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Changes in the Timing of Snowmelt and the Seasonality of Nutrient Loading: Can Models Simulate the Impacts on Freshwater Trophic Status?

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ABSTRACT

The New York City water supply region, located in the Catskill Mountains in upstate New York, has always had a historically variable snow cover, with consequent effects on the magnitude of spring runoff and the relative importance of winter vs. spring periods on annual hydrologic and nutrient budgets. Simulations show that under present conditions (1966–2005), on average 38% (12–70%) of the annual total dissolved phosphorus load occurs during winter (November–February) while future predictions (2046–2065 and 2081–2100) show winter nutrient loads may account for an average of 46% (18–73%) of the annual load. It is expected that changes in the timing of nutrient loading will lead to some increase in phytoplankton growth under isothermal conditions prior to the onset of thermal stratification, a reduced bloom coinciding with the onset of thermal stratification, and on an annual basis somewhat lower levels of biomass. However, future climate simulations using two different one dimensional reservoir water quality models show no strong relationship between changes in algal biomass and the proportion of winter nutrient loading. The lack of a winter response calls into question model assumptions concerning the growth potential of phytoplankton under deeply mixed low light conditions, as well as factors influencing the bioavailability of nutrients input during the winter period. This illustrates the pitfalls of simulating future climate conditions,when the seasonality of model drivers has changed and processes regulating winter conditions are not strongly represented.

Keywords: Winter Hydrology, Limnology, Snowmelt, Phytoplankton, Nutrients, Climate Change.

INTRODUCTION

The geographic distribution and quantity of lakes are strongly influenced by glacial processes so that the greatest number of the world's lakes are located in formally glaciated areas, particularly in the Northern Hemisphere in areas such as the Boreal region (Wetzel, 2001; Lehner and Doll, 2004). These northern locations today are ones where snow has an important influence on the annual hydrologic cycle and where the seasonality of the hydrologic and biogeochemical processes regulating nutrient delivery to lakes are influenced by the accumulation and melt of snow. Despite a strong geographic relationship between the distribution of lakes and the occurrence of snow, there is surprisingly little information on the influence of snowmelt hydrology on limnology. One consistent outcome of studies of the effects of climate change on

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watershed hydrology is a pronounced shift in the timing of streamflow due to increased winter air temperature and rain, decreased snow, and earlier snowmelt. Such a shift in the timing of streamflow will lead to a greater proportion of the yearly nutrient load being delivered to a lake or reservoir during cold, deeply mixed, and possibly ice covered conditions that would not be expected to be favorable to phytoplankton growth.

Winter streamflow can provide an important component of the annual water budget in the NYC West of Hudson water supply, and the ability to simulate the effects of changing levels of winter streamflow and nutrient loading on reservoir trophic status could be important for simulating present and future variations in reservoir trophic structure. The sensitivity of the two reservoir eutrophication models used by the New York City Department of Environmental Protection (DEP) to variations in the seasonality of changing winter nutrient loads had not, however, been rigorously tested. During 2012, the DEP water quality modeling group undertook an examination of (1) the importance of winter nutrient loads to the annual nutrient load of Cannonsville Reservoir and (2) the sensitivity of the DEP's reservoir eutrophication models to this variability.

