Effects of Changes in Snow Pattern and the Timing of Runoff on NYC Water Supply System

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ABSTRACT:

The Generalized Watershed Loading Functions – Variable Source Area (GWLF-VSA) watershed model is used with future climate scenarios derived from different General Circulation Models (GCMs) to simulate future inflows to reservoirs that are part of the New York City Water Supply System (NYCWSS). This study focuses on the effect of projected changes in rainfall, snow accumulation and snowmelt and consequent changes in the timing of runoff on NYC water supply system storage and operation as simulated by the NYC reservoir system OASIS model. Future scenarios that use current system operation rules and demands, but changed reservoir inflows, suggest that changes in precipitation and snowmelt will affect regional water availability on a seasonal basis. Reservoir storage levels and water releases appear to increase and spills appear to be higher and less variable during winter. The combined effect of projected increases in winter air temperatures, increased winter rain, and earlier snowmelt may result in more runoff during winter, which despite increased evapotranspiration later in the year leads to, a reduction in number of days the system is under drought conditions, and earlier reservoir refill in the spring.

Keywords: Climate change, snow and water supply operation, reservoir system OASIS model, reservoir system indicators, watershed modeling

INTRODUCTION

The New York City Water Supply System (NYCWSS) is comprised of a total of 19 reservoirs and three controlled lakes. Reservoirs were initially developed East of the Hudson River (EOH) in and adjacent to the Croton River Watershed. In total 13 reservoirs were built in the EOH portion of the supply, and today these contain approximately 10 % of the water stored in the NYCWSS. In 1905 the New York City Board of Water Supply was created by the New York State legislature with the task of identifying and delivering new water sources for the growing NYC metropolis (NYCDEP 2006). Reservoir construction in areas West of the Hudson River (WOH) began with the development of the Catskill subsystem, which was finalized with the completion of the Schoharie Reservoir in 1926. Additional reservoir capacity was added to the system during the nineteen fifties and sixties with the addition of four reservoirs that form the Upper Delaware subsystem in the WHO region. Today the total reservoir system which includes both the EOH and WOH regions has the capacity to store up to 580 billion gallons water (NYCDEP 2006). In a system as diverse as the NYCWSS the allocation and use of water among the different reservoirs is based on a variety of factors including the relative differences in water availability, water quality, system infrastructure and demands. The combined effects of these considerations have been formalized into a rule set describing NYCWSS operation, and this rule set is the basis of the OASIS (HydroLogics, Inc., 2007) system operations model.

Previous studies have indicated that for mountainous regions like the Catskill Mountains in New York where snow accounts for an important component of the annual precipitation, future changes in temperature and precipitation may lead to changes in winter rainfall, snowpack water equivalent, water loss due to evapotranspiration and a shift in the timing of runoff (Brekke et al., 2009; Burns et al., 2007; Frei et al.,

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2002; Blake et al., 2000). As part of New York City Department of Environment Protection (NYCDEP) "Climate Change Integrated Modeling Project for Water Quantity and Quality" (CCIMP) project (NYCDEP 2008) baseline and future climate scenarios have been developed for the WOH region contributing water to the NYCWSS. The projected climate data are used to drive the Generalized Watershed Loading Functions – Variable Source Area (GWLF-VSA) (Haith and Shoemaker, 1987; Schneiderman et al., 2002; Schneiderman et al., 2007) watershed model to simulate snowpack, snowmelt and inflows to reservoirs. Our objective is to investigate the effect of changes in snowmelt and the timing of runoff on NYCWSS water storage and operation. GWLF-VSA simulated reservoir inflow is input into the NYCWSS OASIS reservoir system model to simulate water storage and NYCWSS operation. A selected number of system indicators output from OASIS are used to represent the instantaneous state of system operations and to assess system performance. These indicators include reservoir storage volume, release and spill, drought conditions occurrence and probability of reservoirs to refill by June 1st.

Reservoir operation rules have evolved over time, and the current rules in NYC OASIS model are based on knowledge gained during years of historical operation of the system to meet demands, maintain high water quality, and provide regulatory releases while balancing diversion from Delaware, Catskill and Croton subsystems. For this study rules and demands used with the future climate simulations were considered stationary and equal to present conditions.

