Supplementary Materials for

When ice meets bedrock: variation in regional lithology as a control on the size variation of the Finger Lakes in Western New York

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Supplementary Text

Lithology of the Finger Lakes Region

The bedrock of the Finger Lakes region is entirely made up of Middle to Upper Devonian age strata, including, from oldest to youngest, the Onondaga Limestone, the shale-dominated Hamilton Group and Genesee Group, and the more siltstone- and sandstone-dominated Sonyea and West Falls Group. A thin band of limestone named the Tully Limestone is also found sandwiched between the Hamilton and Genesee Groups, though its lateral extent is restricted to the Finger Lakes region. The units all dip gently southward at about 9.5 meters per kilometer (Bloom, 2018).

Delving into the specifics about the lithology of the units, the Onondaga Limestone ranges in thickness from 23 to 45 meters and is composed primarily of both cherty and non-cherty limestone, light grey to black chert, argillaceous lime muds, and bentonite (Brett & Ver Straeten, 1993). None of the Finger Lakes cut completely beyond the Onondaga Limestone, though it does serve as the base of the Cayuga Lake trough. This is sensible considering the exceedingly low erosion rates that limestone tends to show, which may sometimes be even less than crystalline lithologies like granite and gneiss, which are, in theory, harder and more resistant rocks (Steinemann et al., 2020). One hypothesis for this seemingly anomalous resistance is that erosion is obstructed by the smoother surfaces that limestone exhibits relative to siliciclastic sedimentary rocks and crystalline rocks. As a result, abrasion is stymied. Moreover, calcite precipitates in limestone often fill in any fractures, joints, or other irregularities, preventing the glacier from finding and exploiting a weak spot in the rock (Blessing, 1976; Steinemann et al., 2020).

Overlaying the Onondaga Limestone, however, is the Hamilton Group, a unit that is more amenable to intense glacial erosion. The Hamilton Group ranges in thickness from 75 meters near Lake Erie to 760 m near Ulster and Greene County farther east and is separated into four shale-dominated formations interbedded with and based on limestone members: the Marcellus, Skaneateles, the Ludlowville, and the Moscow Shales (De Witt et al., 1993). The Marcellus Shale is composed of oil-producing black shale with some limestone nodules, while the Skaneateles Shale and Ludlowville Shale are composed of shale and mudrock. Lastly, the Moscow Shale is largely constituted by calcareous mudrock and shale, with several extensive fossiliferous limestone beds, such as the Tichenor Limestone Member in western New York, which grades into the Portland Port Limestone Member going east towards Ithaca. Facies change is marked in the Hamilton Group as beds of sandstone are interbedded in the unit, particularly within the Marcellus Shale in eastern New York (De Witt et al., 1993).

The Tully Limestone is a thin but distinct unit of limestone and calcareous shale (Baird et al., 2012), and it is overlain by the Genesee Group. West of Canandaigua Lake, the Genesee is constituted mostly by shale and mudrock, with minor components of nodular limestone and argillaceous siltstone (De Witt & Colton, 1978). Here, the Genesee Group is subdivided into the Geneseo Shale, Penn Yan Shale, Genundewa Limestone, and West River Shale Member. A marked facies transition from shale to siltstone occurs by Seneca Lake and near Cayuga Lake, as two thick units of siltstone interlain by the Renwick Shale Member, the Sherburne Flagstone and Ithaca Member, appear and divide the Penn Yan Shale from the West River Shale. Though even neglecting these distinct members, the number of siltstone beds interspersed with the shale members increases, and so too does their thickness, going from west to east, and especially east of Keuka Lake. Though in regards to the two siltstone units, the Sherburne Flagstone Member is an eastward-thickening layer of siltstone, silty shale, shaley siltstone, and very fine-grained sandstone. Similarly, the Ithaca Member is an eastward-thickening layer of medium- to coarse-grained quartzose siltstone that locally contains fine-grained quartz sandstone, shaly siltstone, and silty shale. In terms of thickness, the Genesee Group is only 3 meters thick below Lake

Erie and thickens to around 290 meters near Ithaca and 365 meters on the state line just southeast of Elmira.