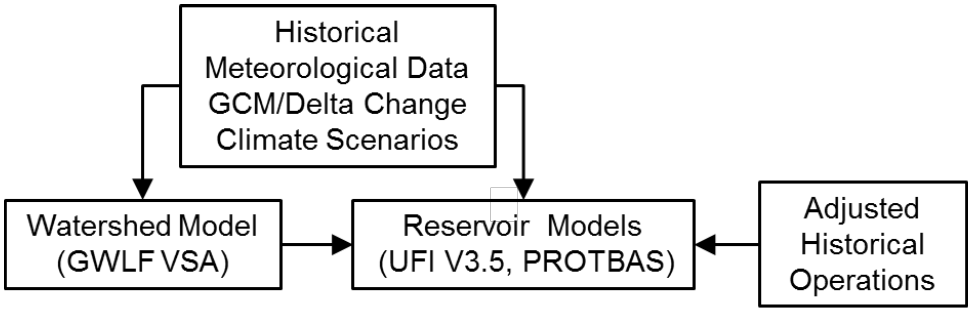

Figure 1. Models and data sources used to simulate changes in reservoir phytoplankton and trophic status. Both watershed and reservoir models are driven by daily changes in meteorological data that are either measured or derived from future climate scenarios. Daily variations in reservoir conditions also depend on reservoir operations, which determine reservoir outflow.

MODELING FRAMEWORK

The models used in this investigation were the GWLF VSA watershed model to simulate reservoir inflow and nutrient load and two versions of a one dimensional reservoir water quality model that focuses on phytoplankton growth and eutrophication (Figure 1). From GWLF VSA, nutrient export is estimated. The timing and magnitude of nutrient loading over any given year varies as a function of the daily variations in air temperature and precipitation that drive the model. Yearly variation in the metrological inputs, therefore, leads to yearly variation in hydrology and nutrient loading, including the proportion of the yearly nutrient load that occurs in the winter. Variations in winter nutrient loads can be examined under contemporary conditions driving the model with measured historical meteorological data or under future conditions by driving the model with air temperature and precipitation data from future climate scenarios. For this study the models shown in Figure 1 were driven using both historical data and future climate scenarios.

The two reservoir water quality models used by DEP are built upon the same one dimensional hydrothermal framework that was developed for DEP by the Upstate Freshwater Institute (Owens, 1998), which simulates the reservoir thermal structure and the rate of inflow, out flow, and vertical exchange between 1 m vertical cells. Both models examined here simulate phytoplankton growth as a function of water temperature, light, and nutrients. The UFI version 3.5 (UFI V3.5) water quality sub-model is based on the model described by Doerr et al. (1998). This model has a single phytoplankton component that has a maximum growth rate that varies as a function of temperature and a single rate of light limited growth that occurs below a fixed light threshold. The second model is based on the PROTECH model as developed by Reynolds et al. (2001), later modified by

Markensten and Pierson (2007), and renamed PROTBAS. In PROTBAS, there are 8 major algal functional groups, each of which has distinct allometric characteristics parameterized by the algal surface area, volume and axial length, characteristics that define need for silica and ability to fix nitrogen, and information related to rates of motility and sinking. When comparing these two models, UFI V3.5 has more detailed and realistic algorithms describing the transformations of nutrients and the effects of nutrient concentration on algal growth, while PROTBAS has a better description of the diversity of phytoplankton and the effects of phytoplankton characteristics on growth.

CLIMATE SCENARIOS

Future Climate Scenarios were based on Global Climate Models (GCM) data obtained from the World Climate Research Program's (WCRP's) Coupled Model Intercomparison Project Phase 3 (CMIP3) multi-model dataset. Daily datasets were downloaded for baseline scenario (20C3M) during the period 1960–2000 and three future emission scenarios (A1B, A2, and B1) during two time periods 2045–2065 and 2081–2100. All data sets were extrapolated to a common model grid; and from these, future climate scenarios were created using a frequency distribution based change factor methodology proposed by Anandhi et al. (2011). For this study, GCM/emission scenarios were chosen that contained all the meteorological variables (air temperature, precipitation, solar radiation, and wind speed) needed to drive both the watershed and reservoir models in the baseline and two future time periods (Table 1).