STUDY SITE

NYCWSS integrates 19 interconnected reservoirs and aqueducts to supply more than 1 billion gallons of drinking water per day to about 9 million people in NYC and nearby counties (NYCDEP 2006). It is the largest surface water supply in the United States with no mechanical filtration (Daily and Ellison 2002). The system includes the WOH and EOH regions. The WOH portion which is the focus of this study includes the Catskill and Delaware system reservoir watersheds (further called subsystems) and supplies more then 90 percent of NYC water demands. The Catskill subsystem includes the Ashokan and Schoharie reservoirs and the Delaware subsystem includes Pepacton, Cannonsville, Rondout and Neversink reservoirs. These watersheds extend for an area of approximately 4103 square kilometers, and have a humid continental climate where cold winters and cool summers are typical. The temperature in this region is impacted by elevation which rises to approximately 1200 m from the Hudson River. The regional hydrology is influenced by snowpack water storage and snowmelt processes that depend on temperature and precipitation patterns. The EOH portion of the system has a total drainage area of approximately 1004 square kilometers. According to the 2000 census the population density is 29 and 499 persons per square mile for WOH and EOH areas, respectively (NYCDEP 2006). Previous studies (such as Burns et al., 2007) have found that a 0.6 degree Celsius increase in yearly temperature and 136 mm increase in precipitation have occurred over the past 50 year period for the Catskill Mountain region. This manuscript examines how a continuation in this trend and a shift in snow processes caused by climate change will affect water availability in the region and the status and operation of the NYCWSS.

METHODOLOGY

Simulated baseline and future air temperature and precipitation using GCMs and a monthly delta change methodology (Anandhi et al. 2010) were used as input to the GWLF-VSA watershed model. GWLF-VSA (Schneiderman et al., 2007) is a lumped parameter model based on the original GWLF model (Haith and Schoemaker 1987) that simulates daily streamflow discharge and monthly sediment and nutrient loads at a watershed scale. GWLF-VSA development included model calibration against measured streamflow data from local gauge stations in the region. For this study GWLF-VSA was used to simulate future evapotranspiration, snowpack, snowmelt and streamflow discharge for all the reservoir watersheds in the WOH part of the NYCWSS system. Reservoir inputs for the EOH portion of the system were based on historical streamflow records, and not adjusted to account for future climate change. This is a necessary approximation that is used in the early stages of the CCIMP given data and time constraints.

Simulated GWLF-VSA stream discharge data were subsequently used as inputs to the NYC OASIS reservoir system model to simulate system operations and evaluate system performance. OASIS (Hydrologics, 2007) is a generalized model that was developed to simulate the operations of interconnected reservoir systems, and that simulates daily changes in storage and the transfer of water within the reservoir system by solving a Linear Program (LP). An Operations Control Language (OCL) built into OASIS is used to set system operating rules and a Graphical User Interface (GUI) is available to represent the current elements of the system and system interconnections (Figure 1). The NYC OASIS model reflects the infrastructure and operation rules that are specific to the NYCWSS. The OASIS model seeks to balance Catskill, Delaware and Croton subsystems, in a process that is based on storage levels, the probability of the system to refill by June 1st and season. Also, a number of rules specific to regulatory requirements for downstream releases, water quality requirements and system operational needs are encoded within the OASIS rule set.

