Project

Assessing Water Management Strategies from a Sustainability Perspective

SUS 7800B (Sustainability in Civil Engineering)

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Abstract

About 50% of New York City’s water needs are provided by the three Delaware reservoirs including Pepacton, Cannonsville, and Neversink (PCN reservoirs). This article analyzed the water policies for New York City, using the PCN reservoirs as a case study. The policies aim to balance the increasing water demand from population growth, industrial development, and natural capacity limits, ensuring sustainable development. The Good Faith Agreement of 1983, aiming to provide reliable water supplies during droughts, led to the reassessment of diversion releases and ecological flows. Expanding the Cannonsville Reservoir and reviewing alternatives for conservation and responsible use of surface water resources, including groundwater, were recommended. The article evaluated the annual water release from the PCN reservoirs and the population growth rate for New York City from 1982 to 2009. The analysis demonstrated that the decisions made significantly reduction in the diversion release for the city despite the rapid increase in population rate and tried to face in a sustainable way to deal with all the challenges related to water consumption, population growth, and climatic conditions, such as droughts.

Keywords: Delaware River, New York City water supply, New York City water consumption, sustainability, water policy, population growth, Pepacton, Cannonsville, Neversink.

Introduction

One of the biggest elements affecting public health is the quality of their drinking water. The situation has slightly improved because of many developing nations' recent focus on reducing waterborne illnesses and creating safe water resources (He et al., 2021). Hydrology, climatology, ecology, sociology, economics, sustainability, and other fields are all impacted by water challenges, among others. Additionally, there have been significant data difficulties and revolutions in the water sector (Josset et al., 2022). Water is a critical resource for New York City, and ensuring adequate supply and efficient use is essential for the city's sustainability. In one hand, with the city's population continuing to grow, it is important to examine the sustainability of current water policies and their ability to meet the demands of a growing population. On the other hand, it is becoming a tremendous difficulty to improve the filtration facilities to satisfy the needs because, as we all know, water consumption is rising in every metropolis day by day (National Risk Management Research Laboratory (US), 2004; Casani et al., 2005). The first step in carrying out this for a certain city is to ascertain what its upcoming water needs are (Aggarwal and Sehgal, 2021).

In the developed regions, no major water resources remain with a regime not being disturbed by human activities (Gleick, 1993). Without the Clean Water Rule, one in three Americans would be getting their drinking water from streams with no obvious safeguards against pollution. The health of 117 million Americans is protected by the rule's finalization (Sanchez-Flores et al., 2016). The other point that should be mentioned is the relation between energy and water, sometimes known as the "energy-water nexus," which has drawn more attention in recent years due to the United States' expanding need for both water and energy resources (US). Each of the several processes of collection, treatment, conveyance, distribution, end-use preparation, reconditioning, and release that make up the US water system has a significant impact on energy. Although these changes toward more energy-intensive water are probably going to have a noticeable impact on future energy demand (Sanders and Webber, 2012).

Most urban populations consume large proportions of water and energy. The world is rapidly urbanizing, and high population growth continually escalates energy–water–food–land nexus pressures. the investment policies and provides support to all climate resilience activities especially at the community level. As a result, sustainability and management of water resources are achieved (Network, 2003; Johnson et al., 2018; Imasiku and Ntagwirumugara, 2020).

Early in the nineteenth century, there was a heated public discussion about the city's water supply and its future in the face of a fast population increase (He et al., 2021). Early efforts by private business owners to construct a piped water delivery system had only been successful in providing subpar water to a small number of residences. Before 1830, the residents of New York City relied on local water sources (Endreny, 2001). With a burgeoning population and deteriorating water quality by 1830, the city looked outside of its immediate area for assistance (Ravindranath et al., 2016). After years of discussion among the public, the New York State Assembly finally passed a law in 1834 allowing the city to build its first municipally owned waterworks. The Croton Aqueduct connected the city to copious amounts of clean water that had been diverted from the Croton watershed in upstate New York, and the city thereafter started a program of aqueduct and dam development (Jervis, 1842; Gandy, 1997). From the 1840s on, residents of New York took pleasure in having one of the best water supplies of any major city in the Western world. Examining how the shifts in developed economies that have been taking place since the 1970s have increased the power of capital to influence public policy is necessary to comprehend the current problem in regulation in the city (Morris, 2022).

Previous studies have shown that water demand and consumption in New York City are influenced by various factors, including population growth, climate change, and economic development. The city's water supply system is complex, involving a network of reservoirs, aqueducts, and treatment plants that provide water to millions of residents and businesses. Several policies have been implemented in the past to manage water demand, including restrictions on outdoor watering, incentives for water-efficient appliances, and public education campaigns. However, it is unclear whether these policies are sufficient to meet the challenges posed by population growth and other environmental factors. In this way, the purpose of this study is to analyze the relationship between water demand and consumption in New York City and assess the sustainability of current water policies considering population growth (Angotti and Morse, 2023).

Background

Water Supply and Population Growth in New York City

The availability of water to city dwellers is one of the most significant variables influencing urban development. The amount of water that is readily available in cities can become constrained, but if the places from which these resources are sourced expand owing to increasing trade and advancements in transportation, these limitations can be overcome and replaced with others. For instance, as railroads replaced river transportation in the nineteenth century, the resource supply increased, and New York City saw growth in its urban population and city borders (Gingrich et al. 2011).

The spatial bounds and form of a city change over time based on the interaction between population expansion, resource constraints, and ways to get around them. The amount of space needed to supply water and nutrients to a city's people is therefore determined by the size of the city and the accompanying demand for resources, or by its "metabolism" (Wolman, 1965).

There were no substantial resource limitations on the city's growth during these early years. Currently, with a population of almost 8 million, the New York Metropolis is the largest metropolis in the United States, the second largest in North America (after Mexico City), and one of the most densely inhabited cities in the world (10,000 people per km2). Numerous authors have already written about the nature and history of NYC's water supply system (Van Burkalow, 1959; Weidner, 1974; Gandy, 1997; National Research Council (NRC), 2000; Swaney et al., 2012; Leeke, 2019; and Malin, 2022).

In the context of a discussion of water-contributing areas of streams, etc., the watershed boundary is typically thought of as being constant across time, and riverine fluctuations are connected to temporal changes in the temperature, weather, and associated processes that take place inside the fixed boundary. For long-term water supply management, e.g., reservoir planning, the watershed concept is essential in determining the placement of reservoirs based on the catchment area necessary to meet demand (Weidner, 1974; Soll, 2013; Cech, 2018).

The watershed areas of the reservoirs that make up the city of New York's water supply system provide a good definition of the watershed today, and the New York Department of Environmental Protection (DEP) made a list of system characteristics including watershed population and average percent of water supply (National Research Council, 2000). In Fig. 1, the New York City Water supply system is shown.

