımının sektörler üzerine etkisi ele alınmıştır. Rezervuarlara giren su miktarı hesaplandıktan sonra her bir sektörün su ihtiyacı belirlenmiş ve 25 yıllık rezervuar işletim kuralları temel alınarak, rezervuarlardan deşarj edilmesi gereken su miktarı Stella programında modellenmiştir. Ayrıca, rezervuar güvenliği açısından önemli bir yere sahip olan dolusavak yapısı dikkate alınmış ve dolusavak akımı modelde hesaplanmıştır. Bunula birlikte, 25 yıl havzada yaşanan kuraklık dönemleri boyunca uygulanan farklı senaryolar modele entegre edilmiştir. Daha sonra model çıktıları gözlem verileri ile karşılaştırılarak model validasyonu yapılmıştır.

Bu çalışma, su yönetimi stratejilerinin belirlenmesinde karar verme yetkisine sahip kişilere yardımcı olduğu gibi, havzada ki paydaşlar için de önemli bir adımdır. Bu çalışma ile havzadaki su taleplerinin karşılanmasında su kaynaklarının korunması ve sürdürülebilirliği sağlanmış olup, suyun sektörler arasında adil paylaşımının gerçekleşmesi hedeflenmiştir. Ayrıca, havzada ki doğal hayatın devamlılığı için önemli bir yere sahip olan çevresel akış çalışmaları kurak dönemler dikkate alınarak modele eklenmiş ve havzanın çevresel su ihtiyacı karşılanmıştır.