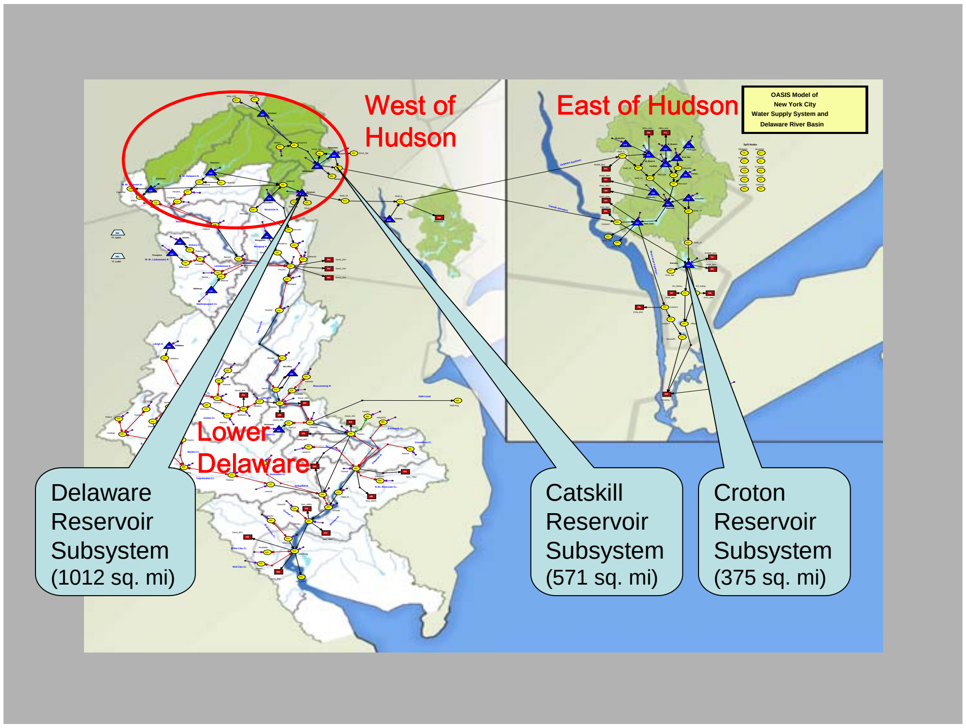


Figure 1. NYC water supply system schematic in OASIS GUI showing the EOH, WOH and LD parts of the systems and the different elements. The dark green color indicates the two direct parts of the NYCWSS; the region in white color is the LD which interacts with the system but is not a direct part of NYC water supply.

Simulations for this study focused on changes in WOH inflow as a result of the different climate change scenarios while assuming EOH and LD inflows, system operation rules and demands are stationary and identical to present day. System indicators are used in this study to help evaluate the NYCWSS response to the simulated changes in WOH inputs. These indicators are generated for the Catskill and Delaware subsystems and include volumes of reservoir storage, controlled releases, and uncontrolled spills; the occurrence of drought conditions; and the probability of reservoir to refill by June 1st. Looking at changes in inflow, storage, release and spill provides information on how the current system (with current rules and demands) can respond to changes in WOH inflow that can be expected under future climate conditions and helps to identify sensitive parts of the system that will require further investigation and analysis. Drought occurrence is based on the volume of water or available storage in the water supply system and different thresholds of storage are used to define three drought levels: watch, warning and emergency. Drought occurrence can be used as a measure of the NYC system performance, as it indicates the number of days per year a particular subsystem is likely to be under drought conditions. The call for a particular drought level is based on a comparison between the total storage of the subsystem with average yearly patterns of storage for each individual subsystem and predefined thresholds indicating drought conditions. The combination of the drought conditions in Delaware and Catskill subsystems determine the drought state for the entire NYCWSS. Drought status can affect the operation of the water supply and lead to voluntary and mandatory water conservation policies. Given the importance of extended periods of low streamflow in determining downstream minimum releases and drought conditions (Matonse and Kroll, 2009; Vogel and Fennessey, 1995) we develop low flow indices. For this study we selected one of the most commonly used low flow indices in the United States, the 7-day, 10-year (7Q10 or $Q_{7,10}$) statistic which is based on 7-day annual minimum flow series (Kroll and Vogel 2002, Matonse 2009). The $Q_{7,10}$ is a statistical estimator of the lowest 7-day streamflow that on average will be exceeded 9 out of 10 years (Stedinger and Thomas 1985). We applied a frequency analysis based on a log-Pearson Type III distribution assumption (Stedinger et al. 1993). The probability of refill by June 1st (PR) is an indicator of the state of the NYC system at a given period of the year. This indicator is a function of: (i) the current day's storage deficit; (ii) expected future water diversions and releases (determined using historical data average values from 1987 to 2004); and (iii) system-wide inflow forecasts between today and June 1st (also determined using historical data). This indicator can assume values from 0 to 1, with 1 being the best or the most desired state.