Table 1. GCM model used to produce future climate scenarios. For each model scenarios were created for three emission scenarios (A1B, A2, and B1) and two future time periods (2045–2065 and 2081–2100)

GCM	Model Name	Source/Country
CCSM3	Community Earth System Model	NCAR/USA
CNRM-CM3	Global Coupled System model Ver 3	CNRM/France
CSIRO-Mk3.0	CSIRO Mark 3	CSIRO/Australia
ECHO-G	ECHAM4 + HOPE-G	Germany/Korea
GFDL-CM2.0	Geophysical Fluid Dynamic Lab CM2	NOAA/USA
MRI CGCM2.3.2	Meterological Reserarch Institute CGCM2.3.2	MRI/Japan

RESULTS AND DISCUSSION

Changes in the seasonality of stream discharge and phosphorus loading, as simulated by GWLF VSA, are illustrated in Figure 2. Increased fall-winter precipitation, lower levels of snow accumulation, and earlier snowmelt all result in increased winter (November–February) streamflow and a somewhat decreased spring (March–April) runoff period. These results are consistent with many other climate change simulations in areas where snow influences the seasonality of streamflow (Barnett et al., 2005) and also with studies of the Catskill region (Burns et al., 2007; Zion et al., 2011) that show a shift in the timing of the spring runoff peak and increased winter levels of streamflow. The Catskill region of New York is an area where not only does the snowpack can play an important role in the yearly hydrologic cycle, but also where the snow accumulation and melt can be highly variable. Consequently, variations in the seasonality of flow, particularly in regards to winter streamflow, are also highly variable; and similar changes in seasonality and variability would also be expected to occur in regards to TDP loading.

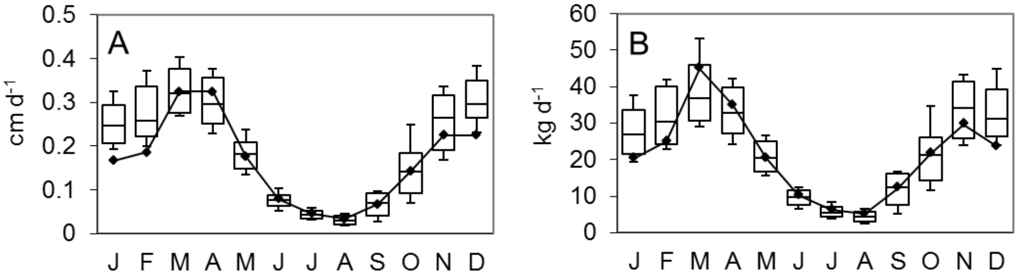

Figure 2. Simulated seasonal variation in streamflow (A) and TDP loading (B) under present and future conditions. The line shows the mean daily values calculated for each month, based on the pooled data from all months in the baseline scenario. Boxplots show the variability in similarly calculated mean values of the 36 future scenarios.

Figure 3 shows the proportion total dissolved phosphorus loading that occur during the winter months (November–February) under present baseline conditions and under future conditions based on data from 36 future scenarios. Even under present conditions, the importance of the winter months in affecting the annual loads is highly variable. Anywhere from 18–63% of the annual streamflow and 12–70% of the annual TDP load can occur in the winter. With increasing winter flows in the future, there is also an increasing contribution of the winter months to the annual load. Median winter streamflow increases from 40% to 48% of the annual load while the median TDP load increases from 38 to 46%. High levels of variability remain in the future simulations, with anywhere from 20 to 72% of the future streamflow and 18 to 73% of the future TDP load occurring in winter.

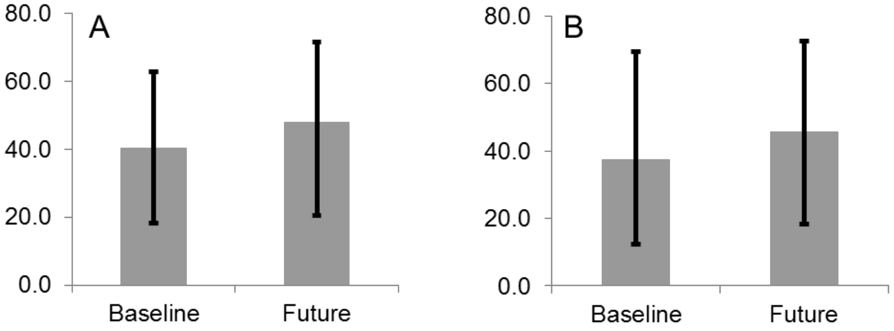

Figure 3. The percentage of the total annual streamflow (A) or TDP load (B) that occurred during the winter months (November–February). Graphs show the median and maximum and minimum of the base line scenario and the combined results of all future scenarios.

