Assessing the Flood Mitigation Potential of Water Resource Reservoirs

Matthew M. Del Ciello
Montclair State University

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Assessing the flood mitigation potential of water resource reservoirs

by

Matthew M. Del Ciello

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Thesis Committee:

Dr. Josh Galster
Thesis Sponsor

Dr. Clement Alo
Committee Member

Dr. Duke Ophori
Committee Member
Abstract

The ability of drinking water reservoirs to retain a large amount of runoff during a storm event may allow them to be used as flood mitigation infrastructure. These types of reservoirs are not typically considered for flood mitigation because they are primarily thought of as a resource for drinking water, irrigation, or recreation. Flood mitigation is a secondary or tertiary use. But conscripting them for flood mitigation creates a flexible water resource system and may provide a simpler and more inexpensive solution to flooding than alternative methods since nothing new would need to be constructed.

The process of determining the potential viability of drinking water reservoirs for flood mitigation is also straightforward. Digital elevation models (DEMs) were utilized to determine the watershed boundaries upstream of the reservoirs. The land use of the reservoir’s watershed was classified using data from the National Land Cover Database. The runoff volume from precipitation events was calculated using the curve number method which is based on land use, hydrologic soil type, and amount of precipitation. The runoff volume was compared to the bonus capacity (the difference between the maximum and normal capacities) of the reservoir. Values for normal and maximum capacity were obtained from the United States Geological Survey. Additionally, discharge and flood height data from a river gage downstream of the reservoir was used to determine if the absorption of that volume of water by the reservoir would change the amount of flooding downstream of the reservoir.

Runoff from the 5-year storm could be absorbed by the bonus capacities of five of the six reservoirs with the Wanaque Reservoir being the exception. Runoff from the 10-year storm event could be absorbed by the bonus capacities of Lake Tappan, Greenwood
Lake, and Lake Hopatcong. Runoff from the 50- and 100-year storms could not be absorbed by the bonus capacities of any of the six study reservoirs.

Installation of permeable pavement was modelled by reducing the curve number values of developed lands upstream of each reservoir by 37 or 50 percent, depending on the starting curve number values in the watershed. Permeable pavement, though an admittedly expensive solution, could reduce runoff in all of the six reservoir watersheds for all four storm events. However, only runoff from the 50-year storm (1.24 x 10^7 cubic meters) for Lake Tappan was able to be reduced (1.03 x 10^7 cubic meters) to within the reservoir’s bonus capacity (1.08 x 10^7 cubic meters). This large reduction in runoff was due to the high percentage of developed land within Lake Tappan’s watershed.

Two of the six study reservoirs, the Wanaque Reservoir and Lake Hopatcong, were shown to have the capability to absorb enough runoff to mitigate flooding downstream during high precipitation storm events. The Wanaque Reservoir had enough available storage space (~1.90 x 10^7 cubic meters) to absorb the flood volumes from Hurricane Irene (4.62 x 10^6 cubic meters) and Tropical Storm Lee (3.96 x 10^6 cubic meters). Lake Hopatcong also had enough available storage space (~4.11 x 10^7 cubic meters) to absorb the flood volumes from Hurricane Irene (1.75 x 10^6 cubic meters) and Tropical Storm Lee (3.06 x 10^6 cubic meters). The Wanaque Reservoir and Lake Hopatcong historically have both shown to have similar available storage space amounts to absorb comparable flood volumes. With proper modification and more flexible management strategies, these reservoirs may be used more effectively for flood mitigation.
Assessing the flood mitigation potential of water resource reservoirs

A THESIS

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MATTHEW M. DEL CIELLO

Montclair State University

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1. Introduction

River flooding can be a concern for those that live near rivers and streams. Its effects can be accentuated by changes in land use and climate. Changes in land use that increase the amount of impermeable pavement may also increase the amount of runoff that occurs during storm events.

Urbanization leads to more impermeable land cover within watersheds. The pavement decreases the infiltration rate of precipitation into the soil and causes an increase in surface water flow. The increased amount of impermeable pavement creates “flashy” watersheds in which runoff accumulates and concentrates quickly which causes streams and rivers within the developed watershed to have a higher peak discharge that occurs sooner than in comparable undeveloped watersheds (Rose 2001, Du 2012, Weng 2001). This can contribute to more intense flooding than would otherwise be present (Suriya 2012).

Urbanization can also cause more flood damage if development is situated within the floodplain (Huong 2013). Towns with little infrastructure adjacent to major rivers and streams will not experience severe flooding impacts during storm events simply because there is less there to be damaged. But towns that have developed immediately (whether recently or historically) next to the river will encounter significantly more flood damage because they have valuable structures (e.g., homes, businesses, and factories) located within the floodplain. In this way, towns can mitigate the amount of flood damage they suffer simply by limiting the amount of development that can occur within the floodplain (Tarbuck 2008).
Climate change can also have a significant effect on flooding. The specific details of projected climate change vary depending on the model and the specific location/region, but there are certain trends that are likely to occur in the future. The northeast United States is projected to see an increase in intense precipitation events (Singh et al. 2013). Winters may be warmer, and precipitation during these months is more likely to fall as rain than snow. These factors together may increase flooding intensity and frequency in the region. Hurricane strength and frequency may also increase in the northeastern United States as the climate changes (Meehl et al. 2007), and damages from these storms will be exacerbated by a rise in sea-level (Kirshen 2008). These storms will bring with them a greater amount of rainfall which will give rise to more flooding.

Hurricane Irene, which made landfall in New Jersey on August 28, 2011, had a significant impact on the state. Northern and central New Jersey experienced significant flooding; the Rockaway, Millstone, Passaic, and Raritan Rivers rose quickly and caused major flooding for the townships near those rivers (Star Ledger 2011). This flooding was exacerbated by the fact that New Jersey experienced above average amounts of rainfall in the weeks leading up to Hurricane Irene (USGS 2011). The soil was already saturated with water, so when Hurricane Irene made landfall, not much of its precipitation was able to infiltrate, thus more became runoff and contributed to flooding.

Due to the significant development within the floodplain, floods are especially damaging in northern New Jersey. The Passaic River Basin covers most of northeastern New Jersey and includes three of the six study reservoirs (Figure 1). The Passaic River Basin Flood Advisory Commission examined fifteen approaches to reduce flood damage in northern New Jersey. In a 2011 report (NJDEP 2011), the Flood Advisory Commission
outlined fifteen strategies to reduce flood damages and put them into three categories: strategies that required no funding, strategies that can be funded but may need additional funding, and strategies that would require significant funding. There have been previous Passaic River Basin flooding reports since the Passaic River Basin has been studied for over a century. These past reports recommended construction of flood control reservoirs and dams, but due to local opposition, these projects were never initiated.

The recommendations that the commission suggested that did not require any funding included improving emergency flood response plans, fostering greater public interest in flood information and plans, adaptation of the National Flood Insurance Program regulations, allowing New Jersey Department of Environmental Protection to make permit approval for repairing retention walls and removing snags easier, and preventing further development within the floodplain (NJDEP 2011).

Eight of the commission’s recommendations were able to be funded by the state government, but may have required additional funding (possibly from the federal government). These included flood risk and inundation mapping, improvement of the flood warning system, de-snagging and dredging, acquisition of open space within the floodplain, removal of Pequannock and Pompton Feeder dams that may contribute to flooding, and implementation of a study to improve the Pompton Lakes Dam Floodgates operation (NJDEP 2011).

The Flood Advisory Commission also recommended buying out residences within the floodplain, and if that is not possible, elevating structures remaining within the floodplain. These two strategies would require significant amounts of funding, though
buying out houses situated within the floodplain and converting that land to open space is the most effective method of reducing flood damages.

In 2007, the state of New Jersey approved the Green Acres, Farmland, Blue Acres, and Historic Preservation Bond Act in order to help develop land within the state in a more sustainable manner. Part of this act, the Blue Acres program, seeks to buy houses and neighborhoods located within the floodplain to mitigate flood damage and use that land for conservation or recreation instead. Blue Acres focuses on areas bordering the Raritan, Passaic, and Delaware Rivers and only buys the houses from voluntary sellers. The program received $12 million in 2007 and was renewed for $24 million in 2009 (NJDEP 2014). Blue Acres received much attention after Hurricane Sandy and was used to purchase houses affected by the storm (NJDEP 2013).