INPUT DATA DESCRIPTION

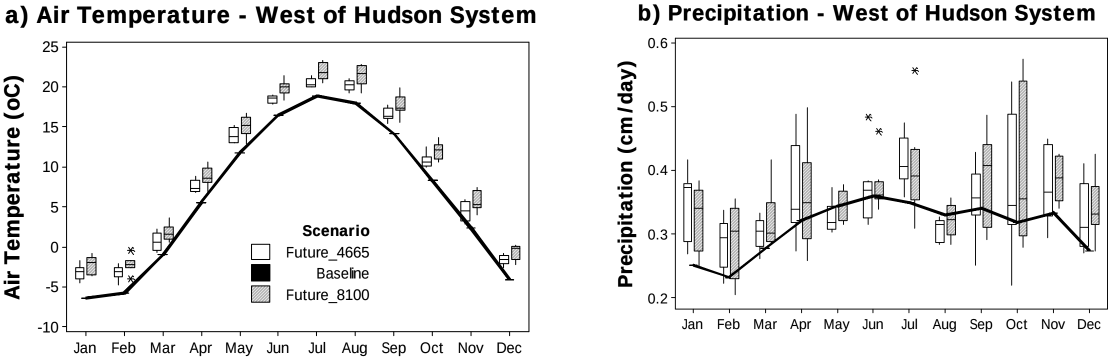
Table 1 summarizes the climate scenarios and time periods used in this study. The model acronyms ECHAM stands for the European Centre Hamburg Model, GISS for the Goddard Institute for Space Studies, and NCAR for the National Centre for Atmospheric Research.

Table 1 General Circulation Models, emission scenarios and time slices applied in this study

GCM	20C3M	Emission Scenario	Time Slices
ECHAM	1981 – 2000	A2, A1B, B1	2046 - 2065, 2081 – 2100
GISS	1981 – 2000	A2, A1B, B1	2046 - 2065, 2081 – 2100
NCAR	1980 – 1999	A2, A1B	2046 - 2065, 2080 – 2099

Future climate scenarios were derived using a delta change methodology (Anandhi et al. 2010), which calculated monthly changed factors based on a comparisons between GCM baseline and future scenarios. Additive factors for air temperature and multiplicative factors for precipitation were applied to the historical time series of daily data associated with each reservoir watershed, in order to produce reservoir specific future climate scenarios. Inflows to the reservoirs constitute major inputs to OASIS model. Future scenarios of air temperature and precipitation were used in GWLF-VSA to derive basin-wide inflows for each of the different climate scenarios, and present day (baseline conditions).

Air temperature, precipitation and snowpack



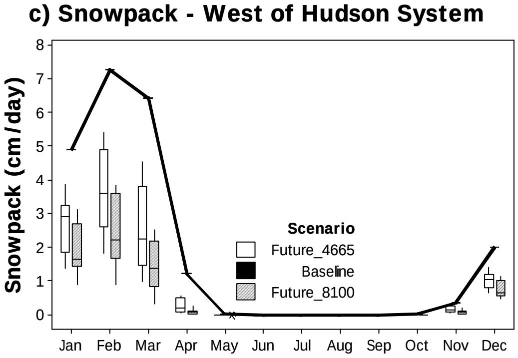


Figure 2. Monthly average daily air temperature, precipitation and snowpack for baseline and future scenarios. These data are areal averages for all WOH watersheds. The Graphs show the 65 year future and 100 year future scenario time slices. The solid line represents the baseline scenario, while boxplots represent future simulations with the mid-way line showing the median value. The extent of the boxes show the range of the middle six scenarios, the whiskers show the range of all eight scenarios.

Air temperature is projected to increase over the West of Hudson (WOH) region under future GCM climate (Figure 2-a). The difference in simulated air temperature by the different scenarios appears slightly higher for the period 100 years forward. Precipitation is simulated to increase during most months except for May, June and August. However, simulated future levels of precipitation show a high degree of variability among different GCMs used in this study (Figure 2-b). Higher temperature during winter resulted in a large reduction in snowpack snow water equivalent as simulated by GWLF-VSA (Figure 2-c). Snowfall and snowpack are projected to greatly decrease during the winter months because the increased temperature causes more of the precipitation to fall as rain and since the snowpack that does develop tends to melt faster and earlier in the year.