Given that phosphorus is the limiting nutrient that regulates phytoplankton biomass in the NYC water supply reservoirs, shifts in the timing of TDP inputs could be expected to impact overall levels of biomass as well as the seasonal patterns of phytoplankton biomass and succession. To examine how climate change will impact reservoir chlorophyll levels, reservoir model simulations were run under baseline conditions and compared to simulations driven by climate scenarios associated with the GCM models in Table 1. The results of these simulations are shown in Figure 4, using both the UFI 3.5 and PROTBAS water quality models.

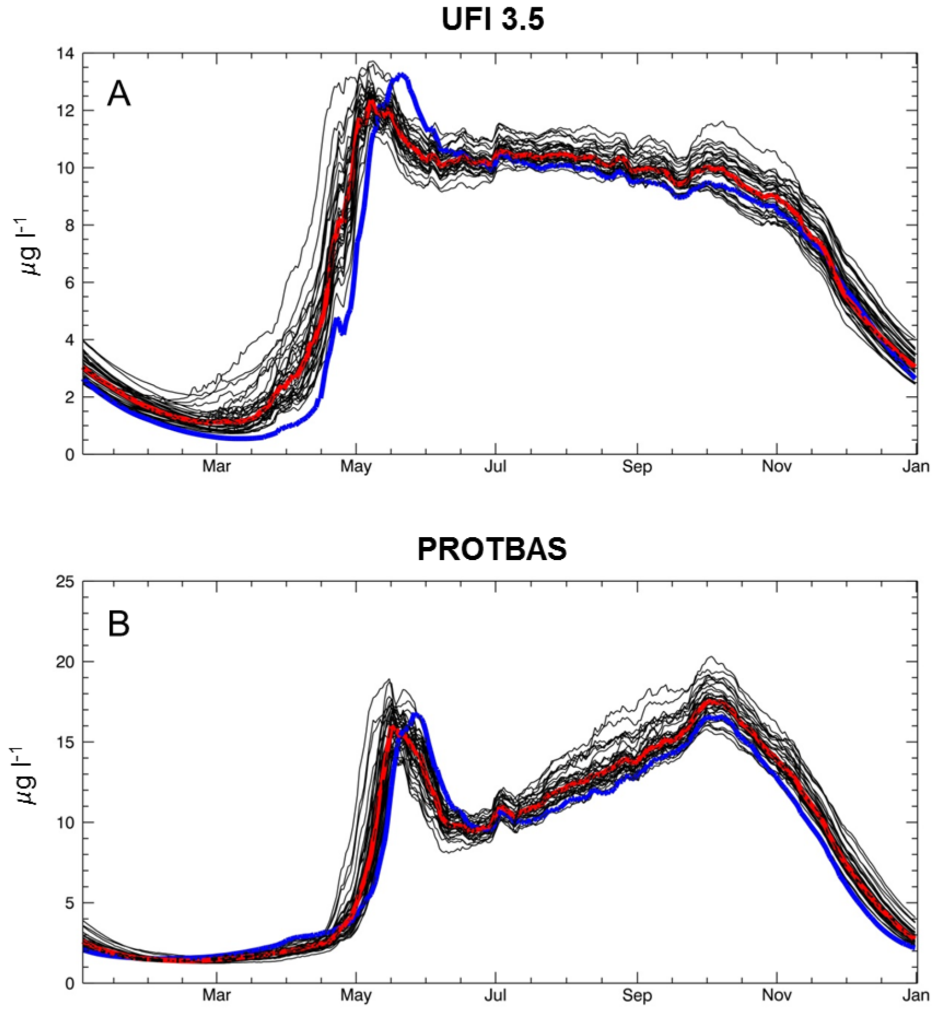

Figure 4. Seasonal variations in mixed layer chlorophyll concentration simulated with the UFI 3.5 and PROTBAS models. Each line is the mean daily value of the data from all years in a given scenario. The blue line is the baseline scenario, black lines are associated with each of the 36 future scenarios, and the red line is the median of the future scenarios.

Both models show moderate 10–15% increases in mixed layer chlorophyll concentrations for some of the future scenarios, and both models also predict that the timing of the spring bloom will move forward by approximately 10–14 days. The somewhat different levels of biomass and different seasonal patterns simulated by the two models are the result of differing assumptions embedding within the two different water quality models. Both models, however, produce