None of the options explored by the Passaic River Basin Flood Commission, however, included using reservoirs for flood mitigation. However, with proper planning and knowledge of a changing climate, existing reservoirs and lakes may be used beneficially for this purpose. While the construction of new flood-control reservoirs is unlikely due to the cost and lack of potential sites, there are several drinking water reservoirs that may help with flood mitigation. The literature demonstrates that reservoirs that are already used for drinking water and other purposes besides flood control can be adapted to absorb excess runoff, if a proper strategy is employed. Optimization of reservoir performance are commonly modelled for reservoirs that serve a single purpose, such as irrigation or drinking water (Rani 2010), and for multi-purpose reservoirs (Raje 2010). Seibert et al. (2014) studied reservoirs in southern Germany and determined the reservoirs in that watershed could also be utilized as flooding mitigation infrastructure.
when operated in coordination with each other. Multi-reservoir optimization for flood mitigation has also been studied mathematically (Yazdi 2012).

Water resource reservoirs are often not considered for flood mitigation purposes due to a variety of reasons. First, there was not much of a need to use them beyond their intended purposes until the floodplain downstream had become significantly developed. Using reservoirs for flood control was not in the collective mindset at their construction but now there is a need for infrastructure that can help mitigate flooding. Additionally, adapting reservoirs for flood mitigation may require modifying their infrastructure since the reservoir dams were not designed with that use in mind. This may entail significant funding which local and state governments may be reluctant to provide. Thus, even if reservoirs had been considered for flood mitigation in the past, high infrastructure modification costs may have dissuaded interested parties from using those reservoirs.

There are conflicting interests between using a reservoir for both drinking water and flood control. Reservoirs managed for drinking water want to be as full as possible in order to meet the potential demands of the population it serves. Flood control reservoirs, on the other hand, want to be as empty as possible in order to contain more runoff. Reservoirs that want to be utilized in both of these regards must be able to balance both interests in their operations.

It may seem obvious that drinking water reservoirs could simply remain full most of the time, and only make storage available when it is needed. This solves the problem of meeting demand while also providing the flexibility to mitigate flooding. The issue with this strategy is that flooding events are not always easy to predict; forecasts can change and often do. Reservoir operations need advance warning in order to make
storage space available. Lake Hopatcong, which was lowered beginning two days before Hurricane Sandy made landfall in October 2012, can be emptied at 0.34 cubic meters per second (NJDEP 2011). If the water level of the lake were to be lowered two days prior to a large precipitation event, the lake managers would only be able to increase the available storage space by 0.08 percent of the lake’s maximum capacity; it could absorb 58,717 cubic meters of additional runoff. This is only a small portion of the total runoff for any storm event, let alone a large one like Hurricane Sandy. Thus, lowering Lake Hopatcong a few days before a large rainfall event might make everyone feel better, but it certainly does not do much to reduce flooding downstream.

Another potential danger of emptying the reservoirs prior to flood events is if the storm does not occur then the reservoir released water that could have been used. This can be especially dangerous in years when demand may exceed the supply. If reservoirs want to be used for flood mitigation a more flexible management policy must be adapted in order to alleviate these two issues.

Adapting reservoirs to serve more than one purpose and have the flexibility to fulfill those purposes has been discussed though never completely examined until recently. DiFrancesco & Tullos (2014) explored what a flexible water system means and demonstrated that theory used in management and information technology can be applied to managing water resource systems. They proposed several metrics to measure water system flexibility, and that financial costs of modifying existing infrastructure for flood management should be carefully considered against the benefits those modifications would bring. It is certainly possible for water resource systems to be managed in such a way to provide flexibility in multiple purposes.
Drinking water reservoirs have bonus capacity which may be able to absorb some
or all of the runoff generated upstream during storm events. Bonus capacity is the
difference between the maximum and normal capacities of the reservoir. Maximum
capacity is the total volume that can be contained within the reservoir without
overflowing the spillway. Normal capacity is the volume used for the reservoir’s intended
purposes (Figure 2). Reservoirs are not always filled to maximum capacity, and the
difference between the maximum and normal capacities (bonus capacity) of the
reservoirs may be sufficient to absorb runoff from storm events. The benefit of using the
bonus capacity is that the reservoirs can be filled to their normal capacity to provide
drinking water and still be able to absorb runoff with their bonus capacity to minimize
flooding downstream.

1.1 Description of Study Reservoirs

1.1.1 Wanaque Reservoir

Construction of the Wanaque Reservoir was finished in 1928 with the completion
of Raymond Dam. The reservoir was built to provide drinking water to towns in Passaic
and Bergen counties, and continues to do so today (NJDEP 2005). Wanaque Reservoir
gets its water from the Wanaque River and two pumping stations located on the Pompton
and Ramapo Rivers when it is unable to meet its water supply demands (NJDEP 2005).
These two pumping stations draw water from outside the watershed of the Wanaque
Reservoir. The area surrounding the reservoir is largely undeveloped due to the
designation of park and preserved land near the reservoir. The watershed area of the
reservoir is about 256 square kilometers (99 square miles). The maximum capacity is
1.35x10^8 cubic meters (4.76x10^9 cubic feet) and the normal capacity is 1.31x10^8 cubic meters (4.62x10^9 cubic feet).

1.1.2 Lake Hopatcong

Lake Hopatcong is located on the border between Sussex and Morris counties in New Jersey (Figure 3). It was originally two large ponds that were two miles apart and eventually drained into the Musconetcong River. The Musconetcong River was first dammed in 1750 which caused the two water bodies to be joined. A new dam was constructed in 1831 which raised the water level to its current elevation. The lake became a popular summer resort in the 1880s and would eventually give rise to a permanent lake community in the 1950s and 1960s (NJDEP 2015). The watershed area of Lake Hopatcong is about 63 square kilometers (24.6 square miles). The maximum capacity of the lake is 7.31x10^7 cubic meters (2.58x10^9 cubic feet), and the normal capacity is 5.95x10^7 cubic meters (2.10x10^9 cubic feet).

1.1.3 Spruce Run Reservoir

This reservoir is located within Hunterdon County, New Jersey (Figure 3), and was completed in 1964. Although its main purpose is to provide drinking water to towns in northern New Jersey during times of drought, it is also used for swimming, fishing, and boating (NJWSA 2015). The reservoir is part of the Spruce Run Recreational Area, a state park, so most of the land surrounding the reservoir remains undeveloped. Camping and hiking are popular in the park. The watershed area of the reservoir is about 106 square kilometers (40.9 square miles). The maximum capacity is 4.16x10^7 cubic meters (1.47x10^9 cubic feet), and the normal capacity is 3.68x10^7 cubic meters (1.30x10^9 cubic feet).
1.1.4 Greenwood Lake

Greenwood Lake is located between Passaic County, New Jersey, and Orange County, New York (Figure 3). It was originally dammed in 1765 to provide water power to a nearby ironworks. It was dammed again in 1837 in a different location which caused the lake to reach its current elevation. Greenwood Lake became a resort after railroad lines to the lake were completed in 1874. Eventually, the lake resort turned into a permanent lake community. The watershed area of Greenwood Lake is about 90 square kilometers (34.7 square miles) (Jasch 2015). The maximum capacity is $3.31 \times 10^7$ cubic meters ($1.17 \times 10^9$ cubic feet), and the normal capacity is $2.61 \times 10^7$ cubic meters ($9.20 \times 10^8$ cubic feet).

1.1.5 Lake Tappan

Lake Tappan is located between Bergen County, New Jersey, and Rockland County, New York (Figure 3). Construction of the reservoir was completed in 1967 with the Tappan Dam. The lake lies on the Hackensack River, and it releases water to the Oradell Reservoir downstream. Lake Tappan is also a popular fishing spot. The watershed area of the lake is about 129 square kilometers (49.7 square miles). The maximum capacity is $2.39 \times 10^7$ cubic meters ($8.45 \times 10^8$ cubic feet), and the normal capacity is $1.31 \times 10^7$ cubic meters ($4.64 \times 10^8$ cubic feet).

1.1.6 Oak Ridge Reservoir

The Oak Ridge Reservoir is located in West Milford, New Jersey (Figure 3). The watershed area of Oakridge Reservoir is about 70 square kilometers (26.9 square miles) (USGS 2015). The maximum capacity is $1.85 \times 10^7$ cubic meters ($6.53 \times 10^8$ cubic feet), and the normal capacity is $1.48 \times 10^7$ cubic meters ($5.23 \times 10^8$ cubic feet).
1.1.7 Summary

Six of the largest reservoirs in New Jersey were chosen for this study based on the initial hypothesis that these reservoirs would be able to contain more runoff with their bonus capacities than other reservoir in the state. The study reservoirs are not the six largest reservoirs in New Jersey however. Due to complications of analyzing DEMs of the Round Valley Reservoir, Boonton Reservoir, and Union Lake, these three reservoirs were not studied. Hydrological analysis of the DEMs of these reservoirs (the first, fifth, and seventh largest reservoirs, respectively, in New Jersey) did not provide clear watershed boundaries for the reservoirs. This made it difficult to estimate the amount of runoff entering each reservoir. The next six largest reservoirs were studied instead. These six reservoirs are all located in northern New Jersey in developed areas that have seen significant flooding within the past five years which gives further incentive to examine these reservoirs for flood mitigation.