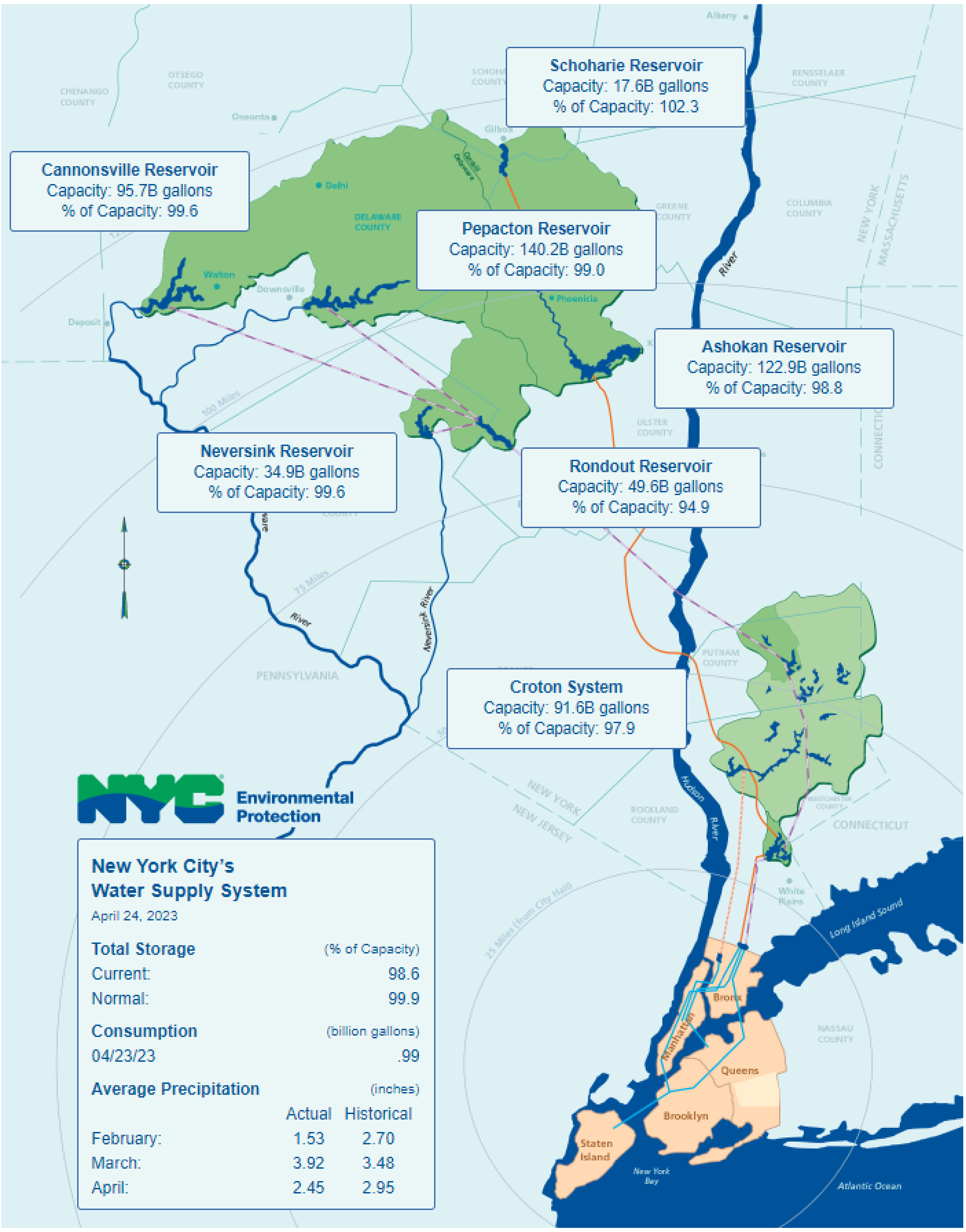

Fig. 1. New York City Water supply system (https://www.nyc.gov/site/dep/water/reservoir-levels.page)

Water Supply and Climate Change in New York City

Climate plays a crucial role in determining the water supply in New York City, as precipitation patterns and temperature affect both the quantity and quality of available water. One of the greatest climate change-related risks to the city's water supply is runoff from heavy rain affecting water quality in reservoirs (Lloyd and Licata, 2015). Since the city relies on a complex system of reservoirs, aqueducts, and tunnels to transport water from upstate New York to the city, it is directly affected by climate change. For metropolitan settlements, the availability of water might change due to precipitation, droughts, and the depletion of aquifer quantities. Climate change is expected to have a significant impact on New York City's water supply in several ways. Rising temperatures can increase the demand for water, particularly during heat waves, while changing precipitation patterns can affect the availability of water. Climate change is an ongoing challenge that affects long-term (2080s, 2100, and beyond), medium-term (2050s), and short-term (2020s) decision-making. The three-time horizons are useful in framing climate risk information and indicators used to guide adaptation planning and implementation (NYCPCC 2019 Report Executive Summary). Even a system as strong as New York City's is susceptible to extreme weather occurrences, as recent experiences have shown. Although Superstorm Sandy in 2012 did not produce much rain, it did cause a storm surge that had an impact on some of DEP's assets in low-lying areas and destroyed vital machinery at important wastewater facilities that were situated along the waterfront. Tropical Storms Irene and Lee in 2011 brought about significant flooding in the city's upstate reservoirs, which led to an unprecedented deterioration in water quality and made it difficult for DEP to provide the city with high-quality drinking water. According to climate scientists, this region of the planet will endure episodic or prolonged dry periods, increased precipitation, and a rise in sea level. An already worn-out infrastructure system that was intended to drain our city is put under pressure by more rain. Storm surges and torrential downpours can damage or disable essential machinery and cause overflowing of raw sewage into the city's waterways (Lloyd and Licata, 2015).