The Sonyea Group is prominent in the region of western Finger Lakes and generally marks the southern boundary of Cayuga and Seneca Lake, though it is of more negligible importance among the eastern Finger Lakes, where it appears at more southern latitudes with respect to the lakes due to the greater thicknesses of the Hamilton and Genesee Group in the region. The Sonyea has a more coarse composition than the two latter groups, being constituted by an appreciable amount of siltstone and sandstone in addition to shale and mudrock (Sutton et al., 1970). The two members of the Sonyea are the Middlesex Shale and the Cashaqua Shale Member, with eastward thickening and facies change to a more siltstone-rich composition being more marked for the latter (De Witt et al., 1993).

The West Falls Group overlies the Sonyea Group and largely falls outside of the Finger Lakes Region, outcropping more so south of the through valleys in the rugged landscape of the Allegheny Plateau. Still, a brief description of the West Falls Group is given due to its appearance in one of the models in this study, namely in the model of Canandaigua Lake. The West Falls contains shale members like the basal Rhinestreet Shale Member that have significant compositions of silty shale, silty mudrock, and siltstones (De Witt et al., 1993). The Rhinestreet Shale is also overlain by a siltstone-dominant member by the name of the Grimes Siltstone. There is even coarser composition farther up the stratum in the form of the Nunda Sandstone, which is made up of thick beds of sandstone (Jacobi et al., 1994).

Additional Model Runs: Uniform Erodibility, No Facies Change, and No Bedrock Thickness

Uniform Erodibility: The Uniform Erodibility Control Case uses the bedrock layers from the Cayuga Lake Case, with the difference being that now all the bedrock layers are set to the same value of C_2, which is equivalent to there being no distinct bedrock layers at all. The C_2 value selected for this case is 1, since this is the average value of C_2 for all the layers above the Onondaga Limestone in the Cayuga Lake Case. As in the previous models, the glacier burrows down to the bottom of the Hamilton Group (Fig. S3). However, while the glacier was stopped by the resistive Onondaga Limestone in previous models, here the Onondaga Limestone has the same erodibility as all the other layers, so the glacier continues burrowing down. No steep cut forms and the morphology of the resulting erosional feature is akin to a lopsided bowl, with the upglacier end of the bowl sloping up more steeply than the downglacier end. When compared to the Cayuga Lake trough, it can be seen that the uniformly eroded feature reaches a lower elevation overall. For example, the uniformly eroded feature has a deepest elevation of -409.44 m relative to sea level, which is 189.24 m deeper than the bottom of the lake in the Cayuga Lake Case (Table S2). The deepest point of the uniformly eroded feature also occurs more northward in the domain at x = 35.1 km, which corresponds to the transition from the exponential to the linear region (Fig S4). The more intense erosion earlier in the domain does, however, come at the expense of erosion farther downglacier. Note that at x = 90.6 km, where the Cayuga Lake trough reaches its maximum depth of -220.20 m, the uniformly eroded feature has only an elevation of -77.79 m. Based on the results of this case, it is clear that distinct bedrock layers play an important role in generating a lake trough feature. The Onondaga Limestone plays a critical role in capping glacial erosion, and the southward dip of the layer allows for the lake trough to deepen southward where there is a greater vertical distance of bedrock that may be eroded down before contacting the limestone.

No Facies Change and No Bedrock Thickness Change:

In regards to creating Canandaigua Lake, a No Facies Change Case (NFCC) and a No Bedrock Thickness Change Case (NBTCC) were performed. In NFCC, the bedrock layer thicknesses of the Canandaigua Lake Case were used, but the C_2 values assigned to the layers were those of the Cayuga Lake Case, indicating a scenario in which bedrock layer thicknesses still thin going east to west but the facies stay the same. The West Falls Group does not appear in the Cayuga Lake Case, so the C_2 for the West Falls Group in NFCC is kept the same as it was in the Canandaigua Lake Case. In NBTCC, the bedrock layer thicknesses of the Cayuga Lake Case were used, but they were assigned the C_2 values that they assumed in the Canandaigua Lake Case. This signifies the opposite scenario, in which the facies fine down going east to west but the bedrock layer maintains uniform thickness.