1.2 Estimating Runoff

In order for reservoirs to be considered as flood mitigation infrastructure, data regarding their watersheds must be collected and analyzed. First, the extent of their watershed needs to be established in order to be able to use any of the runoff-estimating methods. Next, the watershed must be characterized depending on the runoff method being employed. There are several methods for estimating the amount of runoff flowing from an area. The rational method only needs a runoff coefficient and a watershed area to produce a peak discharge. This method computes peak discharge from small watersheds. It uses a runoff coefficient (c), the rainfall intensity (i), and area of the watershed (A). The runoff coefficient is based on land use and the recurrence interval of the storm event.
The rainfall intensity should be based on a storm event with duration greater than or equal to the time of concentration of the watershed. Time of concentration is the amount of time it takes for water to travel from the most distant point within a watershed to the watershed’s outlet, and is a measure of how the watershed behaves in precipitation events (USDA 1990). It is important to use storm events that have duration greater than the time of concentration to ensure that all of the runoff within the watershed is accounted for. Studying storm events with a shorter duration would otherwise underestimate the amount of runoff in the watershed. Maintaining a short time of concentration is also why this method works best on small watersheds.

The curve number method, also known as the NRCS method, estimates the amount of direct runoff flowing from a watershed. Direct runoff is the amount of water that flows over the surface of an area after the soil becomes saturated through infiltration (initial abstraction), generating surface runoff. This method uses land use and hydrological soil group data to assign a curve number (CN) to an area. A precipitation amount is determined based on storm duration and frequency interval. The curve number method utilizes land use and other data to calculate the amount of direct runoff that emanates from an area. Curve numbers can range from 0 to 100 with higher curve numbers signifying more runoff occurring. A curve number for a study area is determined through the combination of land uses and hydrological soil groups that are present. For example, cropland with hydrological soil group A will have a curve number of about 70, and a forested area with the same hydrological soil group will have a curve number of about 55. Conversely, different areas with same land use may have different curve
numbers if their respective hydrological soil groups differ; pastureland can have curve numbers ranging from 70 to 90 depending on the hydrological soil group present.

There are four hydrological soil groups; A, B, C, and D. Group A has the lowest runoff potential of the four groups. The hydraulic conductivity of this group is typically above 40 micrometers per second. These soils are mostly comprised of sand and usually have less than 10 percent clay. Group B soils contain between 50 to 90 percent sand, and 10 to 20 percent clay. The hydraulic conductivity of this group is typically between 10 micrometers and 40 micrometers per second. Group C soils are comprised of approximately 50 percent sand, and 20 to 40 percent clay. The hydraulic conductivity of Group C soils ranges from 1 to 10 micrometers per second. Group D soils have the highest runoff potential of the four groups. This group has less than 50 percent sand and more than 40 percent clay. The hydraulic conductivity of Group D is less than 1.0 micrometers per second (Mockus 2007).

Other factors that may influence runoff include antecedent moisture conditions, land cover type, and treatment. Land cover type is usually incorporated into the land use and factors in characteristics such as impermeable pavement, vegetation cover, and bare soil. Treatment is a term used to describe agricultural lands and is used to alter curve numbers of those lands depending on the type of farming practices employed. For example, contour crops, reduced tillage, and terrace farming will all change the curve numbers (NRCS 2007). This change is usually small and would only have an effect on watershed that have a significant portion of agricultural land.

Antecedent conditions are the general hydrologic state of the watershed, particularly how much moisture is already present in the soil, at the beginning of a storm.
event. Previous storm events, evapotranspiration rates, and if the ground is frozen can all contribute to antecedent conditions. A storm event that generates a large amount of precipitation will most likely cause greater flooding if it occurs after a period of time in which the watershed experienced frequent rainfall than if it occurred after a drier period. This is because the soil in the watershed is already saturated with water and additional rainfall is unable to infiltrate. Thus, more rainfall becomes runoff and increases the peak discharge in streams and rivers in the watershed. This was the situation with Hurricane Irene in August 2011, which arrived after higher than normal precipitation in the preceding weeks.

Once the curve number (CN) has been determined, the following equation is used to calculate the direct runoff (Q) for the study area:

$$Q = \frac{(P - 0.25)^2}{(P + 0.8S)}$$

where $P$ is the precipitation amount (inches) and $S$ is the maximum retention after runoff has begun. Note that precipitation must be in inches because this method was developed using the English system. Maximum retention ($S$) is derived from the curve number:

$$(1000/CN) - 10.$$ Since maximum retention is based on the curve number, land use, and hydrological soil characteristics affect its value as well.

Direct runoff is not a volumetric amount, and only has one dimension (meters). In order to determine the runoff volume, the direct runoff must be multiplied by the area for which direct runoff is being calculated. This will then give the total runoff (cubic meters) and is the estimate of runoff emanating from an area.
1.3 Flood Mitigation

Once the bonus capacities and runoff volumes have been determined, these numbers can be compared to the flood volume. This is the volume of water above the flood stage at the gage downstream of the reservoir, and it is calculated by subtracting the base volume (volume of water just below the flood stage of the gage) from the total volume of water that occurs during the flood event. The flood volume can then be compared to the available storage space of the reservoir to determine if the reservoir can hold back enough water to decrease downstream flooding.

Permeable pavement may be one method for reducing the runoff from developed areas of reservoir watersheds. There are various types of permeable pavement, each with different benefits, but each type allows for storm water to infiltrate into the soil rather than become runoff. Depending on the underlying soil conditions, permeable pavement has curve numbers between 45 and 89 (Bean et al. 2007b).

The goal of this project was to estimate the volume of total runoff entering drinking water reservoirs in New Jersey in order to determine if the reservoir can absorb that runoff, and if that absorption can decrease flooding downstream. This project characterized watersheds, calculated runoff under different scenarios, and compared that runoff to available storage volumes in the reservoirs.

2. Methods

A digital elevation model (DEM) was downloaded from the United States Geologic Survey National Map Viewer website and imported into ArcGIS. Standard surficial hydrologic methods were used to work with the DEM. The DEM was filled to remove sinks (cells that act as closed depressions and are not connected by surface
runoff; these are typically data errors) present within the DEM. The flow direction of surficial runoff on the map was determined by calculating the greatest elevation difference between adjacent cell values. Flow accumulation was then determined based on the flow directions calculated in the previous step. This process gives a DEM in the shape of the reservoir’s watershed which can then be converted into a shapefile to be used in ArcMap with land use and soil group data.

The runoff volume was calculated using the curve number method. This method is based on the predicted precipitation amount, land use, and soil types within the watershed of the reservoir (USDA 1986). The amount of precipitation was based on 24-hour storm events with 5-, 10-, 50-, and 100-year frequencies from the U.S. Department of Agriculture TR-55 document (USDA 1986). Land use data within the reservoir watershed was downloaded from the National Land Cover Database 2011 (NLCD) and imported into ArcGIS where it was combined with hydrological soil group data obtained from the National Resources Conservation Service Web Soil Survey. The combination of these data was used to determine the curve number for each section of different land use within the reservoir’s watershed. Curve numbers were assigned to National Land Cover Database 2011 land uses based on Tables 2-2a, b, c and d from Urban Hydrology for Small Watersheds, TR-55 (USDA 1986). When an unambiguous curve number could not be assigned, such as in the case of a section of the watershed having a dual soil group (e.g., B/D), the average of two curve numbers was used. For example, deciduous forest (NLCD grid code 41) with soil group of A/D was assigned a curve number of 54, the average of the curve numbers for deciduous forest with soil group A (30) and deciduous forest with soil group D (77). Any section that had no hydrological soil group data due to
that section being bare soil or rock was assigned the highest curve number for that particular land use, and any watershed section that had missing hydrological soil group data (listed as "--" in the USGS soil database) used an average of the curve numbers from the four hydrological soil groups.

The curve number was used to calculate the direct runoff (meters) for each section of the watershed. The direct runoff was multiplied by the area of the section to get the total runoff (cubic meters) for that section. The total runoff from each section was added together to arrive at the total runoff volume of the reservoir. The runoff volume was compared to the bonus capacity of the reservoir. A weighted curve number for the entire watershed was calculated as a check to ensure runoff estimates were accurate.

