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Earth's Future

Waterborne Virus Transport and Risk Assessment in Lake Geneva Under Climate Change

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Abstract Climate changes influence lake hydrodynamics and radiation levels and thus may affect the fate and transport of waterborne pathogens in lakes. This study examines the impact of climate change on the fate, transport, and associated risks of four waterborne viruses in Lake Geneva. We used a coupled water quality-microbial risk assessment model to estimate virus concentrations and associated risks to recreational water users for each month in 2019 and 2060. Long-term hydrodynamic simulations suggested that although the annual hydrodynamic transport pattern of Lake Geneva will remain relatively stable, a 1.9°C increase of lake surface water temperature can be expected, while a slight decrease in lake current velocity may occur. The subsequent effect on the fate and transport of the four enteric viruses was found to vary by time of year. During warmer periods, the increase of virus inactivation due to higher water temperature and stronger solar radiation at the earth's surface will compensate for the additional virus discharge brought about by population growth over the time period considered, whereas during winter the virus concentration near the lake shore and the associated infection probabilities risks are likely to increase due to population growth. Additionally, the current estimation of virus inactivation rate shows significant variability, which has a more substantial effect on enteric virus concentrations in the lake compared with changing climate parameters. Overall, the study suggests that future risks posed by enteric viruses with recreational water users near popular beaches around Lake Geneva will likely remain similar to current risks and accurate estimation of the environmental inactivation of viruses is crucial for predicting the fate of enteric viruses in the aquatic system.

Plain Language Summary This study investigates the impact of climate change on the fate, transport, and associated risks of four waterborne viruses in Lake Geneva, Switzerland, using a coupled water quality-microbial risk assessment model. The results indicate that the influence of changing environmental conditions on the fate and transport of enteric viruses varies by time of year. Additionally, the current estimation of virus inactivation rate shows significant variability, which has a more substantial effect on enteric virus concentrations in the lake compared with changing climate parameters. Overall, the study suggests that the risks posed by enteric viruses with recreational water users near popular beaches around Lake Geneva in 2060 will likely remain similar to current risks. However, accurate estimation of the environmental inactivation of viruses is crucial for predicting the fate of enteric viruses in aquatic systems in the future.

1. Introduction

Climate change exerts a large influence on global temperature, precipitation, snow melting, drought and extreme weather conditions (Argüeso et al., 2014; Cook et al., 2018; Loarie et al., 2009; O'Gorman, 2015; Qin et al., 2020; Stone et al., 2002). In addition to altering hydrological conditions and global temperatures, climate change will likely also affect other areas of relevance to human well-being, including the transmission of infectious diseases (Mora et al., 2022). Climate change has been found to facilitate vector-borne disease outbreaks like chikungunya and dengue fever (Semenza & Paz, 2021) and it also increased the occurrence of diseases in some natural and agricultural systems (Altizer et al., 2013). Moreover, several studies have explored the association between climate change and water-borne disease, frequently focusing on the impact of weather extremes (Levy et al., 2016; Patz et al., 2008). In contrast, less attention has been paid to climate change-induced shifts in local hydrological and hydrodynamic conditions, which influence the transport of pathogens in the aquatic systems. Similarly, little is known about how shifts in water temperature and local solar irradiance, which are important controls on persistence of pathogens in surface water (Burkhardt et al., 2000), affect pathogen persistence and subsequent infection risks.
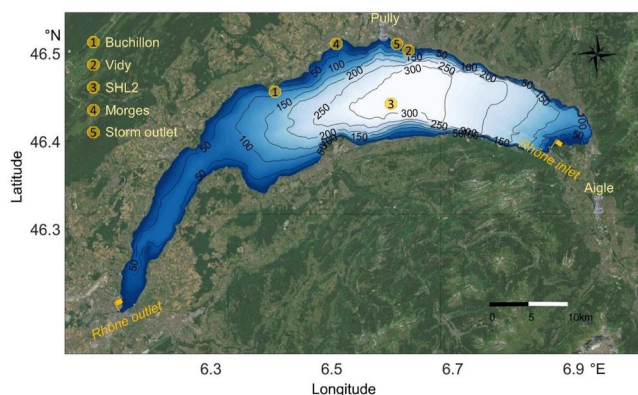
Figure 1. Map of Lake Geneva and the locations of the stormwater outlet as well as the probing sites for hydrodynamics (Vidy, Buchillon and SHL2) and water quality (Morges).

Waterborne viruses are ubiquitous contaminants of recreational water which give rise to illnesses such as gastroenteritis, fever, and pneumonia. Among all the waterborne viruses, several are classified to have a moderate to high health significance, including adenovirus, enterovirus, norovirus and rotavirus (WHO, 2011). Some previous studies have combined water quality simulations with quantitative microbial risk assessment (QMRA) to assess risks posed by waterborne pathogens in varies aquatic systems, such as urban water systems (Sokolova et al., 2015), drinking water distribution system (Blokker et al., 2014), rivers (Schijven et al., 2015), agricultural water system in coastal area (Masciopinto et al., 2020) and estuaries (Foreman et al., 2015). However, most of these studies analyzed past events or simulate scenarios under current conditions while future climate conditions are not taken into consideration. Recently a study by Williamson et al. (2017) simulated the effect of climate change on the inactivation of waterborne viruses in lakes and found that with an increased precipitation that brings more organic matter into lakes, virus inactivation will be weakened due to shielding effect of the organic matter to solar radiation. However, this study did not include risk assessment processes to estimate the influences of such effects on health risks.

In this study, we investigate the effect of climate change on the fate and transport of human waterborne viruses in a large lake, employing the output of a climate change model (National Centre for Climate Services, 2018) and combining water quality simulations and QMRA methods (Li et al., 2023). We investigate how future climate and resulting hydrodynamic conditions will affect the fate and transport of waterborne viruses in Lake Geneva, Switzerland. We first determine the hydrodynamic conditions (water age, flow velocity and water temperature) in the year of 2060 to those in the reference year 2019. We then determine the resulting effects on fate and transport of four enteric viruses: adenovirus, enterovirus, norovirus and rotavirus and evaluate the health risks posed to swimmers by these viruses using QMRA.

2. Material and Methods

2.1. Study Site

The study site is Lake Geneva, which is located on the border of Switzerland and France and has a surface area of 580 km^2 and volume of 89 km^3. As an important drinking water source and receiving water body, it is currently used by more than 800,000 inhabitants around it. A storm outlet near the Vidy bay was used as a major point source for virus release in this study. Three hydrodynamic probing points, the Buchillon station, the Vidy station and the SHL2 station were selected to store the surface water temperature and velocity data for both year 2019 and year 2060, to investigate the change of water temperature and velocity due to variations in driving forces over the four decades, while Morges beach was chosen as the probing site for water quality with respect to virus concentration and risk assessment for swimmers. The locations of the storm outlet and the probing sites are depicted in Figure 1.