Increased evaporation rates are one consequence of warmer temperatures; this can cause reservoirs to have less water available. This may make the problem of water scarcity worse and cause water shortages in New York City. Furthermore, warmer temperatures might cause early snowmelt in mountainous regions, impacting the time and volume of water entering and water delivery systems downstream. The need for more water increases as the temperature rises. People often use more water during heat waves for activities like swimming, bathing, and outside watering, which can put a strain on water delivery infrastructure. As a result of higher temperatures, there would be less water available for the population and more water needed for biological processes, agriculture, and other uses. On the other side, greater temperatures can also worsen the quality of the water. Decadal trends in the yearly maximum daily temperatures during the summer months of June, July, and August vary geographically within the city. One effect of higher temperatures is increasing the evaporation rates, reducing water availability in reservoirs. This exacerbates water scarcity and leads to water shortages in New York City. Additionally, higher temperatures can lead to earlier snowmelt in mountainous areas, which can affect the timing and amount of water that flows into downstream water supply systems. Another effect of higher temperatures is the increasing water demand. During heatwaves, people tend to use more water for activities such as outdoor watering, showering, and swimming, which can strain water supply systems. Higher temperatures can also increase water demand for agriculture, ecological release, etc., which can further reduce the availability of water for the population. On the other hand, higher temperatures can also degrade water quality. Decadal trends in annual average daily maximum summer temperatures in June, July, and

August vary spatially across the city. The amount of water in reservoirs can quickly decrease during droughts, when rainfall is infrequent and evaporation rates are high, resulting in water shortages and interruptions in the provision of water. The amount of water in reservoirs can significantly decrease when there is a drought. Water shortages may emerge from this, particularly during times when there is a significant demand for water, like the hot summer months. To control water demand during certain times, water delivery systems may need to enact water restrictions and conservation measures.

Due to an increase in temperature and a decrease in the amount of dissolved oxygen in the water, the quality of water in reservoirs can deteriorate as the water level falls. This may result in the development of dangerous bacteria, algae, and other diseases, which could impair the quality of the water and necessitate additional treatment. Lower water levels in reservoirs can make infrastructure vulnerable to corrosion and damage, including intake structures and pipelines. Failures in the infrastructure and interruptions in the water supply may result from this. Previous studies have shown the value of paleo-climatic streamflow reconstructions in giving a more objective evaluation of operating guidelines for reservoir systems (Devineni et al., 2013, Woodhouse et al., 2006, Nowak et al., 2012; Stockton and Jacoby, 1976). As a result, using tree-ring chronologies from the upper Delaware River basin, there are created reconstructions of the Pepacton, Cannonsville, and Neversink (PCN) reservoir inflows for NPCC3 (Fig. 2) (NYCPCC 2019 Report Executive Summary).

Using the 12-month average Palmer Drought Severity Index (PDSI), NPCC1 estimated the city's projected future changes in droughts (NPCC, 2010). According to predictions, the frequency of droughts would almost double by the 2050s and increase by five times by the 2080s. This NPCC3 paper focuses on drought indices created using paleoclimate data for the city's main reservoir system (NYCPCC 2019 Report Executive Summary).

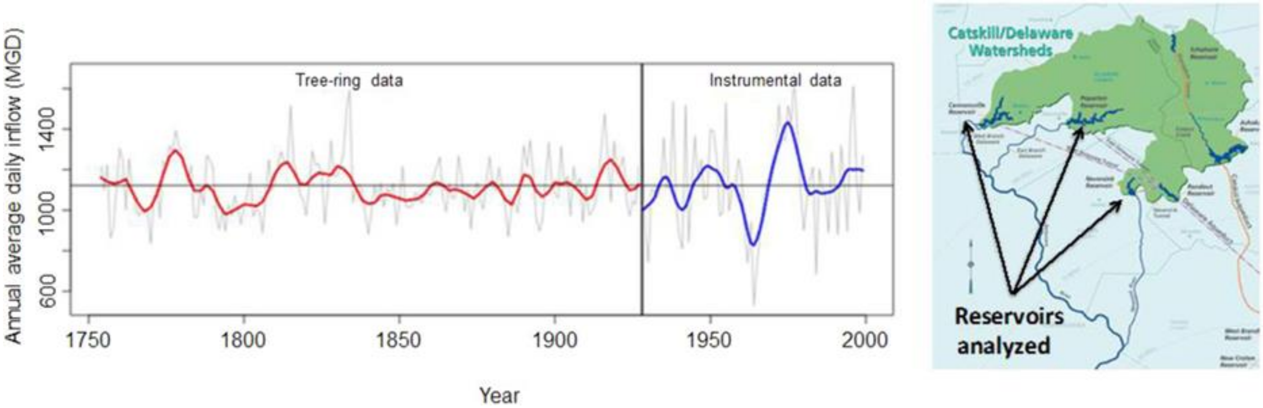

Fig. 2. Reconstruction of the combined annual average daily inflow for the Pepacton, Cannonsville, and Neversink Reservoirs from 1750 to 2000 using eight tree-ring chronologies.

These extensive reservoir inflow records have also been used to generate long-term drought profiles that include duration, severity, and return periods under different water demand thresholds. The frequency and severity of droughts are expected to increase due to climate change, according to the New York City Panel on Climate Change (NPCC), which may result in less water flowing into the city's reservoirs and aqueducts. Climate change can affect water quality in addition to water quantity. For instance, extreme weather conditions like flooding or heavy rain can contaminate water with sewage spills or other contaminants. Increased growth of hazardous algal blooms, which can degrade water quality and need further treatment, is another effect of rising temperatures. The NYCDEP is adopting sustainable measures to strengthen the resilience of its water infrastructure to combat the effects of climate change on the city's water supply. In order to absorb and retain stormwater runoff and lower the need for the city's water supply, this entails investment in green infrastructure such as rain gardens and green roofs. To expand the accessibility of alternate water sources, the NYCDEP is also investigating the usage of desalination, water reuse, and recycling initiatives (NYCPCC 2019 Report Executive Summary).

The Evolution of Water System in New York City

New York City residents relied on the local water sources till 1830 but they faced declining water quality, and the population of the city was growing rapidly. NYC turned beyond the local sources to provide sufficient water for the population. By 1920 City went through Delaware River basin for much more water but some years later New Jersey bought a suit in the us Supreme Court to prevent New York City from using water from Delaware (Endreny, 2001). Triggered by this complaint of New Jersey the court took the decision to permit the City to build two dams Pepacton and Neversink and to divert an average of 19.3 m^3 /s from the basin (stated 440 million gallons of water per day (MGD) in the order) with the provision that it maintains a minimum discharge of 43.47 m3/s (stated as 1,535 cubic feet per second (CFS) in the decree) at the United States Geological Survey (USGS) gage on Delaware at Montague, New Jersey (283 U.S. 336 (1931), DRBC, 2013), (Ravindranath et al., 2016).

Case study (Geographic location of The Pepacton, Cannonsville, and Neversink reservoirs)

The Pepacton, Cannonsville, and Neversink reservoirs (PCN reservoirs) are three of the largest reservoirs in the New York City water supply system. They are in the Catskill Mountains, northwest of the city, and are used to supply clean drinking water to millions of people in New York City and surrounding areas. The reservoirs are part of a vast network of infrastructure that collects and treats water from the Catskill Mountains and delivers it to the city via a system of aqueducts and tunnels. The Neversink reservoir was completed in 1955, followed by the Pepacton and Cannonsville reservoirs in the 1960s. These reservoirs are critical to the city's water supply and play an important role in protecting the health and well-being of New

Yorkers. Considering New York City as a case study with a high population, with water release that comes from Pepacton, Cannonsville, and Neversink reservoirs (PCN reservoirs) derivation of the water policies in collaboration with different institutions, analyzing how sustainable this policy has been in contexts of water consumption ([NYC.gov](NYC.gov)). In Fig. 3, the location of the three reservoirs are shown.