credible patterns of phytoplankton succession and levels of biomass. The patterns in Figure 4 are average seasonal patterns, based on multiple simulation years. Between years, there are significant variations in the levels of biomass as well as in the timing and magnitude of the spring peak and fall bloom

We hypothesized that TDP added to the reservoir during winter would be less likely to increase phytoplankton biomass and that a relationship would exist between the proportion of TDP loading that occurred in the winter and the mean annual mixed layer chlorophyll simulated by our models. Years having a relatively high proportion of winter TDP loading are hypothesized to have less annual biomass. In Figure 5, mean annual mixed layer chlorophyll concentration is plotted against the proportion of winter TDP load using data output from both the UFI 3.5 and PROTBAS models. In both cases there is no clear relationship between the average annual chlorophyll concentration and the proportion of winter TDP loading, despite a large range in the proportion of TDP loading that occurs in the winter.

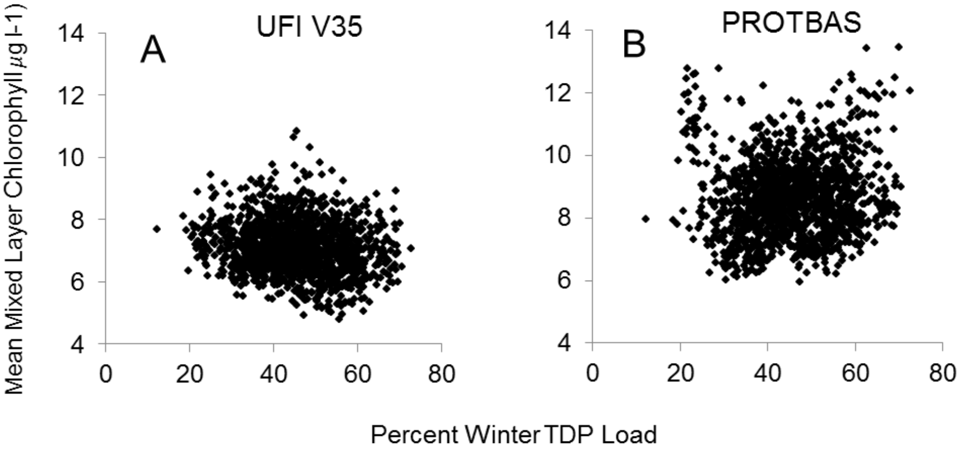

Figure 5. The relationship between mean annual mixed layer chlorophyll concentration and the percent of the annual TDP load that occurs in winter (November–February). Each point is for a single year's data in the baseline and 36 future climate scenarios. The results from UFI V3.5 are shown in A and PROTBAS are shown in B.