Hypothetical changes in land use in the reservoir’s watershed were also examined. A scenario in which impermeable pavement within the reservoir watershed was replaced with permeable pavement in order to reduce runoff was explored. The permeable pavement scenario was modelled in the reservoir watersheds by reducing the curve numbers values for each developed section of the watershed by 37 percent. The sections of the watershed whose curve numbers had been reduced were the developed lands of low, medium, and high intensity (NLCD grid codes 22, 23, and 24). The curve numbers for developed open space areas (NLCD grid code 21) were not altered because these areas are predominately park land and fields, and there would not be a high amount of permeable pavement installed in those areas.

Finally, data from a downstream gage was used to determine if the absorbed amount of runoff water led to a decrease in flooding. Discharge and gage height data in fifteen minute intervals were taken from the USGS website. The flood stage for each
gage was also obtained from the USGS website. Times at which the gage height rose above the estimated flood stage were designated as flood events. The total volume of water was calculated from the discharge recorded for the duration of that flood event. A “base volume” was computed from the discharge recorded when the gage height was at or below the estimated flood stage. The base volume varied between flood events depending on antecedent flow conditions. The flood volume was calculated by subtracting the base volume from the total volume during the flood event. The flood volume was compared to the storage space available within the reservoir which could be a combination of the bonus capacity and the normal capacity.

3. Results

3.1 Total Runoff Estimates and Land Use

The following sections go into detail regarding total runoff amounts and watershed land use composition for each of the six study reservoirs.

3.1.1 Wanaque Reservoir

The majority of land use within the Wanaque Reservoir watershed is forested (69.96%). Developed areas, open water, and wetlands comprise 10.26%, 9.29%, and 8.54% respectively. Barren, agriculture, and other land uses were each less than one percent of the total watershed area. The percentage of runoff from each of these land use categories in regards to the total runoff closely matches the percentages for the watershed area: forest, 59.47%; water, 17.92%, developed, 10.23%; wetlands, 10.07%. Barren, agriculture, and other land uses contributed one percent or less to the total runoff of the watershed (Figure 4).
The total runoff in the Wanaque Reservoir watershed for a 24-hour storm with a 5-year frequency (10.80 centimeters of precipitation) is $1.21 \times 10^7$ cubic meters. The total runoff for the 10-, 50-, and 100-year storm events is $1.84 \times 10^7$, $2.36 \times 10^7$, and $2.92 \times 10^7$ cubic meters, respectively. The Wanaque Reservoir can absorb 32.47% of the runoff from the 5-year storm with its bonus capacity, and 21.47%, 16.65%, and 13.50% for the 10-, 50-, and 100-year storms, respectively (Figure 5).

3.1.2 Lake Hopatcong

Forested areas are the largest portion of the land use (45.48%) within the Lake Hopatcong watershed. Developed land use comprises 25.98% of the total watershed area. Water and wetlands are 16.65% and 10.01% of the watershed area, respectively. Barren, agriculture, and other land uses are less than one percent of the watershed area. The percentage of runoff from each of these land use categories in regards to the total runoff are similar to their land use percentages: forest, 37.56%; water, 28.89%; developed, 20.87%; wetlands, 10.72%. Barren, agriculture, and other land uses contribute one percent or less to the total runoff (Figure 6).

The total runoff for Lake Hopatcong for a 24-hour storm event with a 5-year frequency (10.80 centimeters of precipitation) is $3.43 \times 10^6$ cubic meters. The total runoff for the 10-, 50-, and 100-year storm events is $4.98 \times 10^6$, $6.29 \times 10^6$, and $7.65 \times 10^7$ cubic meters, respectively. Lake Hopatcong’s bonus capacity is $1.36 \times 10^7$ cubic meters so all of the runoff from each storm event can be absorbed by the lake (Figure 5).

3.1.3 Spruce Run Reservoir

About half of the land use within the Spruce Run Reservoir is forested (48.70%). Agriculture comprises 19.66% of the watershed area, and developed land use is 12.78%.
Wetlands, water, and other land uses make up 8.59%, 4.56%, and 5.42% of the watershed area, respectively. Barren is less than one percent of the watershed. The percentage of total runoff from each of the land use categories is similar to the land area percentages: forest, 34.72%; agriculture, 23.68%; developed, 13.79%; wetlands, 13.00%; water, 11.39%; barren, 0.58%; other land uses, 2.85% (Figure 7).

The total runoff for Spruce Run Reservoir for a 24-hour storm event with a 5-year frequency (10.80 centimeters of precipitation) is 3.65x10^6 cubic meters. The total runoff from 10-, 50-, and 100-year storm events is 5.80x10^6, 7.73x10^6, and 9.77x10^6 cubic meters, respectively. Spruce Run Reservoir can absorb 81.24% of the total runoff with its bonus capacity for the 10-year storm event, 61.09% for the 50-year storm, and 48.36% for the 100-year storm. All of the runoff from the 5-year storm event can be absorbed by the Spruce Run Reservoir bonus capacity (Figure 5).

3.1.4 Greenwood Lake

The majority of land use within the Greenwood Lake is forested (59.14%). Developed land, wetlands, and open water comprise 15.90%, 12.04%, and 11.29%, respectively. Agriculture, barren, and other land uses are less than one percent of the area in the watershed. The percent contribution of runoff from each land use category is similar to the land area percentages; forest, 46.82%; water, 22.16%; developed, 15.18%; wetlands, 14.35%. Agriculture, barren, and other land uses each contributed less than one percent to total runoff (Figure 8).

The total runoff for the Greenwood Lake watershed for a 24-hour storm event with a 5-year frequency (10.80 centimeters of precipitation) is 4.19x10^6 cubic meters. The total runoff from storm events with the same duration but with 10-, 50-, and 100-year
frequencies is $6.29 \times 10^6$, $8.10 \times 10^6$, and $1.00 \times 10^7$ cubic meters, respectively. Greenwood Lake can absorb all of the runoff from the 5- and 10-year storm events with its bonus capacity. The lake can absorb 86.30% of the total runoff from the 50-year storm event, and 69.95% runoff from the 100-year storm event (Figure 5).

3.1.5 Lake Tappan

Developed land constitutes 63.11% of the area within the Lake Tappan watershed. Forest, water, and wetlands are 22.01%, 7.77%, and 5.47%, respectively. Agriculture, barren, and other land uses are less than one percent of the land area. The percentage of total runoff emanating from each land use category is similar to the land area percentages; developed, 65.76%; water, 14.14%; forest, 12.12%; wetlands, 6.09%. Agriculture, barren, and other land uses each contribute less than one percent to the total runoff (Figure 9).

The total runoff for the Lake Tappan watershed for a 24-hour storm event with a 5-year frequency (10.80 centimeters of precipitation) is $6.65 \times 10^6$ cubic meters. The total runoff from storm events with the same duration but with 10-, 50-, and 100-year frequencies is $9.74 \times 10^6$, $1.24 \times 10^7$, and $1.51 \times 10^7$ cubic meters, respectively. Lake Tappan can absorb all of the runoff from the 5- and 10-year storm events. The reservoir can absorb 87.20% of the runoff from the 50-year storm event, and 71.48% from the 100-year storm event (Figure 5).

3.1.6 Oak Ridge Reservoir

Forested land constitutes 71.32% of the total area within the Oakridge Reservoir watershed. Wetlands, water, and developed land are 18.78%, 5.21%, and 3.64%, respectively. Agriculture, barren, and other land uses are each less than one percent of the
watershed's area. The percent of total runoff emanating from each land use category is similar to the land use percentages: forest, 65.15%; wetlands, 20.58%; water, 9.75%, developed, 3.32%. Agriculture, barren, and other land uses each contribute less than one percent of the total runoff for the watershed (Figure 10).

The total runoff for the Oakridge Reservoir for a 24-hour storm event with a 5-year frequency (10.80 centimeters of precipitation) is $3.37 \times 10^6$ cubic meters. The total runoff for storm events with the same duration but with 10-, 50-, and 100-year frequencies is $5.10 \times 10^6$, $6.57 \times 10^6$, and $8.07 \times 10^6$ cubic meters, respectively. The reservoir can absorb 72.55% of the runoff from the 10-year storm event, 56.40% from the 50-year storm event, and 45.85% from the 100-year storm event. Oakridge Reservoir can absorb all of the runoff from the 5-year storm event (Figure 5).