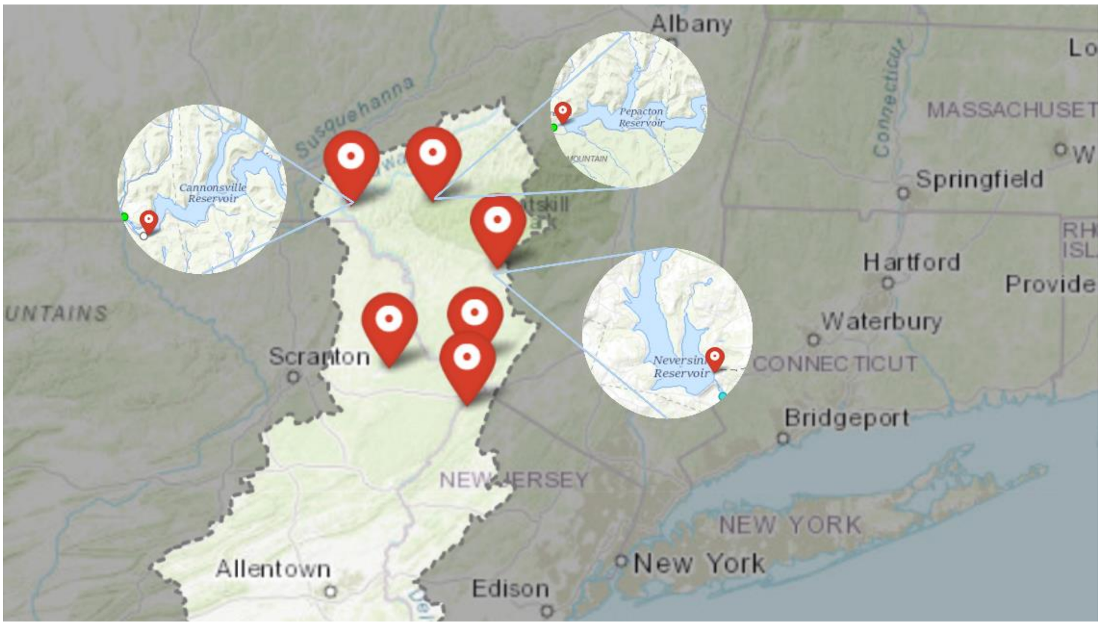

Fig. 3. Geographic location of The Pepacton, Cannonsville, and Neversink reservoirs (PCN reservoirs) on the Delaware River Dashboard.

Population Growth in New York City

In the United States, cities and populations are still growing, raising the question of what can be done to advance sustainable water usage in the future. With nearly 8.4 million people, the city's population is at an all-time high and is expected to reach 9 million by 2040 (Lloyd and Licata, A. 2015). New York City, where the population is anticipated to keep rising in the coming years, is a test bed for these forces. From 1982 to 2009 the population of NYC changed from 7,121,824 to 8,158,449, and it keeps raising nowadays[1] (Fig.4).

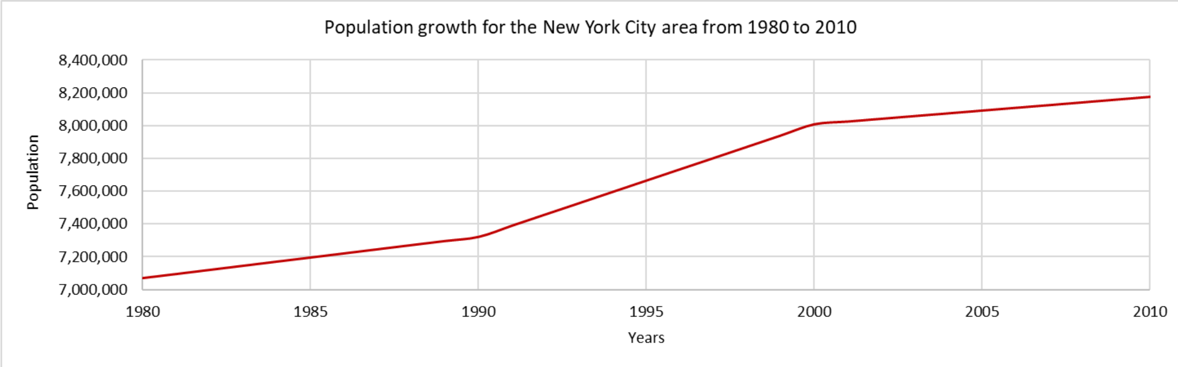

Fig. 4. Population growth in New York City during the period 1980-2010

Water Policy Background in New York City

Delaware Rives since 1954 has been managed under the framework of the Supreme Court and between some intergovernmental collaborations like New York State, New Jersey, Pennsylvania, New York City (NYC), Delaware, and the US federal government (Hirshleifer et al., 1969; Ravindranath et al., 2016).

Daily release data from three upper Delaware reservoirs (Pepacton, Cannonsville, and Neversink, which are frequently referred to in official documents as the PCN reservoirs, and the diversions of these reservoirs constitute about 50% of the City's needs. Balancing the requirements of New York City for divestment in the interests of down-basin stakeholders has been and continues to be the fundamental challenge in water policy and management in Delaware since 1932 (Ravindranath et al., 2016).

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[1] https://en.wikipedia.org/wiki/Demographic_history_of_New_York_City

The Delaware River Basin Commission is a regional governing body that oversees the management of water resources in the Delaware River Basin, including the Pepacton and Cannonsville reservoirs. The commission sets policies related to water releases, water quality, and other issues related to water management in the basin (Ravindranath et al., 2016).

New York, with a population that has been steadily increasing since 1982, has had increasing demands for water consumption. All this population growth has put pressure on the policymakers, who must make decrees and decisions to ensure that the population's demands are fully met while at the same time maintaining ecological flows, reservoir levels, and underground resources at reasonable levels to address future fluctuations and challenges. All of this essentially amounts to sustainable development among all these components.

In 1983 many negotiations of Decree Parties were finalized with the "Good Faith Agreement". This Agreement, recognizing that the sustained yield of the PCN system was considerably less than had been calculated in the 1954 decree, recomputed the yield using the 1960s drought data and specified a staged set of diversion and release reductions based on reservoir storage conditions as specified by a set of seasonal 'Operational Curves' (Ravindranath et al., 2016).