In an exercise such as this, it is difficult to determine if our hypothesis fails as a result of an incorrect theory or as a result of the models not correctly representing the lake processes upon which the theory is based. To gain greater insight into model performance, we systematically varied the timing of nutrient input without changing the amount of annual loading or the meteorological forcing affecting the reservoir model. A number of synthetic loading time series were created from the historical reservoir input data by taking 50% of the combined water and material loads from March and April and redistributing these into a different month. In all, five synthetic loading records were created that redistributed the March–April loads into January and February to simulate the expected future shift to earlier winter runoff and also forward in time to May, June, and July to examine differences in response to shifting the loads to stratified as opposed to isothermal conditions. Shifting 50% of the spring nutrient load to January or February (Figure 6A) resulted in virtually no change in the annual pattern of mixed layer chlorophyll or in the magnitude of the chlorophyll concentrations, which is consistent with the lack of relationship in Figure 5. On the other hand, the model predicts significant changes in the timing of peak biomass, as well as levels of biomass (Figure 6B), when the spring nutrient loading is shifted forward into the thermally stratified period. During winter, the average light exposure experienced by the phytoplankton is low as a consequence of deep isothermal mixing, and light exposure is also limited due to lower incident irradiance during the winter months and the presence of lake ice and snow cover. Under such conditions, simulated rates of phytoplankton growth are strongly light limited; and the input of TDP is not utilized and remains biologically available. Following the onset of thermal stratification the mixed layer becomes shallower and the phytoplankton circulating through this mixed layer are exposed to much higher average light intensity. Growth can then proceed until limited by nutrient availability. This is the classic explanation for the timing of the spring bloom (Riley, 1947; Sommer et al., 1986) and its coincidence with the transition from light-limited to nutrient-limited growth. Our models correctly simulate this transition.