3.1.7 Summary

The NLCD land use codes were simplified into fewer land use categories in order to provide a straightforward evaluation of runoff within each watershed. Land uses were grouped together based on similarity of curve numbers. Developed open space, low intensity, medium intensity, and high intensity land uses had curve numbers above 80 and were grouped into the developed category. Deciduous, evergreen, and mixed forest land uses were grouped into the forest category. Woody and herbaceous wetlands were combined into the wetlands category. Pasture and cultivated crops were combined into the agriculture category. Grasslands and shrub/scrub land were grouped together in the other category. Water land use remained labeled as water.

Total runoff from the 5-year storm event could be absorbed by the bonus capacity of five of the six reservoirs, with the exception being the Wanaque Reservoir. The bonus
capacity of the Wanaque Reservoir was too small to absorb the runoff from any of the storm events since the bonus capacity of the reservoir was small compared to the area of the reservoir’s watershed (Figure 11, Table 1). Lake Hopatcong can absorb total runoff from all of the storm events and will not be mentioned further in this summary for simplicity’s sake.

The total runoff from the 10-year storm event could be absorbed by the bonus capacity of Lake Tappan and Greenwood Lake. The Oak Ridge and Spruce Run reservoirs could not absorb the 10-year storm total runoff. The total runoff from the 50- and 100-year storm events could not be absorbed by the bonus capacities of any of the study reservoirs.

3.2 Runoff Reduction

The installation of permeable pavement within each watershed was modelled in order to determine if total runoff could be reduced to a volume that could be absorbed by the bonus capacity of the reservoirs. Permeable pavement was simulated by reducing the curve number value by 37 percent for each section of developed land (NLCD grid codes 22, 23, and 24) within the watersheds of Lake Tappan, Greenwood Lake, Lake Hopatcong, and the Wanaque Reservoir. Curve number values for the same land uses within the Oakridge and Spruce Run Reservoir watersheds were reduced by 50 percent.

With complete replacement of impermeable with permeable pavement runoff was obviously reduced in all of the watersheds for all four storm events, but only the total runoff from the 50-year storm for Lake Tappan was reduced enough to be absorbed by the bonus capacity of that reservoir. The runoff in the remaining five reservoirs was only reduced by a small percentage of the bonus capacity of each reservoir: Oak Ridge
Reservoir runoff was only reduced by one percent of the bonus capacity for all four storm events; Greenwood Lake runoff was reduced between 2 and 4 percent; runoff from Spruce Run Reservoir watershed was reduced between 4 and 7 percent; Lake Hopatcong runoff was reduced between 1 and 2 percent; and the runoff from the Wanaque Reservoir watershed was reduced between 6 and 9 percent of its bonus capacity (Figure 12).

Permeable pavement decreased the total runoff by 21, 18, 16, and 15 percent for the 5-, 10-, 50-, and 100-year storm events in the Lake Tappan watershed (Figure 12). The new runoff volumes were $5.21 \times 10^6$, $7.96 \times 10^6$, $1.03 \times 10^7$, and $1.28 \times 10^7$ cubic meters for each of the storm events, respectively. The reduced runoff volume for the 50-year storm was small enough to be absorbed by the bonus capacity of Lake Tappan ($1.08 \times 10^7$ cubic meters).

3.3 Flood Mitigation and Reservoir Storage History

Only two of the study reservoirs, Lake Hopatcong and the Wanaque Reservoir, had recorded storage volume data available. The record of data starts at October 1st, 2007 (2008 water year) for both gages and covers the two major flooding events for the reservoirs: Hurricane Irene in late August 2011 and Tropical Storm Lee in early September 2011. Flooding lasted for two days (although the storm runoff lasted for much longer) on the Wanaque River during Hurricane Irene, starting at 16:15 on August 28th and endings at 17:30 on August 30th. Flooding on the Musconetcong River below Lake Hopatcong lasted about five days, starting at 08:15 on August 28th, and ending at 16:30 on September 1st. The Wanaque Reservoir was between 85 to 89 percent of its maximum capacity for the duration of Hurricane Irene flooding. Lake Hopatcong was between 42 and 45 percent of its maximum capacity during the same flooding event. The available
storage space was, on average, 1.90x10^7 and 4.11x10^7 cubic meters for Wanaque Reservoir and Lake Hopatcong respectively. The flood volume for the Wanaque River was 4.62x10^6 cubic meters and would take up 24.34 percent of the available reservoir capacity of the Wanaque Reservoir (3.4 percent of its maximum capacity). The flood volume for the Musconetcong River was 1.75x10^6 cubic meters and would take up 4.27 percent of the available reservoir capacity of Lake Hopatcong (2.4 percent of its maximum capacity).

Flooding on the Wanaque River due to Tropical Storm Lee lasted for about three days in September 2011, starting at 03:00 on September 7th and ending at 01:15 on September 10th. Flooding on the Musconetcong River lasted for almost a week, starting at 20:00 on September 6th and ending at 03:00 on September 13th. The Wanaque Reservoir was between 85 and 86 percent of its maximum capacity during this flood event, and Lake Hopatcong was between 42 and 46 percent of its maximum capacity. The average available storage for both reservoirs was similar to what was available during Hurricane Irene; 1.93x10^7 and 4.08x10^7 cubic meters for Wanaque Reservoir and Lake Hopatcong, respectively. However, the flood volume was less on the Wanaque River (3.96x10^6 cubic meters), and more on the Musconetcong River (3.06x10^6 cubic meters) during Tropical Storm Lee than Hurricane Irene. Thus, the flood volume from the Wanaque River would have filled up 20.54 percent of the available storage in Wanaque Reservoir (2.9 percent of its maximum capacity) and the flood volume from the Musconetcong River would take up 7.59 percent of available storage in Lake Hopatcong (4.2 percent of its maximum capacity).
4. Discussion

4.1 Curve Number Method

The curve number method calculates the runoff from developed areas in one of two ways. The first assumes that all impermeable areas are connected and that the runoff will flow over them to the outlet. This approach is used for developed area with greater than 30 percent impermeable surface coverage. The second approach is used when there is less than 30 percent impermeable surface coverage; a composite curve number is determined based on the amount of impermeable surface and various hydrological soil groups present.

This study assumed that all developed areas within each watershed had greater than 30 percent impermeable surface coverage and were connected to allow for uninterrupted runoff flow. This assumption made it easier to estimate the runoff amounts from developed areas in the watersheds. There were disconnected developed areas within each watershed and calculating a composite curve number for every developed section would have been inefficient. The areas of low, medium, and high development were compact enough to assume that those sections were almost entirely covered in impermeable surfaces.

4.2 Applicability of the Curve Number Method

A disadvantage of the curve number method is that because it gives direct and total runoff, it is unable to calculate the peak discharge from a storm. This limits the method’s ability to relate storm events and runoff to flooding within a watershed. Fortunately, gages downstream of the study reservoir provide data on flooding and can be related to major storm events, such as Hurricane Irene and Tropical Storm Lee in 2011.
The curve number method may also overestimate the amount of direct runoff emanating from a watershed. Other methods, such as the USGS method, calculate direct runoff amounts less than half of what the curve number method predicts (Genereux 2003). However, overestimating runoff volumes is not a disadvantage in this study. Higher runoff volumes provide a more conservative estimate of whether or not the reservoirs can absorb the runoff with their bonus capacity. If the actual runoff entering the reservoir is smaller, then the reservoirs are better at containing the runoff from the storm, and it may even be easier to mitigate flooding downstream since the reservoirs can hold back more runoff than originally predicted.

Another disadvantage of the curve number method is that it does not produce realistic results for low curve numbers and/or low precipitation amounts. Lower curve numbers should predict smaller amounts of direct runoff, but because of the nature of the formula involved, low curve numbers actually predict very high direct runoff values (Figure 13). The value where lower curve numbers begin to predict higher amounts of direct runoff depends on the amount of precipitation used in the equation. Higher precipitation amounts allow for the use of lower curve numbers than smaller precipitation amounts. For example, the estimated direct runoff for a 24-hour storm event with 7.5 inches (19.05 centimeters) of precipitation can use curve numbers as low as 21 to produce realistic results. Twenty-four hour storm events with 4.25 inches (10.80 centimeters) of precipitation can only use curve numbers as low as 32. Any curve number below 20 will predict larger amounts of direct runoff even though it should actually be predicting smaller amounts.
This limitation is caused by the first part of the direct runoff equation mentioned earlier:

\[(P - 0.2S)^2\]

Because \(S\) is a composite of the curve number:

\[\left(\frac{1000}{CN}\right) - 10\]

when \(0.2S\) becomes greater than \(P\) due to low curve numbers, the calculated direct runoff is greater than what it would be with higher curve number values due to the \(P-0.2S\) term being squared.