The New York City (NYC) diversion rate of 35.1 cubic meters per second (800 million gallons per day) was only in being used when reservoir storage levels were above the drought warning threshold. If the storage levels fell below this level, the diversion rate would decrease to 22.8 cubic meters per second (520 million gallons per day). Despite the implementation of augmented conservation releases as part of the 1983 Good Faith Agreement, the conservation community in upper Delaware found these releases to be inadequate and a source of ongoing dispute for decades. Additionally, the 1983 agreement adopted the NYSDEC's recommended location-specific thermal targets and increased the thermal cold-water bank to 48,831,822 cubic meters (12,900 million gallons) of water to help achieve these targets (Ravindranath et al., 2016).

In 1983, the population of New York City was estimated at 7,121,824, and the city was supplied by all three of the Delaware River Basin (DRB) dams after a decree by the Supreme Court in 1952 led to the construction of the third dam in Delaware to increase DRB water diversion. The drought that occurred during the period 1961-1967 had put all responsible structures on alert, and the Good Faith Agreement of 1983, particularly Recommendation 2, stated that: "The basin water management system must be able to provide and protect reliable water supplies for essential uses during a drought of the same severity as the drought of record, occurred during the period 1961-1967. The Commission should modify the Comprehensive Plan to include a specific management criterion that the drought of record is used as a basis for determining and planning for water supply." Recommendation 3 proposed several ideas for managing droughts by reducing diversions, releases, and flow objectives for Cannonsville, Neversink, and Pepacton reservoirs when reservoir storage falls below the drought warning curve. The Good Faith Agreement, in Recommendation 6, grants the State of New York the right to expand the Cannonsville Reservoir in Delaware County, New York, and construction should be completed by 1990. It also states that the requirements of Section IIIB of the U.S. Supreme Court's 1954 Decree regarding excess releases must be removed as it pertains to the additional storage in the Cannonsville modification project (Good Faith Agreement, 1982).

Although there was a growing demand due to the population increase in New York, which had been experiencing an extended drought for two decades, it prompted a review of diversion, releases, and ecological flows. Also, the expansion of one of the three reservoirs aimed to reserve water quantities in case of such climate disasters. The review of all the above-mentioned alternatives for conservation and responsible use of surface water resources, as well as examining the use of groundwater resources during dry periods when consumption was high, recommended that the water sources remain on standby and only used in emergency rates after the year 2000. The increasing pressure predicted for future years led to the consideration of the overlying water reserves as the only source that would meet all current water needs, while the groundwater sources remained untouched (Ravindranath et al., 2016).

During the 1990s and into 2004, fishermen were unhappy with how the water releases from Cannonsville reservoir were being managed. They felt that the releases were too low and varied too much, which was harming the fish populations. One group suggested a solution that would set a minimum amount of water to be released from the reservoir during the summer and winter, but this proposal was flawed because it would put the system into drought conditions and the reservoirs would not refill by spring. In 2006, a coalition of four conservation organizations with technical support from Columbia University developed a new plan called the FFMP that aimed to address the flaws of the current policies and relied on collaboration between the conservation coalition and staff from the NYSDEC. The FFMP (Flexible Flow Management Plan) of 2007-2011 aimed to balance the water supply needs of New York City with the ecological health of the Delaware River Basin, including the Cannonsville, Pepacton, and Neversink reservoirs. The design principles of this plan were in balancing the water supply needs of New York City with the ecological health of the Delaware River Basin, provide more flexibility in water management by adjusting water releases from reservoirs based on natural and human needs, and setting up an adaptive management framework to regularly review and adjust the plan based on monitoring and evaluation (Weiss et al., 2011; Ravindranath et al., 2016).

Water Policy in New York City During Recent Decade

Modified spill mitigation scheme that aims to keep reservoir levels at the Conditional Storage Objective, with a high chance of preserving 10% void spaces between 2011 and 2013 The following FFMP Agreement, which was adopted by the Decree Parties in 2013, expanded on the principles of the earlier FFMP Agreements (FFMP, 2013). Water policy in New York City concentrated on several important projects and goals. According to the Decree, and with certain restrictions, the city is not permitted to exceed 800 million gallons per day (mgd) in the total amount of water diverted, calculated daily over a twelve-month period starting from 2014. The city is also obligated to adhere to specific conditions and requirements regarding the diversions and releases necessary to maintain the Montague flow objective outlined in the Decree. To comply with this Agreement, the city must make releases from its Delaware Basin Reservoirs in accordance with the release schedules incorporated into the Agreement (FFMP, 2014).

New York City's water policy attempted to strike a sustainable balance between the demands of an expanding population and the necessity to save and preserve the city's water supplies. In this regard, the introduction of a new protection program, which intended to maintain the quality of the city's drinking water supply by collaborating with upstream towns and landowners to lessen pollution and other risks to the population, was one of the most notable projects during this time. In order to lower the danger of pollution, this program provided funds for infrastructure upgrades, outreach and education initiatives, and other initiatives (FFMP, 2015).

The most recent Flexible Flow Management Program was planned in 2017. The parties to the Decree have met, conferred, and reached an agreement on a program for the management of diversions, releases, and related operational procedures on the Delaware River. This program will supersede and replace current diversions, releases, and related operational procedures for the Delaware River for the duration of this Agreement (FFMP, 2017).

Promoting sustainable water usage and minimizing waste were two additional key areas of water policy at this period. In order to promote water conservation, the city enacted a number of initiatives and regulations, including public awareness campaigns, refunds for low-flow toilets and other water-saving fixtures, and obligatory water metering for the majority of residential and business users.

In addition to these initiatives, the city has made significant investments in modernizing its deteriorating water infrastructure, including the replacement of old pipes and other equipment to increase dependability and lower the danger of leaks and other issues. In order to address concerns about lead pollution, the city also initiated a program to enhance the drinking water quality in public schools. This initiative involved the installation of water filters and other upgrades.

The 2017 Flexible Flow Management Program (FFMP) was designed to meet water supply demands, safeguard fisheries habitat downstream of New York City's (NYC) Delaware Basin reservoirs, improve flood mitigation, and repel the upstream movement of salt water in the Delaware Estuary. The city of New York recently announced that it has completed an interim review of the FFMP (FFMP, 2017).

Several studies to evaluate the impacts and conditions of the releases, increased diversions, storage, balancing adjustment, and the Excess Release Quantity were set forth in the original 2017 agreement. The 2023 amendment to the agreement acknowledges that progress has been made on these studies, but delays occurred due to the complex nature of the topics and unforeseen events, such as the COVID-19 pandemic. Despite these challenges, the 2017 agreement has been effective, and everyone involved is still committed to carrying out the investigations specified in the agreement (FFMP, 2023).