2.2. Hydrodynamic Modeling

Hydrodynamic simulations were carried out using Delft3D, an open source three-dimensional (3D) hydrodynamic and water quality simulation software (https://oss.deltares.nl/web/delft3d), to perform numerical simulations in the shore–region of Lake Geneva. Both the hydrodynamic flow and the water quality modules were used. The flow model in Delft3D solves the shallow water equations as well as the transport equations in 3D (Deltares, 2015), while the water quality module computes solute transport under a Eulerian framework, directly coupled to the hydrodynamic module. The hydrodynamic model had 100 layers in the vertical direction using the Z-layer gridding system, a horizontal grid resolution of around 400 m and a time step of 1 min, and was fully calibrated and validated for the year 2019 (Baracchini, Hummel, et al., 2020). We employed the results of the hydrodynamic model as our initial condition for velocity and temperature field, which are accessible through an online simulation platform for Lake Geneva (http://meteolakes.ch/; Baracchini, Wüest, & Bouffard, 2020). Meteorological conditions such as wind direction, solar radiation, humidity and temperature were included as

Table 1
Beta Values in Equation 1 and Their Standard Errors Taken From Boehm et al. (2019)

Virus type	$\beta_0 \pm$ SE	$\beta_{tem} \pm$ SE	β_{solar} (surface) $\pm$ SE
Adenovirus	−1.20 ± 0.18	0.07 ± 0.01	0.13 ± 0.26
Enterovirus	−0.25 ± 0.04	0.03 ± 0.004	1.07 ± 0.11
Norovirus	−1.08 ± 0.22	0.04 ± 0.01	0.43 ± 0.49
Rotavirus	−0.60 ± 0.09	0.04 ± 0.01	0.51 ± 0.32

driving forces and the gridded data were obtained from the Cosmo model from MeteoSwiss (https://www.meteoswiss.admin.ch/). The ocean heat flux model was used and a spatially varying wind field was imposed. Cyclic scheme was applied for advection of momentum while transport was solved by the van Leer-2 scheme. The water quality model based on a Lagrangian framework was validated in a previous study (Li et al., 2022). Here, we used the equivalent water quality model but in a Eulerian framework. For the years after 2019, the driving forces were created based on the climate change model used in the CH2018 climate scenarios study (National Centre for Climate Services, 2018). The CH2018 study is dedicated to the simulation of future climate conditions for Switzerland up to the middle of this century and beyond. It forms an important working basis for the government's adaptation strategy allowing them to make well-founded decisions while at the same time indicating the potential ways in which we can protect the climate effectively. The simulation results are based on aggregation of 21 different computer models run at European research institutions, allowing the uncertainties associated with the different climate scenarios to be estimated. The CH2018 study has predicted dry summers, heavier precipitation, more hot days and snow-scarce winters in the future.

In this study, we employed the simulation results from the CH2018 study up to the year 2060. Air temperature and wind condition data from 2020 to 2060 were employed to simulate future hydrodynamic conditions in Lake Geneva. Gridded air temperature data was provided in the CH2018 study; however, only stationed wind condition data was provided. Therefore, the wind field over Lake Geneva was set based on the ratio of the different values between the Pully station data from 2020 to 2060 and in 2019 (Figure 1), and then proportionally interpolated to the whole lake region, using the wind condition in 2019 as a background condition. Solar irradiance is another important factor influencing the hydrodynamics of lakes. Interestingly, the simulated radiation values in Lake Geneva region show a decreasing trend with time, whereas the observation data from MeteoSwiss at the station near the Aigle, ∼10 km away from Lake Geneva (Figure 1), showed an opposite trend (Figure S1 in Supporting Information S1). We therefore estimated solar irradiance for future scenario simulations based on a linear extrapolation of the observation data.

2.3. Virus Inactivation Modeling

Virus inactivation of the four enteric viruses of concern was modeled using the water quality module of Delft3D, directly coupled to the hydrodynamic module from Meteolakes. Each virus species was regarded as a degradable tracer in this module. The transport of viruses was passive and governed by the flow of the hydrodynamic module, whereas the inactivation of each viral species was modeled as a function of water temperature and solar radiation. To account for the spatial and temporal changes in these two variables, water temperature was simulated for the year 2060, while the solar radiation level was extrapolated based on the observations as described above. For calculating the cell specific virus inactivation rate, we followed the linear formula proposed by Boehm et al. (2019):

$$log_{10} \, k = \beta_0 + \sum_{i=1}^{n} \beta_i x_i + \varepsilon \tag{1}$$

where k is the first-order inactivation rate constant (day^{-1}) for a given viral species, β_0 represents the model estimate for background inactivation under reference conditions (in darkness at 15°C), β_i represents the coefficient for each of the model variables x_i (temperature ($T - 15$°C) and irradiance (I)) and ε is a Gaussian white noise term representing the error. Beta coefficients of background (β_0), temperature (β_{tem}) and solar radiation (β_{solar}) as well as the standard errors (SE) of the beta values are summarized in Table 1.

Mean inactivation rate constant for each virus was calculated using the mean values of each coefficient proposed in the linear formula in Boehm et al. (2019) for a standard simulation scenario. In addition, we assessed how variability in inactivation affects simulation outcomes. To this end, a maximum k and a minimum k were considered for each virus, by adding 2*standard errors or subtracting 2*standard errors to the mean value of each coefficient, respectively. Table S1 in Supporting Information S1 summarizes the major variables used in the simulations for both 2019 and 2060.

2.4. QMRA

The concentration of the enteric viruses released at the storm outlet was based on measurements in the influent of the Lausanne wastewater treatment plant (WWTP) reported in Li et al. (2023). Once the virus concentration at the Morges beach was computed using the hydrodynamic–water quality model, the result was used as an input for the QMRA process and the final risks posed to recreational water users (swimmers) were evaluated (Fewtrell, 2013). The calculated infection risks included a dose harmonization, to convert the virus concentrations in sewage measured in units of genome copies (GC/ml) to infectious concentrations, as described in Li et al. (2023).

The procedures for the QMRA were similar as that described in Li et al. (2023) yet some changes were made. Specifically, the intake volume was set to be 16 ml according to Dufour et al. (2006) as opposed to the previously used 100 mL, to avoid risk overestimation. Furthermore, we considered the variability in the inactivation rate constant k but omitted those associated with water intake volumes and dose-response modeling. This choice is based on the fact that dose-response modeling was found to be insensitive to the risk assessment (Viau et al., 2011), and uncertainties related to intake volume were not expected to affect the relative risk between different years and different viruses.

2.5. Comparison of Hydrodynamics and Virus Fate in 2019 and 2060

To assess the impact of climate change on hydrodynamic transport as well as the fate of waterborne viruses, several case studies were carried out for both year 2019 and year 2060. The water age is one of the features that reveals the general transport dynamic of currents in Lake Geneva and was thus chosen as one indicator for the comparison of the hydrodynamic transport in Lake Geneva and was calculated according to (de Brye et al., 2013). To this end, a year-long continuous discharge was applied at the Vidy stormwater outlet to calculate the water age distribution of Lake Geneva over one year, for both 2019 and 2060.

Apart from the large-scale spatial information, point probing values were also computed and analyzed. Three probing points, the Buchillon station, the Vidy station and the SHL2 station (Figure 1) were selected to store the surface water temperature and velocity data for both year 2019 and year 2060, to investigate the change of water temperature and velocity due to variations in driving forces over the four decades.

Finally, the fate and transport of waterborne viruses in Lake Geneva in year 2019 and year 2060 were analyzed. The virus fate and transport studies were simulated for each month in year 2019 and 2060. For each simulation, we assumed a hypothetical scenario of heavy rainfall, which leads to a continuous discharge of combined sewer overflow into the lake surface at the Vidy stormwater outlet over the first 4 days of the simulation period, followed by a period without combined sewer overflow for the remainder of the simulation. For the year 2060, the virus load discharged into the lake was increased by 28% compared to 2019, to account for the increase in population in Lausanne (https://www.bfs.admin.ch/bfs/en/home/statistics/population/population-projections/national-projections.html) anticipated for Switzerland in 2060. Note that we did not consider secondary effects of the population increase on viral shedding, such as enhanced virus transmission in a larger population.

3. Data

The hydrodynamic model employs the results of Meteolakes platform as our initial condition for velocity and temperature field. Meteorological condition data are obtained from MeteoSwiss whereas the results of the CH2018 study were used for simulations till 2060. Virus concentrations were taken from Li et al. (2023). Virus inactivation data were obtained from the earlier publication of Boehm et al. (2019).