Since 4.25 inches (10.80 centimeters) of precipitation is the smallest amount of precipitation used in this study, no curve numbers below 35 were used to estimate direct runoff. Special consideration was taken when modeling how the installation of permeable pavement on developed lands to ensure that reducing the existing curve numbers (to simulate permeable pavement) would not be less than 35.

Additionally, time of concentration is not factored into the curve number method. It was assumed that the time of concentration for the study watersheds were less than 24 hours so that the duration of the storm event would not affect the consolidation of the runoff. The curve number method was designed to work with the 24-hour storm event, thus providing an advantage to using this storm duration. Time of concentration, while an important watershed characteristic, can be difficult to calculate and is not needed in this analysis as these are not large watersheds.

4.3 Runoff Estimates

It should be noted that the curve number approach overestimates that amount of the direct runoff emanating from land covered by water. This is because open water was
assigned a curve number of 100 (as is traditionally done) to simulate that all precipitation falling in that area becomes runoff (Wehmeyer 2011). The disadvantage of modeling open water in this way is that it appears to lessen the contribution of runoff from other land uses, particularly developed land uses. Developed lands should contribute a higher percentage of runoff than its percentage of land area due to the presence of impermeable pavement. However, this is not shown within the results (Figures 4, 6-10). Open water contributes much more than its relative percentage of land area and developed lands contribute to the direct runoff only slightly more than their percentage of total land area than what would originally be predicted.

The runoff volumes for the Wanaque Reservoir appear to be much larger than runoff volumes from the other reservoir watersheds. However, this is due to the large watershed that is contributing runoff to the Wanaque Reservoir. The specific retention volume, which is the volume of bonus capacity per area of reservoir watershed, for the Wanaque Reservoir ($1.69 \times 10^4$ cubic meters per square kilometer) is the lowest of the six study reservoirs (Table 1). Lake Hopatcong, on the other hand, has the highest specific retention volume ($2.08 \times 10^5$ cubic meters per square kilometer). This is why the runoff amounts in Figure 5 appear to be so large for the Wanaque Reservoir and so small for Lake Hopatcong.

The specific retention volume can be a good metric for determining which reservoirs to examine for their use at mitigating flooding. Reservoirs with high specific retention volumes will be able to retain larger amounts of runoff (e.g., Lake Hopatcong and Greenwood Lake) whereas reservoirs with low specific retention volumes will not be able to do so (e.g., Wanaque and Spruce Run reservoirs). The specific retention volume is
a straightforward value to calculate and can help guide future studies that wish to examine reservoirs for their flood mitigation potential. Note that maximum annual precipitation for the river catchment and the watershed were not factored into these specific retention volumes because they remained constant across the six study reservoirs, but should be included if the reservoirs are located in different regions.

4.4 Permeable Pavement

The curve number values for the developed land uses (low, medium, and high intensity) were decreased by 37 percent to simulate the installation of permeable pavement in those areas. This is an ideal scenario, and represents the runoff generated that would occur if all of the impermeable pavement was replaced with permeable pavement, which is probably not practical. Developed open space (grid code 21) was left out of this estimate. Developed open space is typically parks and open fields, and if permeable pavement were to be installed on this land it would have minimal effect and possibly even counter-productive. Developed open space comprises a significant portion of developed land in each watershed so this lessens the impact that permeable pavement might initially appear to have on reservoir watersheds (Figure 14).

On average, installation of permeable pavement would reduce the total runoff for each watershed by less than ten percent of the bonus capacity with the runoff reduction decreasing for storm events with greater recurrence intervals. Unfortunately, the runoff volumes could not be reduced to less than the bonus capacities for five of the six reservoirs for any of the storm events. The amount of unabsorbed runoff varies greatly for each watershed, but typical values are between 11 and 80 percent of the bonus capacity.
The exception to this is Lake Tappan due to a large portion of its watershed (65.76 percent) being developed land (Figure 9). Installation of permeable pavement in this watershed would reduce the total runoff of a 50-year storm to be less than the bonus capacity of Lake Tappan. This reservoir is the only one to have its runoff reduced sufficiently to be absorbed by its bonus capacity, showing that reservoir watersheds would need to be mostly developed for permeable pavement to be effective. It may be effective to install permeable pavement in order to reduce runoff (especially runoff containing sediment or chemical) entering the reservoir, but it may not be worth it if the runoff reduction is small.

Permeable pavement costs between $21.53 and $69.97 per square meter for porous concrete, and between $5.38 and $10.76 per square meter for porous asphalt (UMD 2011). The developed area of the Lake Tappan watershed covers 25.82 square kilometers, and complete installation of permeable pavement would cost between $138 million to $1.8 billion depending on the type of permeable pavement used. Installation of permeable pavement in the other study watersheds could cost between $14 and $309 million (Table 2). While these are large costs, impermeable pavement does not have to be replaced all at once; the permeable pavement can be installed as the original impermeable pavement needs to be replaced. This method would spread the costs over a longer period of time instead of being paid up front and would make the replacement more feasible.

4.5 Flood Mitigation

Comparing the flood volume downstream of the Wanaque Reservoir and Lake Hopatcong to the available storage space within those reservoirs at the time of flooding shows that flooding downstream of those reservoirs during high-precipitation storm
events has the potential to be reduced. The Wanaque Reservoir could have contained the flood volume within its available storage capacity for both Hurricane Irene and Tropical Storm Lee of the reservoir was operated to do so. Lake Hopatcong could also have contained the entire flood volume for both storms within its available storage capacity at the time of the storm, though the flood volume for Tropical Storm Lee was greater than that of Hurricane Irene.

The available storage capacity from 2007 to 2013 of the Wanaque Reservoir, which is used for drinking water, is usually greater than what was available during both Hurricane Irene and Tropical Storm Lee (Figures 15 – 20). This is particularly true during the summer and into the autumn when hurricanes are most prevalent in eastern North America (NOAA). The Wanaque Reservoir has been below 90 percent of its maximum capacity for the past eight years. It is almost always below 85 percent and commonly less than 80 percent for a significant portion of the year. The reservoir was at 85 percent of its maximum capacity during Hurricane Irene and Tropical Storm Lee. The flood volume from Hurricane Irene and Tropical Storm Lee would have taken up 3.4 and 2.9 percent of the reservoir’s maximum capacity, respectively. The Wanaque Reservoir water level tends to decline after June and remain low for the rest of the summer. This would allow more space for runoff to be absorbed and flood volumes to be contained during the height of the Atlantic hurricane season.

Lake Hopatcong showed a different trend to that of the Wanaque Reservoir in terms of its available storage space. The lake is used for recreation, particularly boating, so it is managed differently than the Wanaque Reservoir. Lake Hopatcong tends to increase its water level in the spring (typically in the beginning of March) in order to
ensure the water level is sufficient for boating to take place during the summer. The lake attempts to remain at this level throughout the summer; going below would prevent boats from being able to use the lake (Figures 21 – 26).

Despite the goal of maintaining a constant water level, Lake Hopatcong is typically less than 45 percent of its maximum capacity and very commonly less than 40 percent of that maximum capacity. This is about the same amount of available storage space that was present during Hurricane Irene and Tropical Storm Lee. The flood volume from Hurricane Irene and Tropical Storm Lee would have taken up 2.4 and 4.2 percent of the lake’s maximum capacity, respectively. So while the available storage space in Lake Hopatcong does not increase over the course of the hurricane season, what is present would be enough to mitigate flooding downstream of the lake.

This method shows that these two reservoirs could hold back enough water to reduce flooding immediately downstream. It should be noted that the reservoirs do not need to contain all of the runoff in order to reduce flooding; only the flood volume needs to be contained within the reservoir’s bonus capacity. Even if the bonus capacity of a reservoir is much smaller than the volume of runoff entering it, such as in the case of the Wanaque Reservoir, if the flood volume is less than the bonus capacity, the reservoir may still be able to mitigate downstream flooding. For example, the flood volume from Hurricane Irene was $4.62 \times 10^6$ cubic meters compared to the bonus capacity of the Wanaque Reservoir, $3.94 \times 10^6$ cubic meters. Not only would the bonus capacity be able to absorb most of the flood volume, but the available storage space in the reservoir during the time of flooding ($1.90 \times 10^7$ cubic meters) could contain all of that flood volume.
The disadvantage to using the bonus capacity to absorb runoff is that holding the excess water within the reservoirs may cause flooding along the shoreline of those reservoirs. While this may not be an issue for the Wanaque Reservoir where most of the surrounding land is undeveloped and flooding due to holding excess water would not cause serious damage to infrastructure (Figure 27). The shoreline around Lake Hopatcong, however, is much more developed (Figure 14). A significant increase in water level on the lake has the potential to damage homes located near the shoreline. Mitigating flooding in order to save homes downstream of Lake Hopatcong by flooding homes upstream is counterproductive to flood control. Even a small increase, if held for a longer period of time, could damage stationary docks. And while damage to these docks may be minor, if the cost of fixing the docks is not less than the damages that could have occurred downstream if the flooding was not prevented, then there is little economic incentive to hold back the water within the reservoir.