Water Policy in New York City from the Future Perspective

The 2017 FFMP will depend on the first operations plan described in Appendix A of the 2017 agreement until May 31, 2028, when it will expire. The modification updates and continues the research that were specified in the first agreement (FFMP, 2023).

Although it is challenging to make a firm prediction about New York City's water supply and policy for the future, for example until 2050, there are several efforts and patterns, nevertheless, that may offer some insight into the future course of the city's water policy.

The city's plan, containing various sustainability goals and targets for the future, is one of the significant endeavors that might influence the future development of New York City's water policy. The strategy aims to invest in infrastructure, encourage water conservation, and lessen waste to guarantee that all New Yorkers have access to clean, cheap, and dependable water. Through initiatives and regulations that encourage conservation and waste reduction, the city may also keep advancing the sustainable use of water.

The city may also need to deal with the effects of climate change on the water supply, such as increased frequency and intensity of storms and sea level rise, by making investments in strategies that lower the risk of flooding and stormwater runoff and strengthen the water system's resilience to ensure service continuity in the event of a disruption.

In the longer term, the city could have to deal with more complicated issues including population growth, water shortages, possible effects of technology improvements, and new trends in the water industry. Therefore, a variety of causes and difficulties will likely influence

New York City's water supply and policy in the future. To preserve the sustainability and dependability of its water supplies for future generations, New York City will need to keep adapting and innovating.

Methodology and Analysis

In this study, we estimate the annual water release from daily data for the PCN reservoir and the total annual sum of water release from these three reservoirs, going as a water supply for NYC. Data for the three reservoirs Cannonsville, Pepacton, and Neversink from the DRB reservoir systems were obtained from the Office of the Delaware River Master and used here. Diversion releases, labeled as 'NYC Diversions', are controlled out-of-basin discharges for New York City consumption (Office of the Delaware River Master).

The amount of water released from each of these reservoirs is determined based on policies that aim to achieve a balance between the increasing demand for city water, development, and processes that require more water consumption (since, as we know, industrial development for many activities requires an increase in water demand), as well as addressing natural capacity limits, which of course have a limit that should not be exceeded. In Fig. 5, it is shown the annual releases for each of the reservoirs and the total.

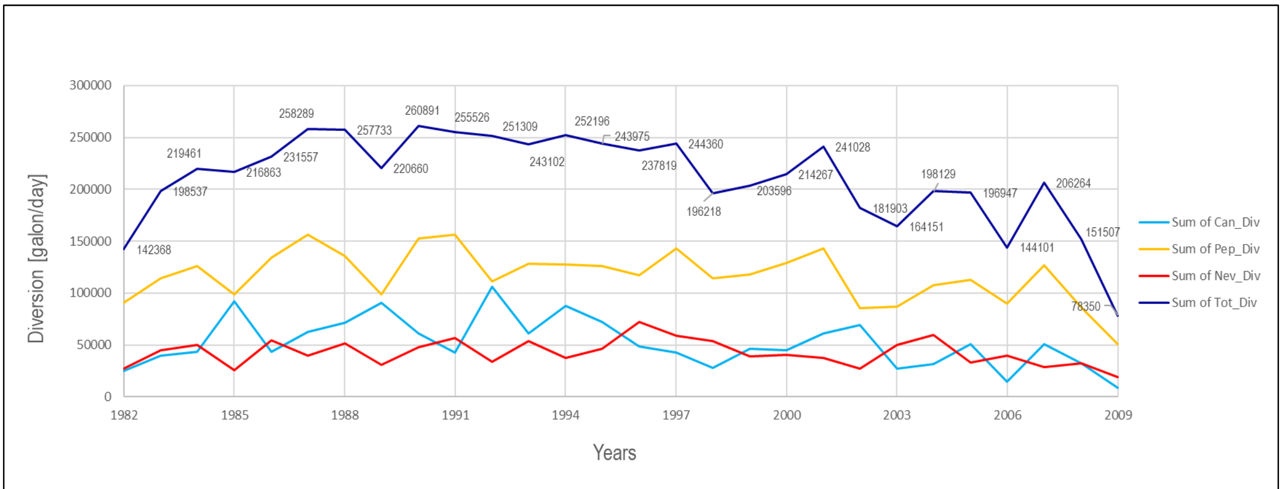

Fig. 5. Annually observed release for three reservoirs and the sum, for each of the 28 years on record

As it can be seen in Fig. 5, the red line is the time series of diversion daily data aggregated in year data for the Neversink Reservoir, the blue line is the time series of diversion daily data aggregated in year data for the Cannonsville Reservoir, the yellow line is the time series of diversion daily data aggregated in year data for the Pepacton Reservoir, the purple line is the total sum of release from three of these reservoirs (PCN Reservoirs).

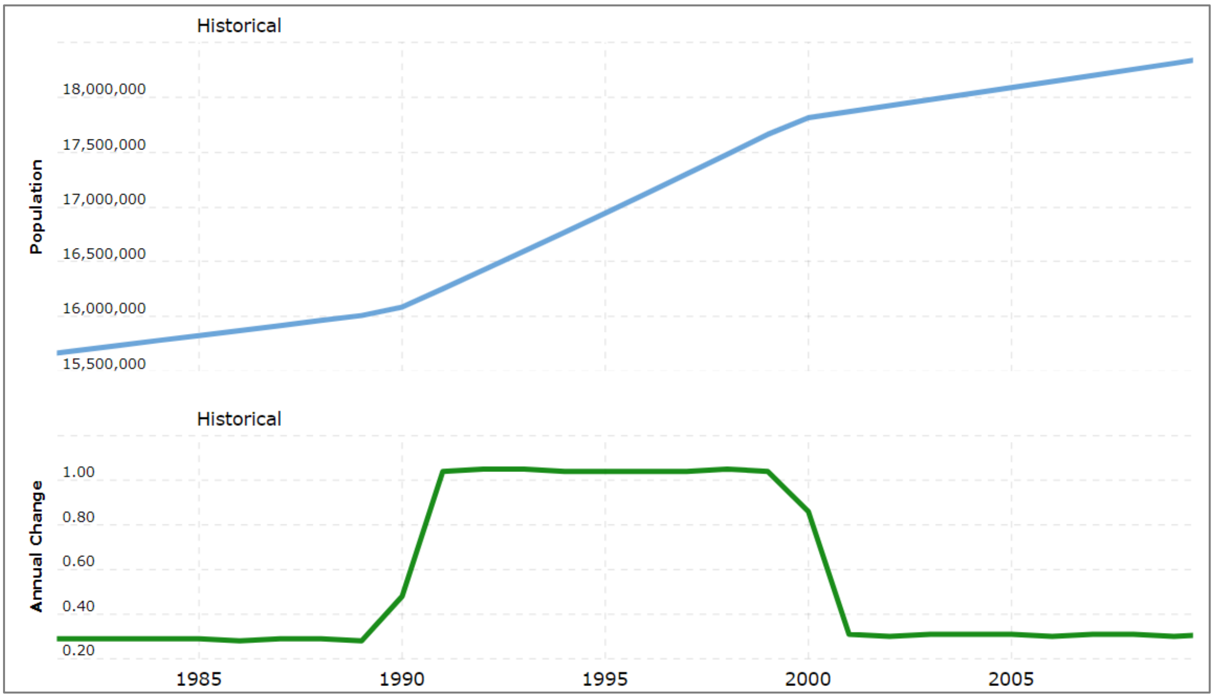

Fig. 6. Population-level and growth rate for the New York City metro area from 1982 to 2009