4. Results

4.1. Hydrodynamics in 2019 and 2060

Water age in year 2019 and year 2060, as well as the difference in the water age between the 2 years are computed and illustrated in Figure 2. The water age distribution in Lake Geneva was mostly similar in both years, with an aged region near Geneva and a younger region near the Rhône River inlet. The youngest zone lies to the west of the discharge site while the water age near Geneva is the oldest. From the differential heat map (Figure 2c) it can be seen that there would be an increase in water age of around 30 days in the open water area of the lake, whereas
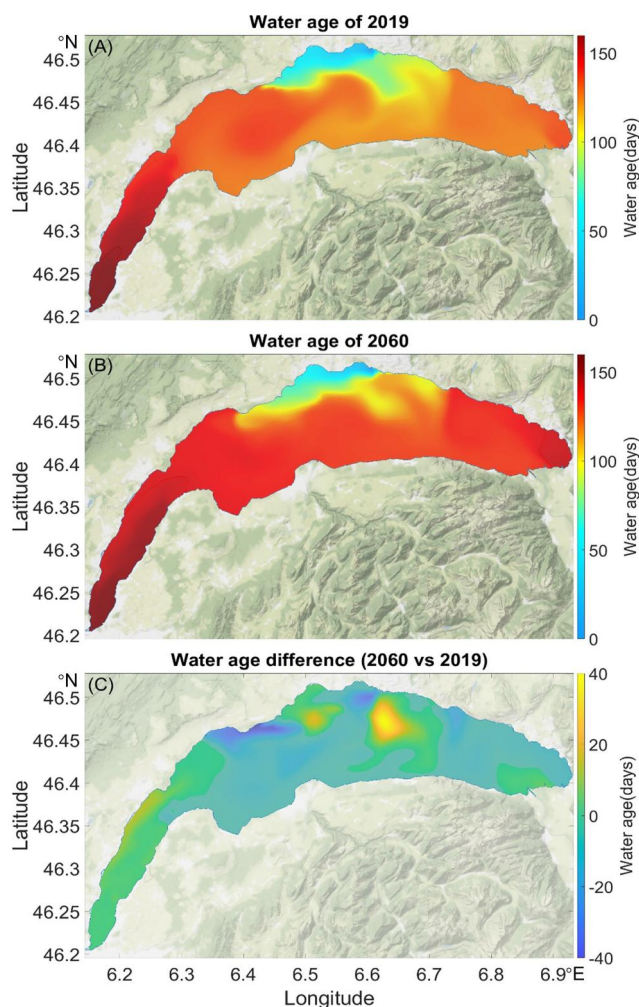
Figure 2. Modeled water age of Lake Geneva in (a) year 2019 and (b) year 2060 and the difference in water age between the 2 years (c).

that near the north shore of Lake Geneva may decrease by 25%. For the region of the beach of Morges, the change in water age was less than 3%.

The simulated surface water temperatures and velocities in years 2019 and 2060 for three virtual probing sites - Buchillon, Vidy, and SHL2, are depicted in Figure 3 and the annual mean values are summarized in Table S2 of Supporting Information S1. The mean water temperature difference calculated over the three sites between 2019 and 2060 was 1.9°C, while the mean difference in velocity was approximately 0.01 m/s. Simulated water temperature and surface water velocities at the three sites were similar. The change of water temperature amounts to around 15% of the annual mean temperature while the change of velocity was less than 8% of the annual mean. The largest water temperature difference from 2019 to 2060 was observed in spring and early summer, while the temperature changes in midsummer and winter were less pronounced.

4.2. Fate and Transport of Waterborne Viruses and the Associated Risks in 2019 and 2060

The fate and transport of the four enteric viruses of concern in this study were analyzed for each month in 2019 and 2060. Figure 4 illustrates the infectious virus concentration of each month in 2019 and in 2060. A corresponding illustration on a log-scale, is given in Figure S3 of Supporting Information S1 to visualize the lower virus concentrations of selected months. Furthermore, Figure 5 shows the relative change in the peak virus concentrations from 2019 to 2016, and the simulated peak and final nearshore virus concentrations at the end of each simulation period are listed in Tables S3 and S4 of Supporting Information S1. Norovirus had much higher concentration than the other three viruses in summer, whereas both rotavirus and norovirus were estimated to have high concentrations in winter. The model predicted an increase in the peak nearshore virus concentrations in 2060 during the colder months (January, February, March, April, and December; Figures 4 and 5), whereas during the warmer months (May–September) the virus concentrations remained similar or decreased between 2019 and 2060. Specifically, virus concentrations increased by at least 22% in the colder months, but decreased by > 40% in June, July and August. Notably, the decrease was virus-specific, with adenovirus and norovirus decreasing to a lesser extent than enterovirus and rotavirus. In several months (March, April and November), the hydrodynamic transport greatly differed between 2019 and 2060, leading to distinct virus concentration curves. In October and November, on average, the nearshore virus concentration for all four viruses were low.

The potential infection risks to recreational water users (swimmers) posed by these viruses in 2019 and 2060 are illustrated in Figure 6, while the different maximum risk values are summarized in Table S5 of Supporting Information S1. The risks were always highest for norovirus, even in the months when rotavirus had similar or higher concentrations (e.g., January, February; Figure 4). The difference in infection risks between 2019 and 2060 was generally within one order of magnitude for all viruses at most simulation periods, except for adenovirus and rotavirus at the end of August, for which the infection risk decreased by a factor of 10 or more. The change of peak risks in between the years differed between viruses. For example, in February, peak risk for rotavirus increased by 33% while that for norovirus increased by only 5%.

4.3. Individual Contributions of Hydrodynamic Transport and Environmental Stressors to the Fate of Norovirus at Present and in the Future