Another disadvantage of using reservoirs in this manner is that over-filling the reservoirs can be very damaging. Dam are designed and constructed with certain usage and storage parameters in mind. Using the dam outside of these parameters can damage it and cause further hazards. Over-filling a reservoir can cause erosion at the top of the dam and may eventually lead it to fail, endangering nearby residents to flooding and creating significant costs in dam repair or replacement (Lima 2015). This is why drinking water reservoir operators are incentivized to fill up the reservoir only to a certain point, even though they want the reservoir to be as full as possible. If the reservoir gets too close to its maximum capacity, reservoir operators risk over-filling the reservoir during the next high precipitation storm event and harming the dam and reservoir. Thus, although the
reservoirs can be filled to their maximum capacity, it does not necessarily mean it is always beneficial to do so.

Additionally, care should be taken to ensure the reservoir is operated in such a manner that adopting a flood control strategy will not create any negative effects downstream of the reservoir. Releasing water from the reservoir should be done over time and not all at once in order to avert creating flooding downstream of the reservoir. Also, water should not be withheld longer than necessary so that streamflow can be restored as soon as possible. This will reduce the risk to downstream communities that may rely on having a certain amount of streamflow and water available to them. While establishing this balance may be difficult, it is essential in order to minimize the negative effects of changes in reservoir operations.

4.6 Other Factors Affecting Flood Mitigation

The presence of floodplains upstream of the reservoirs can complicate the arrival of runoff to that reservoir. Runoff travels through floodplains and wetlands slower than through other land use categories. The volume of water flowing over a floodplain spreads out over a larger area, decreasing its velocity and thus causing it to take more time to get to the watershed reservoir outlet. Floodplains and wetlands act as a type of natural flood control since they withhold and the release runoff over time. The presence of these lands within the study reservoir watersheds increases the flood mitigation potential of those reservoirs because they allow for the reservoir to absorb the same amount of runoff over a longer period of time. In other words, the reservoirs are not required to have as much available storage capacity at one time and only need to absorb the runoff arriving directly after the storm event. Thus, for reservoirs that have large
wetland areas and floodplains within their watershed, such as Oak Ridge Reservoir and Greenwood Lake (Figures 8 & 10), it may not be accurate to assume that all of the runoff enters the reservoir within a reasonable amount of time.

It should also be noted that two of the study reservoirs, the Wanaque Reservoir and Lake Tappan, have other reservoirs located within their watersheds. Lake DeForest is located in Clarkstown, New York and is upstream of Lake Tappan. Greenwood Lake is located on the border of New Jersey and New York and is the reservoir upstream of Wanaque Reservoir. The six studied reservoirs were not analyzed with these upstream reservoirs in mind, and any other reservoirs located within those watersheds were treated as normal open water bodies. Because of these upstream reservoirs the runoff estimates for the Wanaque Reservoir and Lake Tappan may not be as accurate since Lake DeForest and Greenwood Lake were treated as open water bodies with curve numbers of 100. In reality, these upstream reservoirs could be managed to withhold runoff, delaying it like a floodplain or wetland as described earlier. This added benefit would result in the downstream reservoir not having to absorb as much runoff as originally estimated. This is a benefit for the study reservoirs whose bonus capacity is smaller than total runoff volumes from certain storm events (e.g., the 50- and 100-year storms for Lake Tappan).

The reservoirs could also coordinate their operations. For example, the more upstream reservoir could be kept filled more than normal and the downstream reservoir can be emptied to absorb runoff and mitigate flooding. If a potential storm was not as intense as forecasted, water from the upstream reservoir could be transferred to the downstream reservoir to refill it. This can provide resiliency for the reservoirs because it allows for flood mitigation without risking the reservoirs’ ability to supply water. The
downside to having these two reservoirs so close together is that it will take more effort to coordinate their operations to deliver the most efficient and effective flood mitigation strategy. This can be problematic for reservoirs located in different municipalities or states.

4.7 Future Work

Highly developed watersheds upstream of reservoirs such as Lake Tappan should be evaluated to determine how the installation of permeable pavement may affect runoff within that watershed. Permeable pavement may be able to reduce total runoff enough in developed areas to allow the runoff to be absorbed by the bonus capacity of the reservoir, or even reduce it enough to eliminate the “flashy” peak discharge effect of urban areas and mitigate flooding in that way. However, the effects of installing permeable pavement should be studied to ensure that it does not interfere with supply to the reservoir that the reservoir have relied on given the past state of the watershed.

Closer examination of the Wanaque Reservoir in terms of its operations and responses to storm events should be explored. This reservoir is the most promising of the six study reservoirs to mitigate flooding immediately downstream. Not only is it one of the largest reservoirs within the state of New Jersey, but the state park land surrounding it make it ideal for absorbing excess runoff and filling up to its maximum capacity. Options for reservoir management and modifications to Raymond Dam should be considered to adapt the Wanaque Reservoir for flood mitigation purposes. Outlets of reservoirs may need to be modified in order to serve this new flood mitigation purpose. Raymond Dam was not built with the intended purpose of flood control and modifications may be
necessary to effectively employ this strategy. The adaptation of existing infrastructure would create a flexible water resource as described by DiFrancesco et al. 2014.

Lake Hopatcong, while being able to absorb enough runoff to mitigate flooding on the Musconetcong River, is not an ideal candidate for a multi-purpose flood mitigation reservoir. The permanent lake community on its shores hinders it from utilizing its complete capacity; flooding homes along the lake to prevent flooding downstream would not be productive. Regardless, Lake Hopatcong can be further studied to determine if it can be used at least for some flood mitigation.

5. Conclusions

Six reservoirs in northern New Jersey were studied for their potential to mitigate flooding downstream. The curve number method was employed to estimate runoff entering into each reservoir during 5-, 10-, 50-, and 100-year storm events. Total runoff estimates were compared to the bonus capacity (difference between the maximum and normal capacities of the reservoirs) of each reservoir. Five of the six reservoirs could absorb runoff from the 5-year storm. Two of the reservoirs (Lake Tappan and Greenwood Lake) could absorb the total runoff from the 10-year storm. None of the reservoirs could absorb the runoff from the 50- and 100-year storm events.

Installation of permeable pavement within reservoir watersheds that are more developed can reduce the runoff entering those reservoirs. Complete replacement of impermeable pavement with permeable pavement within the Lake Tappan watershed could reduce total runoff to less than the bonus capacity of that reservoir. Utilizing permeable pavement in the other five reservoir watersheds was not enough to reduce runoff to less than the bonus capacity, but could still help mitigate flooding downstream.
by the simple fact that more water is infiltrating into the soil than becoming runoff and entering streams and rivers.

The Wanaque Reservoir and Lake Hopatcong could hold enough water to mitigate flooding downstream during extreme flooding events such as Hurricane Irene and Tropical Storm Lee. This reduction of flooding downstream may come at the cost of flooding the shoreline around each of the reservoirs. It would not be a problem for the Wanaque Reservoir where the surrounding land is undeveloped, but may be in issue for Lake Hopatcong which hosts a large lake community along its shores.
6. References


Appendix A – Tables

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Maximum Capacity</th>
<th>Normal Capacity</th>
<th>Bonus Capacity</th>
<th>Watershed Area (km²)</th>
<th>Specific Retention Volume (m³/km²)</th>
<th>Percentage of Developed Land</th>
<th>Reservoir Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wanaque</td>
<td>1.35x10⁸</td>
<td>1.31x10⁸</td>
<td>3.94x10⁶</td>
<td>234</td>
<td>1.69x10⁷</td>
<td>10.26</td>
<td>Drinking, recreation</td>
</tr>
<tr>
<td>Lake Hopatcon</td>
<td>7.31x10⁷</td>
<td>5.95x10⁷</td>
<td>1.36x10⁷</td>
<td>66</td>
<td>2.08x10⁷</td>
<td>25.98</td>
<td>Recreation, drinking</td>
</tr>
<tr>
<td>Spruce Run</td>
<td>4.16x10⁷</td>
<td>3.68x10⁷</td>
<td>4.73x10⁶</td>
<td>107</td>
<td>4.42x10⁶</td>
<td>12.78</td>
<td>Drinking, recreation</td>
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<tr>
<td>Greenwood Lake</td>
<td>3.31x10⁷</td>
<td>2.61x10⁷</td>
<td>7.11x10⁶</td>
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<td>1.01x10⁷</td>
<td>15.90</td>
<td>Recreation</td>
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<tr>
<td>Lake Tappan</td>
<td>2.39x10⁷</td>
<td>1.31x10⁷</td>
<td>1.08x10⁷</td>
<td>127</td>
<td>8.50x10⁴</td>
<td>63.11</td>
<td>Recreation</td>
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<tr>
<td>Oak Ridge</td>
<td>1.85x10⁷</td>
<td>1.48x10⁷</td>
<td>3.71x10⁶</td>
<td>71</td>
<td>5.23x10⁴</td>
<td>3.32</td>
<td>Drinking</td>
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</tbody>
</table>

Table 1. Summary of reservoir characteristics. Maximum, normal, and bonus capacities are listed in cubic meters.