Simulated future Inflow to WOH reservoirs

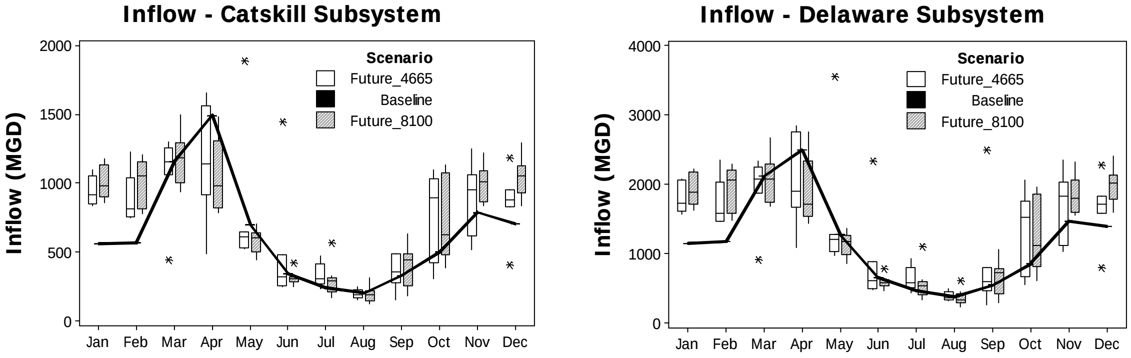


Figure 3. Average monthly inflows for the baseline and different simulated future climate scenarios for the Catskill and Delaware subsystems. The solid line represents the baseline and the box-plots represent the different future simulations aggregated by time period.

Most GCMs project increased winter and reduced early spring reservoir inflow due to earlier future snow melt (Figure 3). There are particularly strong indications that levels of winter streamflow will increase since future predictions all fall well above simulations of contemporary conditions in December to February. This is true for both the Catskill and Delaware subsystems. The disagreement between the different GCM simulations is high for April, October and November in particular when simulating the time period 50 years forward. These are also the months with the largest disagreement in snowpack and/or precipitation in Figure 2 above. Annual inflow is higher for most future scenarios but also with variations in magnitude between estimations from different GCMs. On average simulations associated with different GCMs indicate an increased $Q_{7,10}$ for the future 50 and 100 years forward in both Catskill and Delaware watersheds (Table 2) with values for the later period being slightly less than the next 50 years, a result that can be related to the difference in average evapotranspiration for the two periods and the impact of extreme climate scenarios.

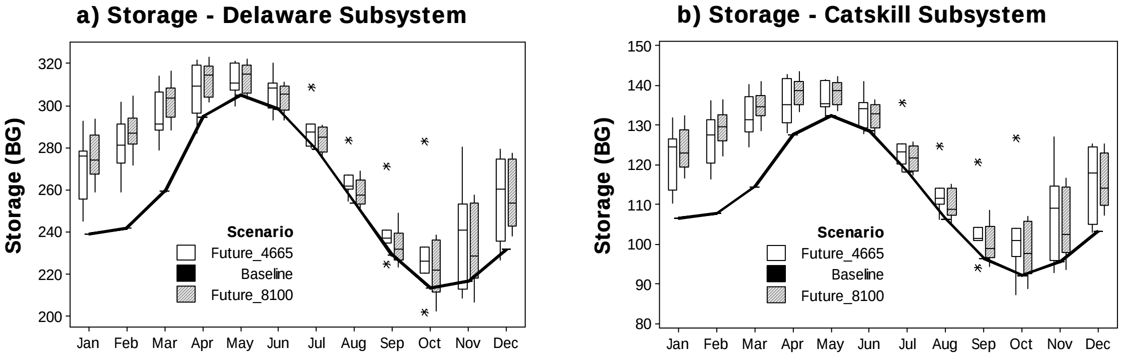
Table 2 $Q_{7,10}$ low flow statistics for the baseline and future simulated 50 and 100 years forward

	Catskill (MGD)	Delaware (MGD)
Baseline historical	4.4	22.1
Mean 50 years forward	5.7	28.3
Mean 100 years forward	4.3	23.4

If the shift in runoff timing associated with earlier snowmelt was the only effect of climate change one would expect less water being available during low flows periods due to more water being lost during winter. The simulated future $Q_{7,10}$ suggest that for low flows the combined effect of earlier snowmelt and increased rainfall is more important leading to potentially more water being available for the reservoirs throughout the entire year.