To unravel the main drivers of the observed virus concentration differences, the impacts of hydrodynamic transport (HD in Figure 7) and environmental stressors (ES in Figure 7) were separately investigated by either including or omitting virus inactivation by environmental stressors in the simulation (Figure 7). This analysis
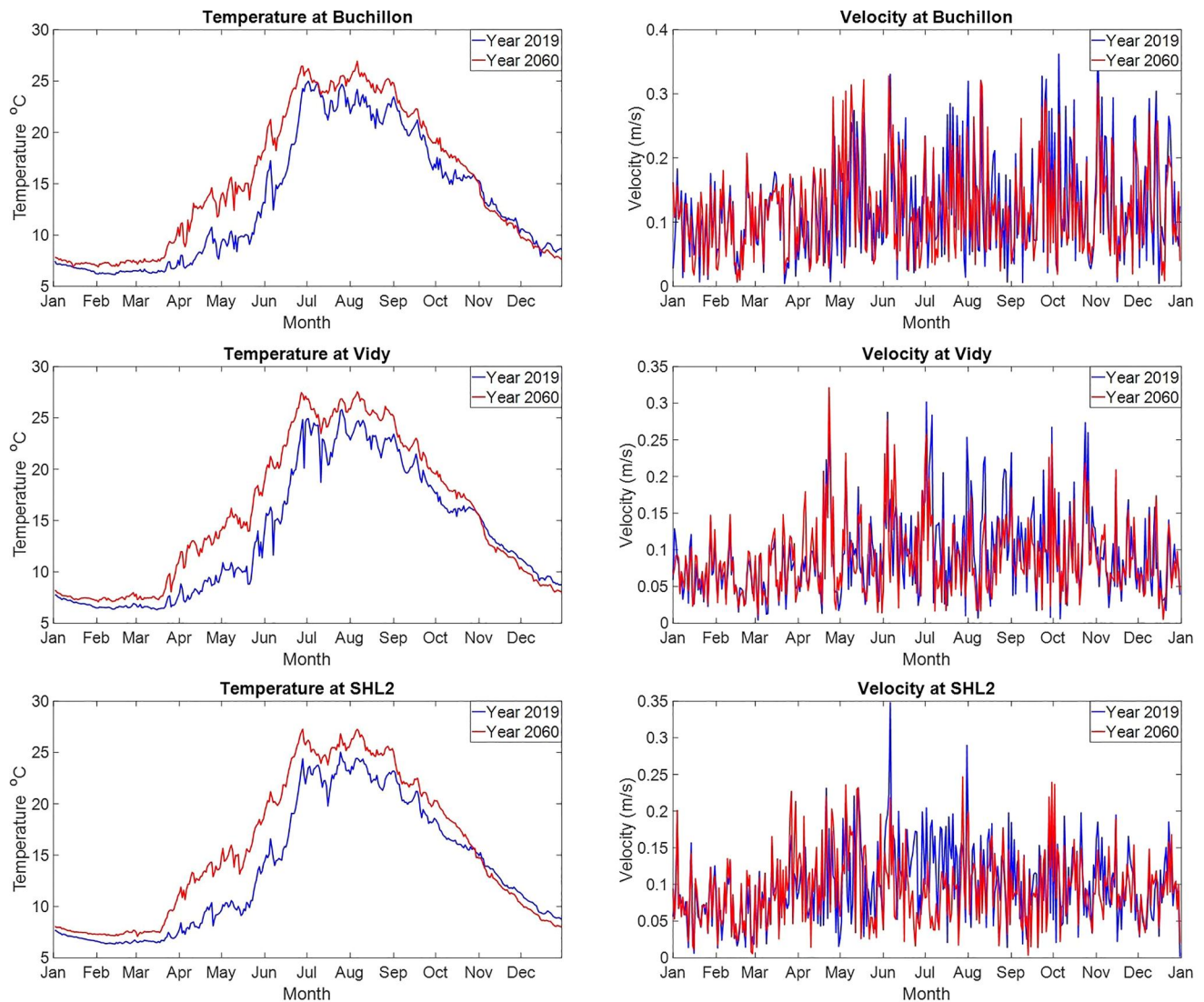
Figure 3. Simulated water temperature and velocity in 2019 and 2060 for the three probing stations (Buchillon, Vidy, and SHL2).

was performed for a subset of 4 months (February, May, August and November) to capture varying environmental conditions. We furthermore focused on norovirus, as it exerts the highest infection probabilities among the viruses studied (Figure 6). Differences in norovirus concentrations in early November 2019 and 2060 clearly stemmed from differences in hydrodynamic transport (blue lines in Figure 7), whereas for other months the HD conditions were similar. As expected, the contribution of environmental stressors to the reduction of the infectious virus concentrations was the largest in the warmest month (August) and the lower in the coldest month (February), for both years considered. The most significant effect of environmental stressors can be seen in August, when high water temperature and solar irradiance in 2019 caused a 45% reduction in the peak norovirus concentration compared to the concentration expected based on virus transport alone. In August 2060, climate change enhanced the effects of environmental stressors, resulting in a reduction in the peak concentration by 60% compared to virus transport only. A similar increase in the effect of environmental stressors due to climate change can be seen in May, when they reduced peak norovirus concentrations by 18% in 2019 and by 27% in 2060. In both February and November, the contributions of environmental stressors remained low even if accounting for the effects of climate change, with reductions in peak concentrations in 2060 of 12% and 17%, respectively.
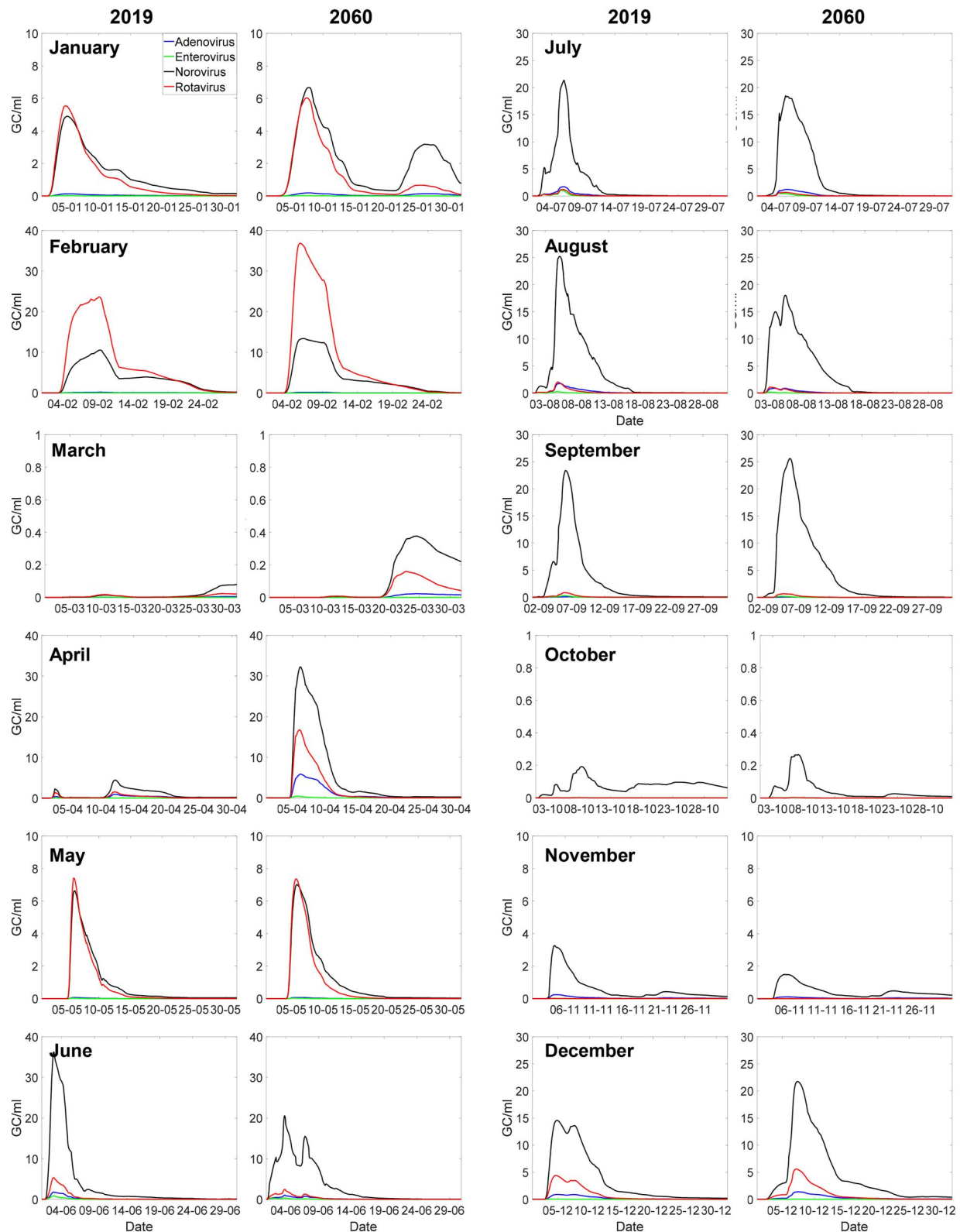
Figure 4. Nearshore virus concentration of each month in 2019 and 2060. Virus concentrations are expressed in genome copies (GC)/ml. For simplicity, the effects of virus inactivation are represented as a reduction in GC, even though inactivation by environmental stressors do not necessarily cause genome degradation.
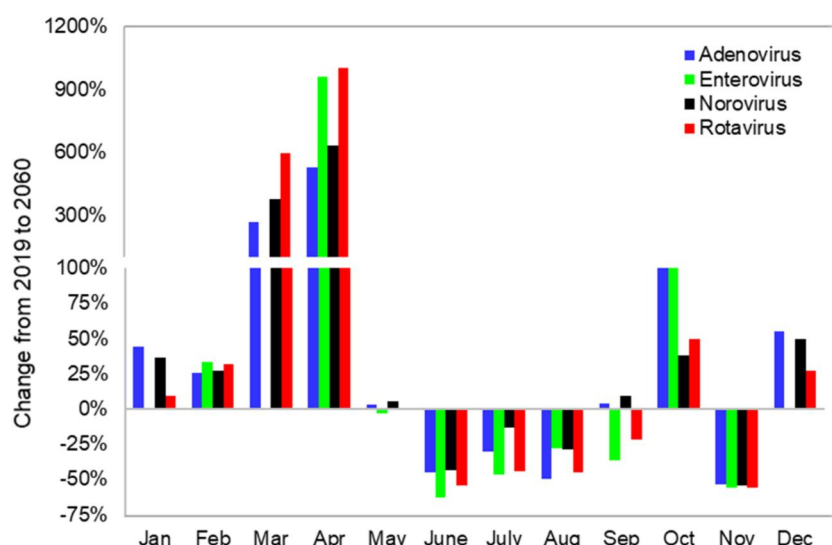
Figure 5. Percent change in the peak nearshore virus concentrations of each month between 2019 and 2060. Values below 0% indicate a reduction in the virus concentration in 2060; values above 0% indicate an increase.