As for the resulting lake troughs from the models, it can be seen that the Canandaigua Case and NFCC display little disparity from each other (Fig. S5). NFCC is 23.9 km long and deepens to 69.96 m below sea level. The lack of disparity is sensible considering that the change in C_2 isn't exceptionally large between the Cayuga and Canandaigua Case. Moreover, the highly resistive West Falls Group dampens how much changes in the C_2 of the lower layers affect the resulting erosion. Even if the Genesee and Hamilton Group are made more erodible, the glacier still has to first erode through the West Falls Group, which is too time-consuming for the quicker erosion of the Genesee and Hamilton Group to be consequential.

A larger disparity is seen between the Canandaigua Case and NBTCC. NBTCC has an extraordinarily large size, reaching a length of 65.8 km and a deepest elevation of 278.21 m below sea level, making it longer and deeper than Cayuga Lake. This size increase in NBTCC is sensible considering the fact that the size of Canandaigua Lake was limited by the thinness of highly erodible bedrock layers. The Onondaga Limestone being shallower in the Cayuga Lake Case, and likewise in NBTCC, accounts for the NBTCC trough being shallower than the Canandaigua trough upglacier from the deepest point.

An equivalent No Facies Change Case (NFCS) and No Bedrock Thickness Change Case (NBTCS) was done for Skaneateles Lake. NFCS uses the bedrock layer thicknesses of the Skaneateles Case with the C_2 values of the Cayuga Case, while NBTCS uses the bedrock layer thicknesses of the Cayuga Case with the C_2 values of the Skaneateles. Predictably, NFCS is far larger than Skaneateles Lake (Fig. S6), since the factor holding back the growth of Skaneateles Lake in spite of its large thickness of bedrock was the coarse facies. NFCS approaches dimensions similar to Cayuga Lake, with a length of 59.8 km and a deepest elevation of 252.83 m below sea level. NBTCS, at 32.8 km in length and deepening to 10.97 m above sea level, shows less disparity from the Skaneateles Case due to the bedrock layers of the Cayuga and Skaneateles Case being largely similar, in that, for both cases, the Hamilton Group has nearly the same thickness and the Sonyea Group outcrops towards the end of the domain.

ELA Sensitivity Testing

To test the effect of the height of the ELA on the erosional feature produced in the model, the Cayuga Lake Case was run three more times with different ELAs but the same bedrock layers, alongside the base Cayuga Lake Case within the main paper with the ELA set to 1000 m. The additional ELA values that were tested were 1200 m, 600 m (corresponds to the transition point from the exponential to the linear region), and 500 m. Figure S7 plots the final erosional feature from all three cases, alongside the base Cayuga Lake Case, together on the same graph.

Raising the ELA from 1000 m to 1200 m leads to a starkly different model behaviour. With less horizontal distance over which ice can accumulate, the glacier quickly burrows downward. The amount of ice accumulating above the ELA towards the start of the domain is not enough to replenish the large amount of ice that dips below the ELA and melts away. As such, by 1400 years, all the ice has melted away, leaving behind a deep bowl-like feature that is reminiscent of a cirque, albeit much deeper and more steeply walled, at the base of the steep topography at the beginning of the domain (Fig S2).

On the other hand, reducing the ELA from 1000 m to 600 m or 500 m does not change the final resultant erosional feature to any appreciable degree (Fig. S2). There is more divergence between the three cases during the earlier timesteps in the model. For example, the 600 m case forms a V-shaped cut into the Hamilton Group at 400 years and, in general, erodes to the base of the Hamilton Group more quickly than in the case where the ELA is 1000 m, which is to be expected given the fact that the lower ELA allows ice to build up over the area where the base of the Hamilton Group is most shallow, that is the transition between the exponential and linear region in the topography, right from the start of the runtime of the model.