RESULTS ON SYSTEM INDICATORS AND DISCUSSION

Reservoir storage, release and spill



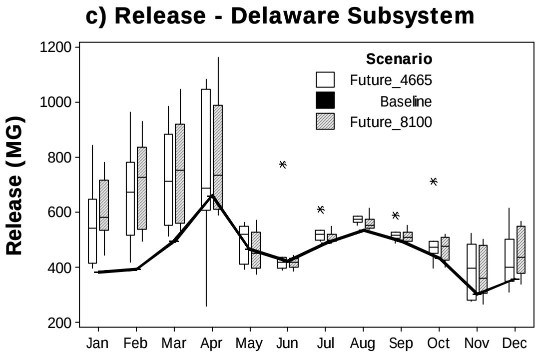


Figure 4. Inflow, storage and release patterns for Delaware and Catskill subsystems for the baseline (white), future 50 years forward (light gray) and future 100 years forward (dark gray) scenarios. Box plots show the median and interquantile range.

Simulated future reservoir storage, release, and spill show a pattern that is directly related to changes in snowmelt amount and timing of runoff. As shown in Figure 4 the combined effect of changes in snowmelt and timing of winter – spring runoff for simulated future scenarios leads to the reservoirs filling earlier in the year. The future simulations suggest that there will be increased future storage levels during winter months, while showing similar storage levels with less variability in summer. The disagreement in the simulated average storage among the different GCM simulation scenarios is greater during late fall and earlier winter than during the summer. The relationship between snowpack, snowmelt and reservoir releases is complex, given that OASIS attempts to maintain a void in reservoir storage of 50% of the estimated watershed snow water equivalent. Higher projected winter inflows cause the reservoirs to fill up earlier (Figure 5), and as a result OASIS increase releases in order to maintain, a void in the reservoirs. However, since the snowpack is also projected to decrease in the future, the size of the required void also decreases. The overall effect is an increase in controlled releases during winter and earlier spring.

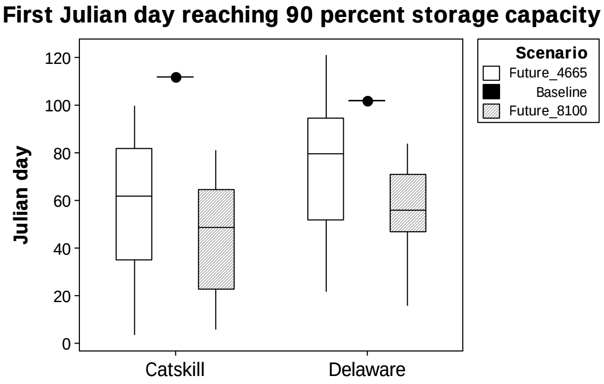


Figure 5. First Julian day when reservoirs in Catskill and Delaware subsystems pass the level of 90 percent of the total storage capacity. The dark dots represent the baseline and the box-plots the future simulated by the different scenarios aggregated in future time period.

Figure 5 further illustrates how reservoirs fill earlier under future simulated climate. It is striking that the Catskill reservoirs are projected to reach a 90% storage level two months earlier 100 years into the future. The effect is somewhat less pronounced in Delaware subsystem, since as described above this subsystem also is expected to show an increased release of water to the lower Delaware watershed. Figure 6 shows box-plots for the spill volume from November (previous year) to before March 1st. The volume of spill during this period increases in both subsystems under the simulated future scenarios. This increase is slightly more pronounced for the future period 100 years forward.