4.4. Influence of Variabilities in the Inactivation Rate Constants

Given that the contribution of environmental stressors to infectious virus reduction is the largest in summer (Figure 7), we assessed how uncertainty in the associated inactivation rate constants affects virus fate in August 2019 and 2060. The nearshore virus concentration as well as the associated risks of each type of virus under different inactivation rate scenarios for year 2019 are demonstrated in Figure 8, while the concentration and associated risk of norovirus under different inactivation rate scenarios for year 2060 are depicted in Figure 9. Norovirus was chosen as the representative virus as on average it poses the highest risk among all the viruses studied.

It can be noted in Figure 8 that the inclusion of the variabilities of the k values in the simulation can dramatically change the nearshore concentration and hence the risks posed by some of the viruses in 2019. For example, when a maximum inactivation rate was assumed for norovirus, the peak virus concentration was 10 times lower and the infection risk at the last time step was more than three magnitudes lower than the case where a mean inactivation rate was applied. If the minimal k was applied, both norovirus concentration and infection risk only deviated minimally from the scenario where only hydrodynamics were considered. Similar findings were also made for adenovirus and rotavirus. In contrast, for enterovirus, the inclusion of environmental decay always dramatically reduced the nearshore concentrations and resulting infection risks, even if a minimum k was applied. Specifically, the infection risk for enterovirus at the last time step of the simulation using the minimal k is still more than five orders of magnitude lower compared to the simulation based on hydrodynamics alone.

Finally, the variability in k had a comparable effect on virus peak concentrations and infection risks in 2019 and in 2060. As seen for the example of norovirus (Figures 8 and 9), the peak concentrations and infection risks in both years are well within one order of magnitude.

5. Discussion

In this study, the impact of climate and global change on the hydrodynamics and fate and transport of waterborne viruses in a large lake was investigated. Simulations indicated that the hydrodynamic flow conditions would be similar in 2060 as compared with those in 2019 while the influence of climate and population increase on waterborne transport and risk assessment depends on the time of year. Variabilities in virus inactivation rate constants were shown to have essential importance in the accurate estimation on virus persistence in lakes and thus the associated health risks to recreational water users.
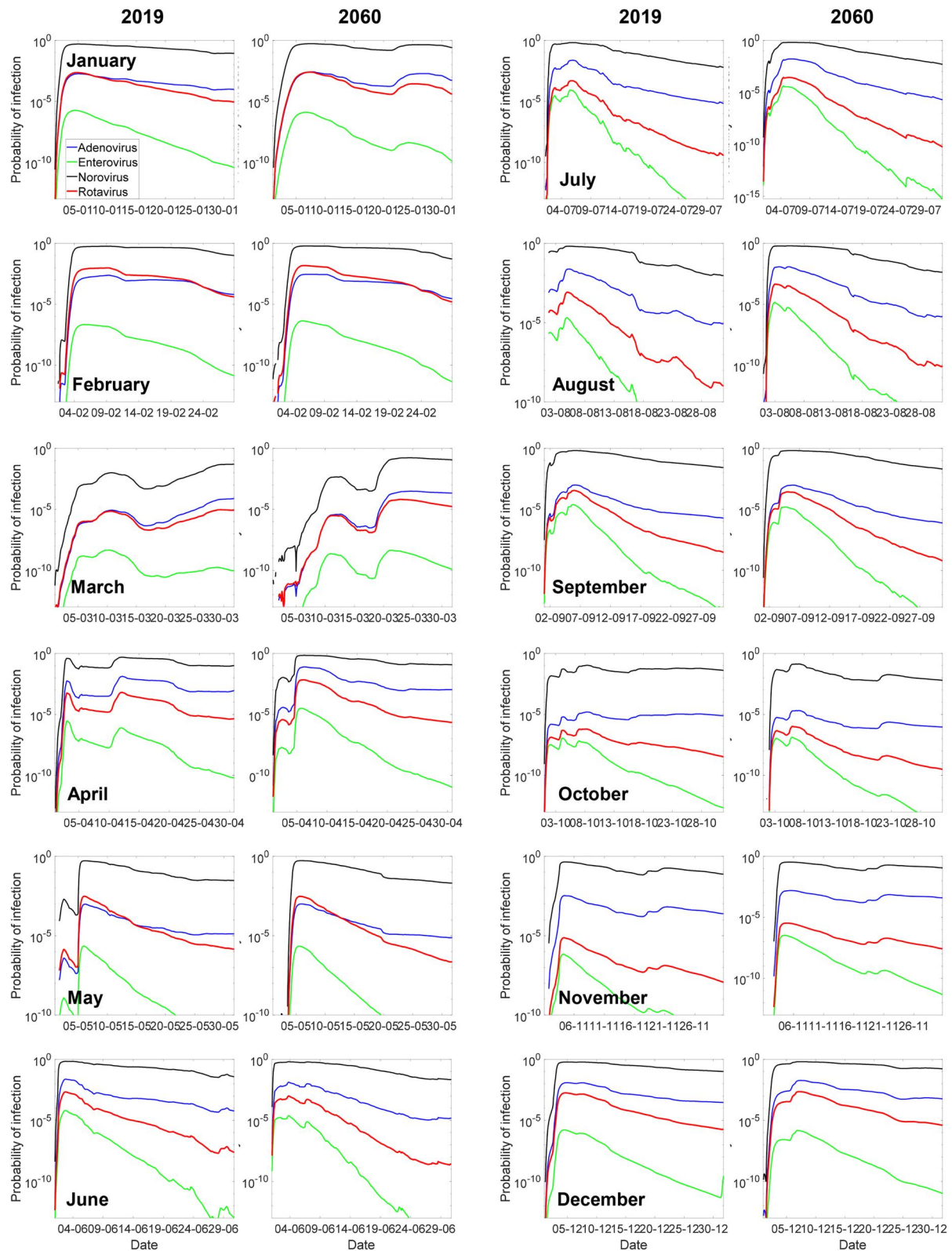
Figure 6. Infection risks of the four enteric viruses of each month in 2019 and 2060.
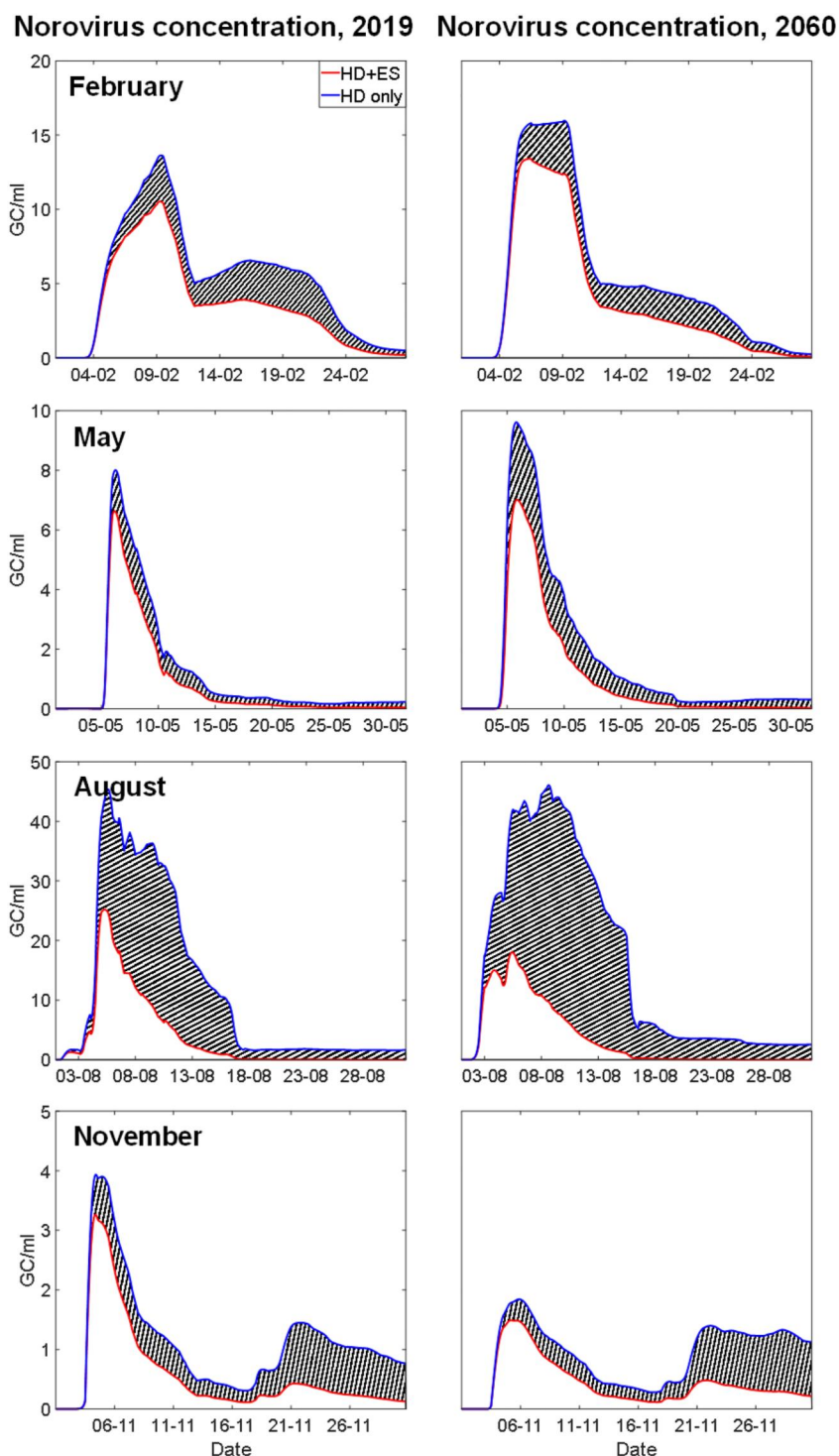
Figure 7. Concentration of norovirus under the influence of both hydrodynamic transport and environmental stressors (red line) and the contribution due to hydrodynamics only (blue line) for year 2019 and 2060. The shadow area indicates the reduction in virus concentration due to environmental stressors, compared to hydrodynamics alone.