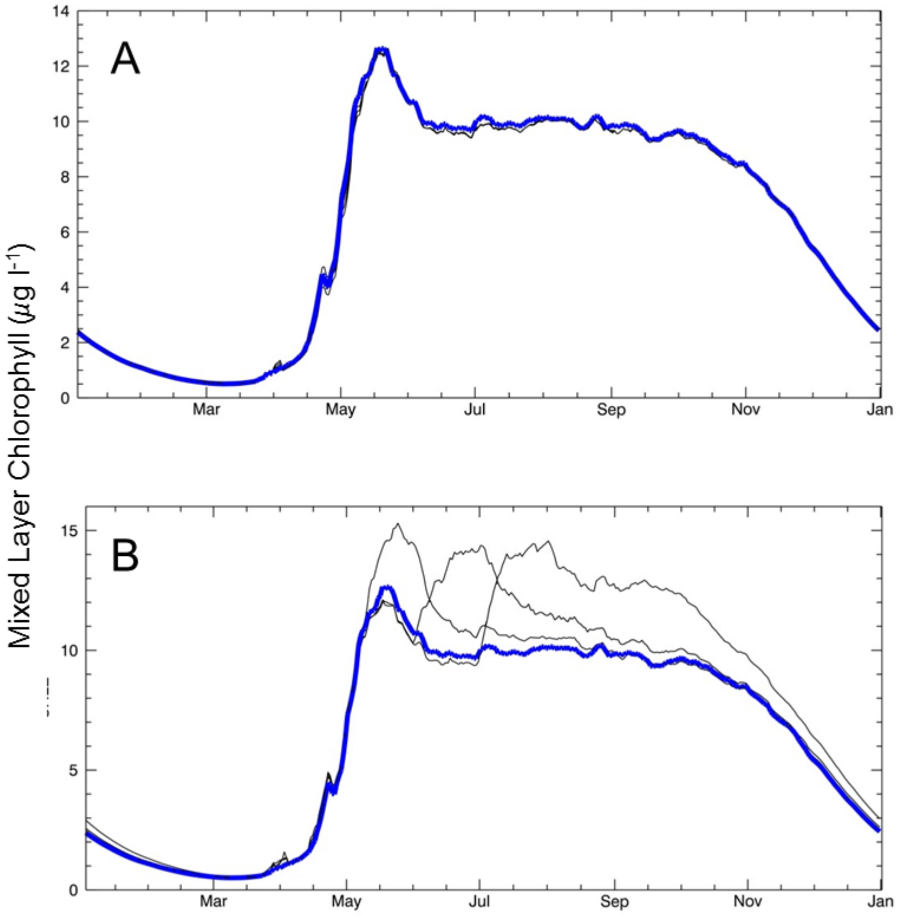

Figure 6. Sensitivity analysis, which examined the effects of shifting 50% of the March +April nutrient load to winter conditions (A. January and February) and summer conditions (B. May, June, and July). Figures show mean daily patterns calculated from the full simulation time period. The thick line shows results under baseline conditions with no redistribution of the nutrient loads. Thin lines show traces associated with redistributed loads. These are results using the UFI V3.5 model. The PROTBAS model showed similar results.

What is less clear is whether the models are correctly simulating the conditions that occur during the winter that affect phytoplankton growth and TDP bioavailability. For the models to be completely insensitive to the timing of TDP inputs during the winter period (Figure 6A) requires that virtually no phytoplankton growth occurs and that no processes impact the bioavailability of TDP inputs during the winter. Both assumptions are not supported by lake studies under winter conditions. There are a number of studies that suggest microbial (Tulonen et al., 1994; Reitner et al., 1997) and phytoplankton (Phillips and Fawley, 2002; Kiili et al., 2009) growth under winter conditions, which would reduce the store of bioavailable TDP prior to the onset of thermal stratification. Furthermore, there are also numerous studies that have reported the phytoplankton blooms occurring under ice cover (e.g., Catalan, 1992; Pettersson et al., 2003; Twiss et al., 2012) or during deeply mixed ice free conditions prior to the onset of thermal stratification (Horn et al., 2011). Correctly simulating these effects would require accurately simulating the onset and loss of lake ice, stratification and mixing under ice, phytoplankton light adaptation to deeply mixed low light conditions, and the effects of microbial activity on phosphorus bioavailability. The lack of sensitivity of our models to the changes in winter nutrient loading should not, however, be seen as a failure of the models since our models were developed to simulate peak phytoplankton concentrations during the period of thermal stratification when drinking water concerns and the effects of watershed management would be most evident. Emphasis was placed on simulating the processes that occur during this period, and model process studies and calibration (Auer and Forrer, 1998; Doerr et al., 1998) were almost entirely focused on the stratified period. As a result, the models do respond as expected when spring nutrient loads are shifted into the summer period (Figure 6B).

CONCLUSIONS

Studies of climate change focused attention on the winter and the effects of processes whose importance are changing as the seasonality of model drivers changes with the climate. This study illustrates the importance of carefully examining model assumptions and testing the sensitivity of models to changes that would be expected as a consequence of future climate change. This study also illustrates the added advantage of testing models beyond the realm of typical concern. Considering the effects of climate change on snow, snowmelt hydrology, and the seasonality of nutrient loading focused our attention on the winter period and illuminated model processes that need further investigation even under contemporary conditions. In the NYC water supply region, snow accumulation and melt are naturally variable so that the proportion of winter nutrient loading is highly variable even today (Figure 3). As a result, the need for studies examining the relative importance of the timing of nutrient loading as well as the magnitude of nutrient loading on the NYC water supply reservoirs has become clear.

This study highlights the challenges and pitfalls associated with simulating the future impacts of climate change using complex ecosystem models. Such models are, by necessity, simplifications of the lake/reservoir system and focus on the processes considered most important for the question/interest at hand. Phytoplankton models, therefore, often focus on processes affecting growth and succession during the period of thermal stratification when biomass is greatest and blooms could become problematic. Climatic impacts affecting winter processes in these models may not be well represented. As model use shifts to simulating expected effects of climate change, impacts need to be clearly articulated and the model structure and algorithms simulating these need to be systematically evaluated.

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