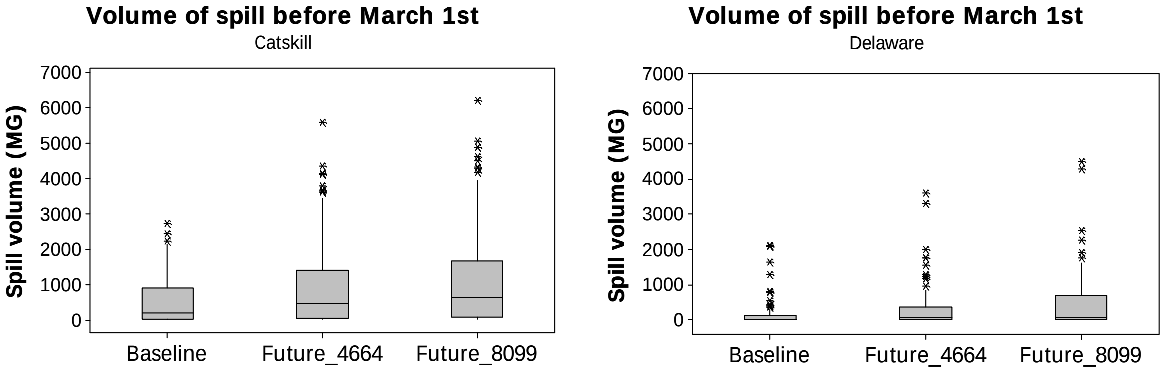
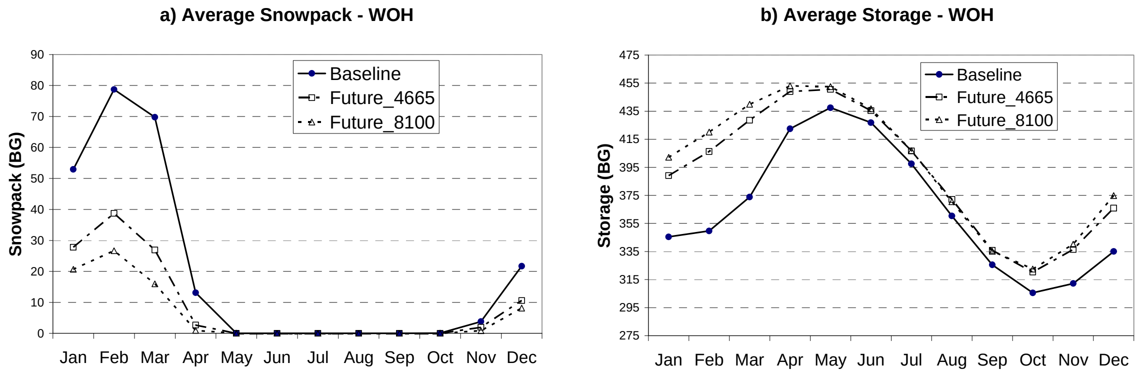


Figure 6 Yearly volume of spill from November to before March 1st for the Catskill and Delaware subsystems

It is important to note that the increase in volume of spill does not directly address any issue related to flooding, which was not part of this study, but rather is an indicator of water that would no longer be available in the system for water supply. The increased water loss from the water supply system is of course, related to greater winter stream discharges (Figure 3) that lead to the reservoirs filling earlier and spilling more. This is ultimately a consequence of the projected increase in snow melt and a decreased amount of water stored in the snowpack. Also, higher winter inflows may occasionally result in elevated turbidity, which under extreme circumstances, may trigger a reduction in the use of the Catskill subsystem resulting in greater simulated spills. In Figure 7 we show baseline and future estimates of the storage of water in the reservoir system, snowpack and the combination of the two. From these data it is apparent that while future scenarios show the reservoir system to fill earlier, this occurs at the expense of snow storage. This when combined with greater levels of evaportranspiration later in the year might have potentially led to relatively decreased reservoir storage levels during summer.