5.1. Flow Conditions Are Similar in 2019 and 2060 While Temperature Undergoes Noticeable Change

The annual water age map as shown in Figure 2 indicates similar patterns in the flow condition in Lake Geneva in 2019 and 2060. The youngest zone lies to the west of the discharge site, suggesting that the current near the north
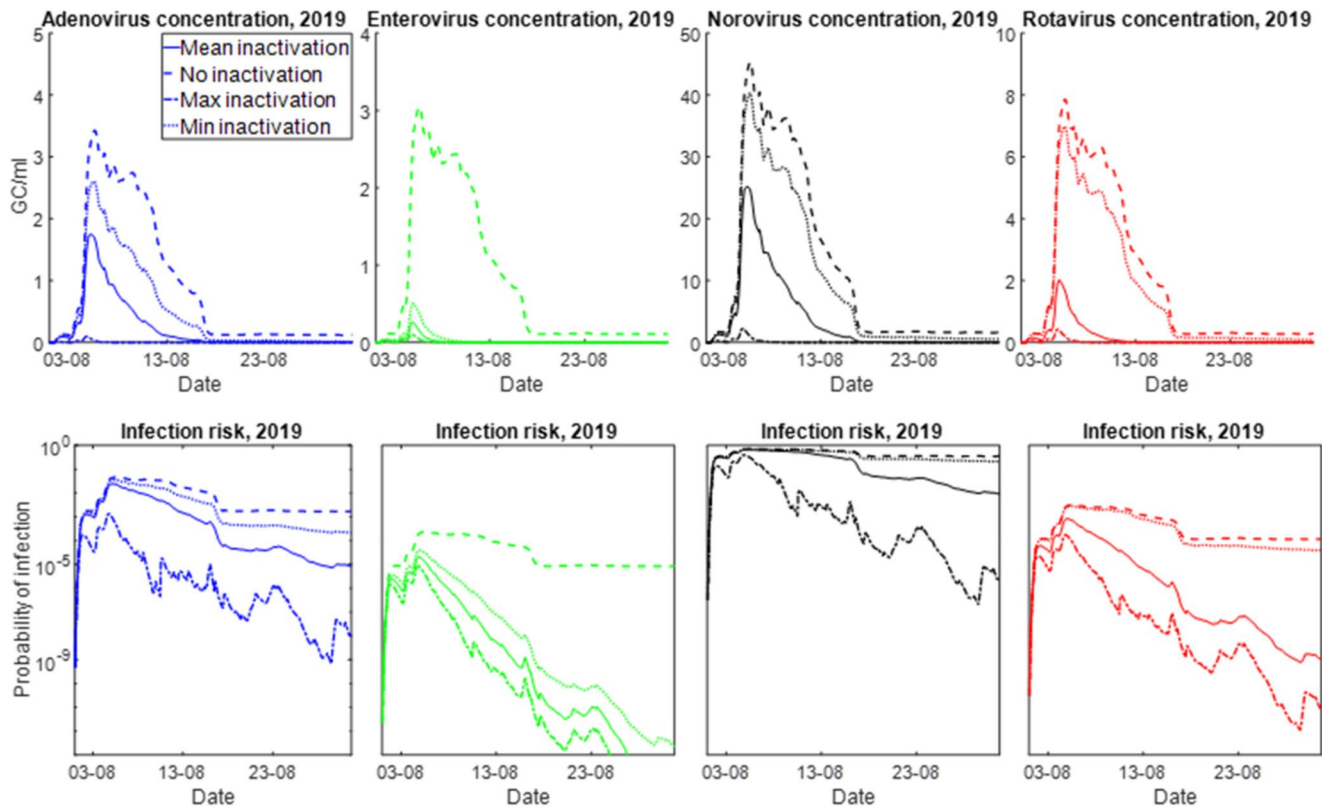
Figure 8. Nearshore virus concentration and the associated risks for the four types of enteric viruses in concern for year 2019 under different inactivation rate scenarios: mean inactivation (solid line), no inactivation (dashed line), maximum inactivation (dashed and dot line) and minimum inactivation (dotted line).