According to Fig. 6, during the first period of 1982-1990, the population of New York experienced a growth rate of 0.28%, while the diversion release from DRB continued to increase except for the year 1989 when the diversion release sum was quite low. Reviews of decrees and the drought of the period 1961-1967 led to a reassessment of things and the approval of the Good Faith Agreement changed the approach to diversion release from these three reservoirs. Even though during the period of 1990-2000 the population of New York City was experiencing a rapid growth rate of 1%, the decisions made significantly reduced the diversion release for the city[2]. The Pepacton reservoir always provided the highest yields in the city's water supply systems, while the Cannonsville reservoir, during the years 1992-1994, recorded the highest values of the amount of water it released for the city. In 1992, the demand for water from the Cannonsville reservoir, which was the highest of this entire period, was being studied, while this reservoir would have a reduced release as the goal was to conserve as much water as possible for emergency cases, but the drought of 1991 and the increasing demand from the city forced the use of water reserves from the Cannonsville reservoir. During the late second decade (1990-2000), the diversion release from DRB reached a significant level while the population continued to increase in number. After the year 2000 (in the third decade of this period under review), New York City significantly reduced its water consumption, as the actual values of the yields from the Delaware reservoirs indicated a decrease in the amount of water that these reservoirs were providing to the city. Meanwhile, the population of the city continued to grow at a rate of 0.3%.

The percentage values of the releases to the total sum of the three PCN reservoirs, the total release (in million gallons), and the number of populations for the respective years (Table. 1).

Table. 1. indicates data for the time period 1982-2009 on the percentage of water allocated to three different reservoirs (Can_Div, Pep_Div, Nev_Div) for NYC and the total amount of water allocated (Tot_Div) [million gallons] from the three reservoirs PCN Rez. of Delaware River Dashboard. The table also includes the population for each year.

The colors from dark red to dark green indicate values from high to low. It is noticeable that

[2] https://www.macrotrends.net/cities/23083/new-york-city/population

the largest inflows come from the Pepacton Reservoir, and the period of 1987-1997 has a relatively high consumption compared to the entire studied period, meanwhile, the NYC population has been increasing throughout these years.

Table. 1. Water allocated to three different reservoirs (Can_Div, Pep_Div, Nev_Div) for NYC

Years	Sum of Can_Div	Sum of Pep_Div	Sum of Nev_Div	Sum of Tot_Div	Population
1982	17.3%	63.7%	19.0%	142368	7109105
1983	19.9%	57.4%	22.7%	198537	7181224
1984	19.8%	57.4%	22.8%	219461	7234514
1985	42.5%	45.5%	12.0%	216863	7274054
1986	18.6%	57.9%	23.5%	231557	7319246
1987	24.1%	60.4%	15.5%	258289	7342476
1988	27.6%	52.5%	19.9%	257733	7353719
1989	41.2%	44.7%	14.1%	220660	7344175
1990	23.3%	58.5%	18.2%	260891	7335650
1991	16.8%	61.1%	22.2%	255526	7374501
1992	42.2%	44.3%	13.5%	251309	7428944
1993	25.1%	52.8%	22.1%	243102	7506166
1994	34.7%	50.5%	14.8%	252196	7570458
1995	29.6%	51.5%	18.9%	243975	7633040
1996	20.3%	49.4%	30.3%	237819	7697812
1997	17.6%	58.4%	24.0%	244360	7773443
1998	14.1%	58.4%	27.5%	196218	7858259
1999	22.9%	58.0%	19.1%	203596	7947660
2000	20.9%	60.3%	18.8%	214267	8008278
2001	25.3%	59.3%	15.4%	241028	8024964
2002	38.0%	46.9%	15.0%	181903	8041649
2003	16.5%	52.8%	30.6%	164151	8058335
2004	15.8%	54.1%	30.0%	198129	8075020
2005	25.9%	57.3%	16.9%	196947	8091706
2006	10.2%	62.4%	27.4%	144101	8108391
2007	24.6%	61.4%	13.9%	206264	8125077
2008	21.4%	57.1%	21.5%	151507	8141762
2009	11.0%	64.4%	24.6%	78350	8158448

The influence of the policies implemented on the use of water has also been reflected in its daily consumption, as the tendency for daily water consumption per capita has declined during all these years. This shows that the implemented policies have had a positive impact in the context of minimizing water consumption by preserving the minimum levels that should not be compromised. On the other hand, the increase in the population has made it difficult for policymakers and implementing institutions to manage emergency situations, such as prolonged droughts. Table. 2. presents detailed annual data on water consumption (NYC OpenData, Water Consumption in the City of New York).

Table. 2. Water Consumption in the City of New York

Year	New York City Population	NYC Consumption (Million gallons per day)	Per Capita (Gallons per person per day)
1982	7,109,105	1,382	194
1983	7,181,224	1,424	198
1984	7,234,514	1,465	203
1985	7,274,054	1,326	182
1986	7,319,246	1,351	185
1987	7,342,476	1,447	197
1988	7,353,719	1,484	202
1989	7,344,175	1,402	191
1990	7,335,650	1,424	194
1991	7,374,501	1,469	199
1992	7,428,944	1,369	184
1993	7,506,166	1,368.50	182
1994	7,570,458	1,357.70	179
1995	7,633,040	1,325.70	174
1996	7,697,812	1,297.90	169
1997	7,773,443	1,205.50	155
1998	7,858,259	1,219.50	155
1999	7,947,660	1,237.20	156
2000	8,008,278	1,240.40	155
2001	8,024,963.50	1,184	148

Continuous Table. 2. Water Consumption in the City of New York

2002	8,041,649	1,135.60	141
2003	8,058,334.50	1,093.70	136
2004	8,075,020	1,099.50	136
2005	8,091,705.50	1,138	141
2006	8,108,391	1,069	132
2007	8,125,076.50	1,114	137
2008	8,141,762	1,098	135
2009	8,158,447.50	1,007.50	123

Assessing the sustainability of water policies in the context of population growth, one key indicator to consider is water availability. If water resources are becoming scarcer or more difficult to access, this may indicate that current policies are not sustainable. Sustainable water management requires using water resources in a way that assures their long-term availability and quality, while also considering the interests and rights of all stakeholders. As the population grows, the demand for water increases, leading to water scarcity when the demand exceeds the available supply. Sustainable water management practices, such as water conservation, effective use of water resources, preservation of water sources from pollution and degradation, and ensuring equitable and fair water distribution, are necessary to ensure water sustainability in the context of population growth.