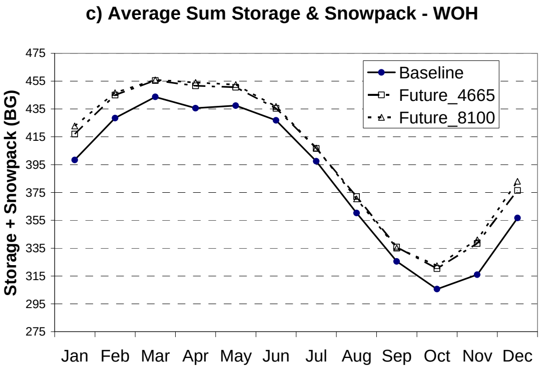
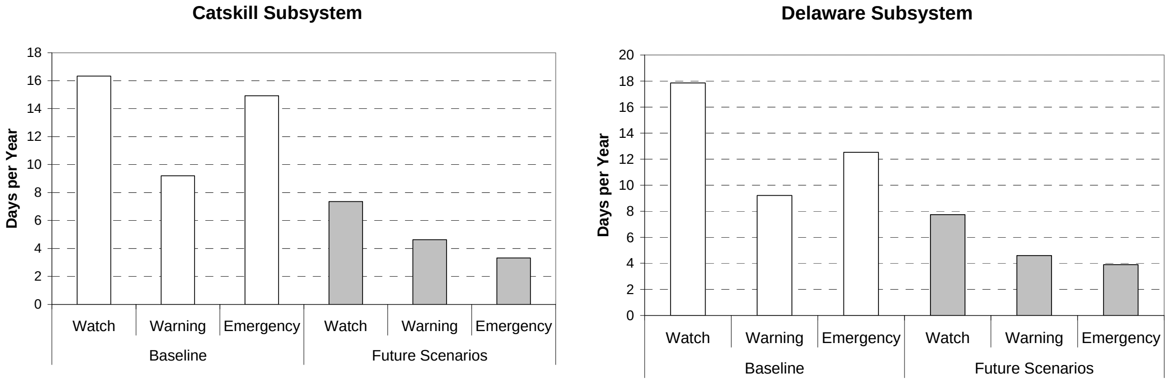

c) Average Sum Storage & Snowpack - WOH

Figure 7. Baseline and average over all scenarios monthly snowpack, storage and storage plus snowpack for the WOH subsystems.

However, as shown in Figure 7c, the future storage levels are increased as a result of an overall increased precipitation (Figure 2b). This result also explains the improvements in simulated $Q_{7,10}$ low flow statistics (Table 2) and reduction in drought conditions occurrence (see next section). It is worth noting that the uncertainty in future projections of precipitation is large, so that the loss of snow storage still could be an issue of concern.

Drought conditions occurrence and probability of refill by June 1st


Catskill Subsystem

Delaware Subsystem

Figure 8. Baseline and simulated future average number of days per year the Catskill and Delaware subsystems are in watch, warning and emergency drought conditions

On average simulated future conditions may result in a reduction in average number of days per year the system is under Drought Watch, Warning and Emergency (Figure 8) even thought there was high variability between GCM predictions. Also, both the Catskill and Delaware subsystems show an increased probability of refill by June 1st for future scenarios compared to present conditions. This reduction in drought conditions occurrence and increase in probability of refill by June 1st are consistent with an average increase in $Q_{7,10}$ low flow statistic and more water availability during the traditional summer low flow (Figure 7c).

SUMMARY AND CONCLUSIONS

The state of the NYCWSS described by the water balance between streamflow inputs, storage, release, and spill is complex and dependent on various rules and constraints within the system. In OASIS the total daily withdrawal of water from the system must account for NYC demand, all other required releases, and any changes in system storage._The NYC OASIS model was used to model baseline historical and future climate simulated water supply system operation. Changes in snowmelt and runoff timing appear to have an affect of increasing reservoir storage levels, spill and releases during winter and early spring, thereby improving the probability of refill by June 1st and decreasing the number of days the system is likely to be under watch, warning and emergency drought conditions. These positive effects come at the expense of loss in snow water storage that would otherwise persist longer into the year, drain into the reservoirs at a slower rate, and would more likely be stored in the reservoir than lost as spill during winter. In terms of the total winter storage, the loss of snow storage is relatively small, and this loss of spring runoff water is apparently compensated for by projected increases in precipitation.

These results are preliminary because of assumptions concerning EOH and LD inflows and stationary rules and demands. However, they show how the NYCWSS can adjust to changes in climate and how an increase in both temperature and rainfall can result in a reduced risk of drought. Future work will examine whether or not these changes will require changes in reservoir operation policies to optimize use of the NYCWSS under future climate conditions.

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