shore of Lake Geneva flows westwards, which inherits the inertia from the Rhône River. The water age near the city of Geneva is much greater than the water age in the open water area of the lake. This could be explained by the fact that the currents are likely to be trapped by a gyre before entering the "Petit Lac" of Lake Geneva, a phenomenon discovered by Lemmin and D'Adamo (1997). As a result of the westward movement of the major
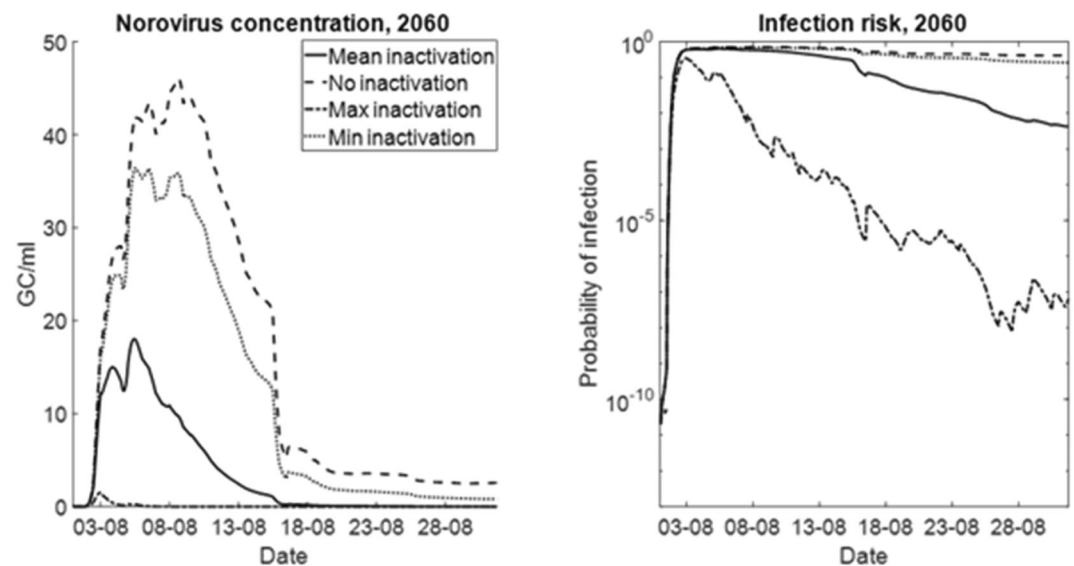

Figure 9. Nearshore virus concentration and the associated risks for norovirus for year 2060 under different inactivation rate scenarios: mean inactivation (solid line), no inactivation (dashed line), maximum inactivation (dashed and dot line) and minimum inactivation (dotted line).

currents in Lake Geneva, for both years, the water age near the outlet of the Rhône River would be around 50 days older than that near the inlet of the Rhône River, even though the distances from the releasing source to the two boundaries are close. The major increase in water age will occur in the open water area in Lake Geneva where large gyres may trap the water parcels for a longer period of time, as described by Bauer and Graf (1979). However, for the beach of Morges, the difference in water age between the years was minor, thus the hydrodynamic transport conditions of the current condition and the future condition will likely remain similar in the region of interest in this study.

When it comes to the flow velocity and the surface temperature of the Lake at the three probing sites, little spatial variation was observed. All stations indicated analogous results that the temperature would increase by around 1.9°C while the flow velocity would decrease by about 0.01 m/s, from 2019 to 2060. The simulated results are comparable to the climate change simulations performed by Desgué-itier et al. (2023), who also found that an increase of around 2°C for surface water temperature in Lake Geneva can be anticipated for year 2060 under RCP8.5 climate conditions. This scenario assumed that the current greenhouse emission situation will remain and no significant measures are taken to alleviate climate change, which has been a typical scenario to consider for the simulations till the middle of the 21st century. In the intermediate case of RCP7, the lake surface temperature was estimated to increase by around 1.7°C, whereas in the most sustainable case of RCP2.6, only a 1.2°C of increase in surface water temperature was predicted. These two latter scenarios are more suited for longer term simulations, such as cases from 2070 to 2100. Seasonal patterns of temperature change could be observed in all three stations that the major increase of water temperature occurred in spring and early summer between year 2060 and 2019, while the difference of surface water temperature in mid-summer and winter was less significant. This seasonal pattern is consistent with observations in Hondzo and Stefan (1993) who found that the largest differences in water temperatures occurred in April under climate change in lakes in Minnesota, USA.

5.2. Climate Change-Induced Shifts in the Fate and Transport of Waterborne Viruses Vary by Season

The monthly simulation results for the present conditions and the future scenarios revealed that the effects of climate change on the fate of viruses in Lake Geneva differs between warm and cold seasons. This is evident from a simple comparison of the predicted increase in virus shedding by 2060, and the resulting virus concentrations in the lake. Specifically, we here assumed that the 28% percent population growth estimated for 2060 will lead to a proportional increase in viruses discharged into the lake. If the hydrodynamics and the inactivation of viruses in the lake remain unchanged, a corresponding increase in lake virus concentrations would be expected. The simulation results demonstrate that such an increase in virus concentration was indeed observed in the winter (December to February), when the peak concentrations averaged over all viruses surged by 22%–33% in 2060 as compared with 2019 (Figures 4 and 5). This implies that the effects of climate change on hydrodynamic conditions as well as virus inactivation in winter are negligible, and the virus concentrations predicted for the Morges beach are a direct result of enhanced virus discharge due to population growth. This finding is not surprising, as our results show that the contribution of environmental stressors to virus decay in the winter is small in both 2019 and 2060 (Figure 7), a finding consistent with our previous work demonstrating a subordinate effect of environmental stressors in the winter (Li et al., 2023). This can be rationalized by the small change in surface water temperature in winter between 2019 and 2060 (Figure 3), and the low solar irradiance in winter (Figure S2 in Supporting Information S1), leading to low thermal and solar inactivation rates, independent of the year.

The simulated changes in peak virus concentrations in winter between 2019 and 2060 also affected the resulting infections risks (Figure 6). Among the four viruses studied, the most noticeable increase in peak concentration in was observed for adenovirus (55%) and norovirus (49%) in December. Notably, the infection risk for norovirus was always higher than that for rotavirus even though the nearshore virus concentration of rotavirus similar to (January) or was twice as large as (February) the norovirus concentration. This is because the probability of norovirus infection increases more rapidly with dose than rotavirus, such that even a very low norovirus concentration can result in illness (Haas et al., 2014; Teunis et al., 2020). For example, while the increase in peak risk for rotavirus in February was 33% and thus almost proportional to the increase in concentration, the increase in peak risk for norovirus was much lower (5%). This also stems from the difference in the dose-response curves, as discussed in Li et al. (2023): for rotavirus, the second order derivative of the dose-response curve is close to 0, thus the risk will change linearly with the concentration. However, for norovirus, at a genome copy number of around 200 (nearshore concentration in February (13 GC/ml) × ingestion volume (16 ml)), the second order derivative of the dose-response curve is well below 0, thus the dose-response curve serves as a buffer to the change of virus

concentrations and weaken the effect of any increase or decrease in nearshore virus concentration values on the resulting infection risks.