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Area</th>
<th>Cost Porous Asphalt</th>
<th>Cost Porous Concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m²</td>
<td>Low ($5.38)</td>
<td>High ($10.76)</td>
</tr>
<tr>
<td></td>
<td>km²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wanaque Reservoir</td>
<td>4.42x10⁶</td>
<td>$23,775,332</td>
<td>$47,550,663</td>
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<tr>
<td>Lake Hopatcon</td>
<td>3.96x10⁶</td>
<td>$21,291,458</td>
<td>$42,582,915</td>
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<tr>
<td>Spruce Run Reservoir</td>
<td>3.13x10⁶</td>
<td>$16,860,817</td>
<td>$33,721,633</td>
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<tr>
<td>Greenwood Lake</td>
<td>2.69x10⁶</td>
<td>$14,480,141</td>
<td>$28,960,282</td>
</tr>
<tr>
<td>Lake Tappan</td>
<td>2.58x10⁷</td>
<td>$138,968,271</td>
<td>$277,936,541</td>
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<tr>
<td>Oak Ridge Reservoir</td>
<td>3.86x10⁷</td>
<td>$2,076,690</td>
<td>$4,153,380</td>
</tr>
</tbody>
</table>

Table 2. Costs for the installation of permeable pavement in developed sections of each of the study watersheds. Prices are shown in USD per square meter.
Figure 1. Map of the Passaic River Basin showing sub-watersheds and other major rivers within the basin. Three of the six reservoirs are located within the Passaic River Basin. Map from the Passaic River Institute, Montclair State University.
Figure 2. Diagram showing normal and bonus capacities of a reservoir. The sum of the bonus and normal capacities is the maximum capacity of the reservoir.
Figure 3. Location of study reservoirs within northern New Jersey. Land use is shown according to the National Land Cover Database 2011 grid codes.
Figure 4. Percentage of total reservoir watershed area and runoff for each land use category for the Wanaque Reservoir. Note the larger than predicted contribution of Water to the runoff. See Discussion for more details.
Figure 5. The total runoff from each reservoir watershed for each storm event normalized to the bonus capacity of the reservoir. The red line represents the maximum runoff that can be absorbed by the bonus capacity for each reservoir.
Figure 6. Percentage of total reservoir watershed area and runoff for each land use category for Lake Hopatcong. Note the larger than predicted contribution of water to the runoff. This is caused by assigning a curve number of 100 to open water thereby overestimating the amount of runoff emanating from open water land uses.
Figure 7. Percentage of total reservoir watershed area and runoff for each land use category for Spruce Run Reservoir. This watershed has the largest percentage of Agriculture of any of the study reservoirs. Note the larger than predicted contribution of water to the runoff. This is caused by assigning a curve number of 100 to open water thereby overestimating the amount of runoff emanating from open water land uses.
Figure 8. Percentage of total reservoir watershed area and runoff for each land use category for Greenwood Lake. Note the larger than predicted contribution of water to the runoff. This is caused by assigning a curve number of 100 to open water thereby overestimating the amount of runoff emanating from open water land uses.
Figure 9. Percentage of total reservoir watershed area and runoff for each land use category for Lake Tappan. This watershed has the largest percentage of developed land of any of the study reservoirs. Note the larger than predicted contribution of water to the runoff. This is caused by assigning a curve number of 100 to open water thereby overestimating the amount of runoff emanating from open water land uses.
Figure 10. Percentage of total reservoir watershed area and runoff for each land use category for Oakridge Reservoir. Note the larger than predicted contribution of water to the runoff. This is caused by assigning a curve number of 100 to open water thereby overestimating the amount of runoff emanating from open water land uses.
Figure 11. Bonus capacity of each reservoir normalized to the watershed area of that reservoir. This is known as the specific retention volume. Lake Hopatcong not only has the largest bonus capacity of the six study reservoirs, but also the smallest watershed; it has the highest specific retention volume. The bonus capacity of the Wanaque Reservoir is not small ($3.94 \times 10^6$ cubic meters) but it has the largest watershed of the study reservoirs thus it is unable to adequately absorb runoff from its watershed (small specific retention volume).
Figure 12. Reduction of total runoff in terms of percentage of bonus capacity for each reservoir when all impermeable pavement in developed lands of each watershed is replaced with permeable pavement. Lake Tappan has the greatest reduction of total runoff because it has the highest percentage of developed land of the six study reservoirs.
Figure 13. Relationship of direct runoff (Q) to curve number values for 4.25 inches of precipitation. Note how curve numbers less than 35 predict direct runoff amounts larger than what should be occurring at low curve numbers. This happens when the $0.2S$ term (S is a composite of the curve number) in the direct runoff equation becomes greater than the precipitation amount ($P$).
Figure 15. 2008 reservoir storage in terms of percentage of maximum capacity for the Wanaque Reservoir. Reservoir storage declines during the summer months when high precipitation storms can occur.
Figure 16. 2009 reservoir storage in terms of percentage of maximum capacity for the Wanaque Reservoir. Storage for this year remained relatively constant, but was generally less than during Hurricane Irene and Tropical Storm Lee.
Figure 17. 2010 reservoir storage in terms of percentage of maximum capacity for the Wanaque Reservoir. Storage declined significantly during the summer months in this year and any runoff from high precipitation storm events could easily be absorbed.
Figure 18. 2011 reservoir storage in terms of percentage of maximum capacity for the Wanaque Reservoir. Note the two small peaks around September; these represent Hurricane Irene and Tropical Storm Lee.
Figure 19. 2012 reservoir storage in terms of percentage of maximum capacity for the Wanaque Reservoir. Although there was an increase in reservoir storage during early summer, it declined later on in the season allowing for runoff to be absorbed.
Figure 20. 2013 reservoir storage in terms of percentage of maximum capacity for the Wanaque Reservoir. Reservoir storage during this year was generally higher throughout the summer than in previous years, decreasing the effectiveness of absorbing runoff from the watershed.
Figure 21. 2008 reservoir storage in terms of percentage of maximum capacity for Lake Hopatcong. Reservoir storage generally remained constant throughout the summer when high precipitation storm events occur, but was less than the storage during Hurricane Irene and Tropical Storm Lee.
Figure 22. 2009 reservoir storage in terms of percentage of maximum capacity for Lake Hopatcong. Reservoir storage was generally constant during the summer months in this year, but still less than during Hurricane Irene and Tropical Storm Lee.
Figure 23. 2010 reservoir storage in terms of percentage of maximum capacity for Lake Hopatcong. Storage decreased during the summer months of this year which increased the effectiveness of absorbing runoff from the water.
Figure 24. 2011 reservoir storage in terms of percentage of maximum capacity for Lake Hopatcong. Note the two peaks around September; these represent Hurricane Irene and Tropical Storm Lee.
Figure 25. 2012 reservoir storage in terms of percentage of maximum capacity for Lake Hopatcong. Although storage increased later on in this year than in previous years, it remained constant throughout the summer.
Figure 26. 2013 reservoir storage in terms of percentage of maximum capacity for Lake Hopatcong. Reservoir storage was about the same during the summer months as in previous years.
Figure 14. Land use within the Lake Hopatcong watershed using National Land Cover Database 2011 grid codes.
Figure 27. Land use within the Wanaque Reservoir watershed using National Land Cover Database 2011 grid codes.
Figure 28. Land use within the Spruce Run Reservoir watershed using National Land Cover Database 2011 grid codes.
Figure 29. Land use within the Lake Tappan watershed using National Land Cover Database 2011 grid codes.
Figure 30. Land use within the Greenwood Lake watershed using National Land Cover Database 2011 grid codes.
Figure 31. Land use within the Oak Ridge Reservoir watershed using National Land Cover Database 2011 grid codes.