In this study, we have considered the total water supply from three reservoirs (Neversink, Pepacton, and Cannonsville) accounting for about 50% of the total water supply for New York City. To get a better idea of the relationship between water consumption and water supply, we calculated the ratio of consumption to supply for each year. This ratio represents the percentage of available water that was consumed and can give us an idea of how sustainable the water policies were over time. Water consumption data from 1982-2009 (in million gallons per day), which, when multiplied by the population number and the number of days in a year, gave us the average annual consumption for a given year. Since the water supply from these reservoirs covers 50% of NYC's consumption, we divided the calculated annual consumption by two to compare it with the annual water supply from the three reservoirs.

To fully meet the needs of the population, there are two options: either make changes to the current water policies or use other water sources to supplement the supply. These calculations were used to compare the annual water supply from the three reservoirs. Looking at the ratio over time, we can see that it generally increased from 1982 to 2009, indicating that more of the available water was being consumed. This is not necessarily a bad thing as long as the available water supply is sufficient to meet the demand. However, the fact that the ratio consistently increased over time suggests that water policies may not have been fully sustainable. It's also worth noting that there were some years when the ratio decreased, indicating that water consumption decreased relative to water supply. This could have been due to factors such as conservation efforts, changes in population, or changes in industry and economic activity. We can see that the overall trend suggests that water policies may not have been fully sustainable, as evidenced by the increasing ratio of consumption to supply over time. It's possible that more aggressive conservation efforts, better infrastructure for capturing and storing water, or other measures could have helped to make water policies more sustainable. In Fig. 7. showed the ratio between supply and consumption, where negative values mean more consumption than supply and the opposite is for the positive values, which means that water supply was higher than water consumption.

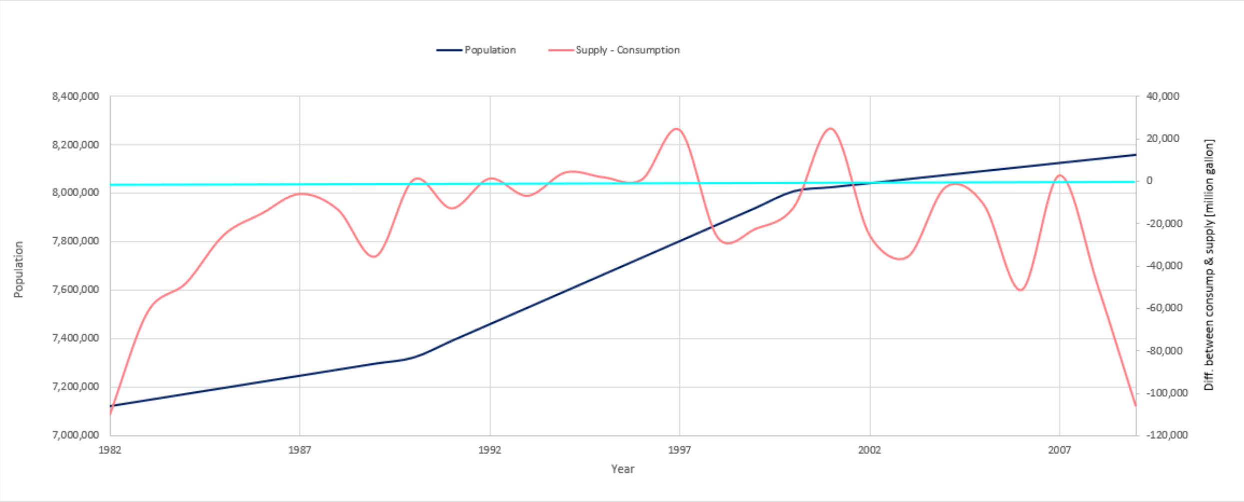

Fig. 7. The difference between the release from the Delaware reservoirs (PCN reservoirs) and water consumption

As can be seen in Fig. 7, the red line in the graph shows the difference between the release from the Delaware reservoirs (PCN reservoirs) and water consumption, while the blue color represents the population number. The light blue line (horizontal one) has been used to provide a visual distinction between positive and negative values of the differences between water supply and consumption.

Discussion

The data analysis in this study indicates that New York City's water consumption has consistently exceeded its water supply, indicating potential challenges in meeting the water demands of its growing population. The ratio of consumption to supply over time shows that the water supply from the three reservoirs was sometimes inadequate to meet the population's needs.

To address the growing water demands, current water policies must be modified, or other sources should be used to supplement the supply. The increasing ratio of consumption to supply suggests that water policies may not have been entirely sustainable. However, the decrease in the ratio during certain years could be attributed to factors such as climate change, conservation efforts, changes in population, or changes in industry and economic activity. Implementing more aggressive conservation efforts, improving water capture and storage infrastructure, and taking other measures could help make water policies to become more sustainable.

Conclusion

In New York City, it is observed that both water consumption and supply have increased over time, reflecting the growth of the city's population and economy. Given the rising concern over the last decades about water supply nationwide, the City of New York finds itself under immense pressure to reconcile a difficult dilemma: providing adequate water regarding population growth. However, the rate of increase in water consumption has been higher than that of water supply, indicating a potential supply-demand imbalance. Secondly, from the water deficit calculation, which is the difference between water supply (release from PCN reservoirs) and water consumption the data shows that the water deficit has fluctuated over time, with some years showing higher deficits than others. Water consumption generally increased from 1982 to 2009, with some fluctuations. Meanwhile, water supply is also increased, but at a slower rate than water consumption. This indicates that there was some effort to keep up with increasing demand, but the water supply may not have been able to meet it completely and in a sustainable way.

Recommendation

Overcoming and dealing with these challenges its needed to involve public education campaigns to promote reduced water usage and incentives for businesses and industries to adopt more water-efficient practices. At the same time, NYC should also explore alternative sources of water, such as desalination or wastewater reuse, to supplement its water supply. Promoting fairness and equitable water distribution, the city should consider a tiered pricing system that charges higher rates for excessive water usage. Additionally, the city should invest in infrastructure, such as rainwater harvesting systems and green roofs, to capture and store water and decrease reliance on reservoirs. Another way is to regularly monitor water consumption and supply data and review its water policies to ensure their sustainability for the growing population. This will enable the city to identify areas for improvement and ensure sufficient water supply to meet the needs of its citizens in the future.

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