In contrast to the winter simulation, and despite population growth, peak virus concentrations from May to August did not increase or even decreased in 2060 compared to 2019 (Figures 4 and 5). This can be explained by the effects of climate change on environmental stressors, which lead to more efficient virus inactivation in 2060 compared to 2019 (Figure 7). Specifically, the largest increase in water temperature between 2019 and 2060 occurs in late spring and early summer, specifically between April and June (Figure 3). This large temperature difference between the years effectively increased the temperature-driven inactivation of viruses. In addition, solar radiation levels are relatively high in spring and summer for the Lake Geneva region (Figure S2 in Supporting Information S1), leading to substantial solar inactivation. The increase in solar radiation from 2019 to 2060 (Figure S1 in Supporting Information S1) further enhances solar virus inactivation rates by 2060. This effect is particularly evident for species that are prone to inactivation by sunlight, such as enterovirus and rotavirus (largest β_{solar} in Table 1). Correspondingly, these virus concentrations in May to August decrease more extensively between 2019 and 2060 compared to the more sunlight-tolerant adenovirus (Figure 5). In September, the changes in virus concentrations from 2019 to 2060 are rather small. This could be explained by the fact that the increased virus load were partially compensated by the elevated water temperature and solar radiation level. However, as the increase of water temperature and solar radiation are less pronounced in early autumn than in summer, the effect of environmental virus inactivation were less significant than in the summer months.

The results in Figures 4 and 5 indicated that virus concentration and associated risks in November 2060 are lower than those in 2019, however, the reason behind the lower values can be attributed to changes in hydrodynamic transport rather than in virus inactivation. This dramatic influence of hydrodynamic transport patter is also very likely the explain for very different concentration curves in March and April in Figure 4, as gyre formation in Lake Geneva may largely influence the transport of substances (Li et al., 2022). In November, as shown for norovirus, even in the absence of environmental stressors, the peak virus concentration in 2060 is simulated to be only half that of 2019 ("HD only" scenario in November, Figure 7). In contrast to changes in hydrodynamics, the effect of environmental stressors on virus concentrations are negligible.

5.3. Accurate Knowledge of Inactivation Rate Constants Is Critical for Assessing the Effects of Climate Change on Virus Fate

A range of thermal and solar inactivation rate constants has been reported for the viruses studied herein, and this variability leads to vastly different estimates of virus concentrations and associated risks (Figure 8). Much greater changes were observed in norovirus than in enterovirus for the varying inactivation scenarios, whereas effect of such variability for adenovirus and rotavirus ranged in between the other two virus types. This could be rationalized by the fact that the standard errors of the mean for the inactivation rate constants of norovirus are much greater than that for enterovirus (Table 1), likely because the inactivation of norovirus in surface water is less studied than enterovirus (Boehm et al., 2019; Ngazoa et al., 2008). Another important feature is that without inactivation, norovirus may remain in the surface water for a rather long period (see "HD only" scenario in November; Figure 7). This implies that passive particles, such as environmentally stable viruses, could persist in the bay area without being flushed out. The extended presence of passive particles in the bay has also been revealed in earlier simulation studies on Lake Geneva (Cimatoribus et al., 2019) and Lake Michigan (Gloege et al., 2020). Under such hydrodynamic conditions, inactivation is a critical process to enhance microbial water quality.

To improve risk estimates, more research on norovirus inactivation in the environment is needed. Thanks to the recently developed human intestinal enteroid system, which allows to determine norovirus infectivity, improved data on norovirus persistence in the environment is now obtainable. For example, Shaffer et al. (2022) and Kennedy et al. (2023) recently reported infectivity-based inactivation rate constants of norovirus in surface water, which correspond to or slightly exceed the values used herein based on the review by Boehm et al. (2019).

Compared to the variability introduced by the uncertainties associated with inactivation rate constants, the climate-induced shift in virus concentrations between 2019 and 2060 are minor (Figures 7 and 8). This suggests that changes in the environmental stressors in the future would play a lesser role in estimating virus concentrations than the variabilities in the k values itself. An advance in the estimation of the inactivation rate would thus be more helpful in understanding the future fate of norovirus and other enteric viruses rather than efforts in achieving a better precision for predicting the climate variables in the future.

5.4. Limitations in This Study

This study considered both the hydrodynamics and the varying inactivation rates of waterborne viruses for risk assessment at present and in the future for swimmers near Lake Geneva. Yet, several limitations remain. First, climate change-induced water quality variations were not considered. For example, as indicated in the study by Williamson et al. (2017), increased precipitation may lead to higher concentration of organic matter in lakes, which in turn will result in more pronounced screening of sunlight. As a result, these authors expect solar virus inactivation to decrease. This finding is opposite to the one discussed herein, where future solar virus inactivation is promoted by clearer skies and hence more sunshine. The net effect of climate change on solar virus inactivation remains to be fully understood. Second, advances in management of combined sewer overflow have not been taken into account. Expansion of the capacity of WWPTs to capture and treat all raw wastewater even during storms, or the implementation of sewer separation, will reduce pathogen input into the lake. Third, medical advances such as new vaccinations, which can dramatically change the dose-response curves of the viruses investigated herein, were not considered. Rotavirus vaccines have demonstrated impact in reducing diarrheal morbidity and mortality worldwide (Burke et al., 2019). Updates in the dose-response curve would be needed once the population exposed to virus contaminated water is vaccinated. And lastly, the work presented herein considers only a single climate scenario for a single year (2060). Future work should consider simulations over longer time scales and under different climate scenarios, to assess their effect on virus behavior.

Although the above-mentioned limitations deserve further consideration and may affect the results presented herein, this study utilizes a comprehensive model that coupled water quality simulation and QMRA to analyze not only the hydrodynamics but also the fate and transport of waterborne viruses in a large lake, informing the possible magnitude of changes in flow conditions as well as virus inactivation rates in the lake. This work reveals the relative importance between the estimation of virus inactivation rate constants in aquatic systems and the evaluation of climate change factors on a more accurate risk assessment for recreational users for large lakes in the future.

6. Conclusion

This study employed results from a climate change model for Switzerland to support a coupled water quality-QMRA model to investigate the hydrodynamic and the fate and transport of waterborne viruses in Lake Geneva for the year of 2060 and 2019. Long-term hydrodynamic simulations revealed that the yearly hydrodynamic transport pattern of Lake Geneva will not vary dramatically, while a 1.9°C increase of lake surface water temperature could be expected. The fate and transport of four major enteric viruses of interest, however, may change depending on the time of year. During the warmer months, the increase of virus inactivation due to higher temperature and stronger solar radiation will compensate for the additional sewage discharge brought about by population growth, whereas for the colder winter months, the virus concentration near the lake shore and the associated risks are likely to rise proportionally to the increase in sewage discharge. However, as hydrodynamic conditions may change constantly, a simulation is always necessary for the prediction of any specific time period. Furthermore, uncertainties in reported virus inactivation rates affect simulated enteric virus concentrations in the lake to a greater extent than the varying climate conditions. A more accurate estimation of the environmental inactivation rates of viruses would thus be more critical for predicting the future fate of enteric viruses in aquatic systems. Overall, the results from this study imply that with a steady growth of population in the region of Lausanne and an unchanged wastewater treatment technology, the risks posed by the enteric viruses to the recreational water users near the popular beach sites will likely be similar to the present situation.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The data (measured virus concentrations and radiation levels) and code (hydrodynamic and water quality simulations and QMRA) on which this article is based are available in Li and Kohn (2023).

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