As for the 500 m case, in the snapshots from 400 to 900 years of model runtime, it can be seen that the topography underneath the glacier decreases before rising slightly and then decreasing once more. This stems from the low ELA allowing the ice to build up over the parts of the domain where the Hamilton Group, Tully Limestone, and Genesee Group outcrop from the start of the model runtime. This ridge in the topography occurs due to the erosion of the Tully Limestone proceeding more slowly than in the Hamilton Group, which outcrops farther to the left, and the Genesee Group, which outcrops farther to the right. Once the Tully Limestone is eroded through, a uniformly decreasing topography is able to be established (Fig. S7).

Overall, so long as the glacier does not ablate completely prior to the full runtime of the model, modifying the elevation of the ELA has little effect on the final erosional features produced in the model.

C_2 Sensitivity Testing

To test the effect that C2 has on the model, eight cases, as laid out in Table S5, are considered (Fig S8). Case A is just the base Cayuga Lake Case from the main paper. Cases B-H all use the same bedrock layer thicknesses as the Cayuga Lake Case, though they have different C2 values. Case B considers the case of Sonyea Group and Genesee Group having the same C2 as the Hamilton Group does in Case A, that being 1.5. Case C is the same as Case B, with the exception that it sets the Tully Limestone to a C2 of 1.5 as well. Whereas the exponential region, as defined by the region in the first 35 km of the domain that is between the topography and the linear curve that constitutes the topography rest of the domain extrapolated back to the z-axis, has its own separate C2, in Case D, this condition is removed and the C2 in the region is determined by the bedrock layers as it is in the rest of the domain. Case E adds 1 to the C2 values of all the bedrock layers from Case A. Case F gives the Onondaga Limestone the same C2 value as the Tully Limestone in Case A, that being 0.5. Case G halves the C2 values of all the bedrock layers from Case A. Finally, Case H inverts the stratigraphic order of the C2 values of the bedrock layers from Case A. As such, the uppermost bedrock layer, the Sonyea Group, has the C2 value of the lowermost bedrock layer, the Onondaga Limestone.

Case B, C, and D all produce lakes that are of similar bathymetric profiles and dimensions as Case A. The Case A lake, as described in the main paper, has a length of 62.4 km and a deepest elevation of 221 m below sea level. The Case B lake has a length of 69.3 km and a deepest elevation of 277 m below sea level. The Case C lake is slightly shorter at 68.9 km in length, though it is deeper, having a deepest elevation of about 300 m below sea level. The Case D lake is substantially smaller than the prior two cases, having a length of 62.4 km and a deepest elevation of 219 m below sea level. That Case B and Case C produced larger lakes than Case A is unsurprising, given that they involved an increase in C2 values. The dimensions of the Case D lake are about the same as that of Case A, which is also sensible given the fact that the exponential region is constituted primarily by the Sonyea and Genesee Groups, which, in Case A, both have C2 values that are about the same as the C2 of the exponential region.

In Case E, the high erodibility of the bedrock layers causes the glacier to melt away before the full model runtime is completed, showing the impracticality of using C2 values greater than 1.5 for the majority of bedrock layers, especially when there is no resistive underlying layer to prevent the glacier surface from falling well under the ELA.

In Case F, the lower resistance of the Onondaga Limestone allows the glacier to cut substantially into the layer, especially towards the left side of the domain, which is in contact with the glacier from early on in the model's runtime. This leads to the north shore at 45 km of horizontal distance having an elevation -136 m relative to sea level, which is 205 m lower than what it is in Case A. The bathymetric profile of the Case F lake thus does not deepen as substantially as it does in Case A or as it does in the real life Finger Lakes, once again highlighting the critical role that a resistive underlying layer in the form of the Onondaga Limestone must have had in conferring the Finger Lakes with their bathymetric profile. Predictably, the halving of the C2 values of the bedrock layers in Case A causes the lake in Case G to be smaller, while still maintaining the same bathymetric profile. Namely, the lake is 47.6 km long and deepens to 30 m above sea level.

The inversion of the stratigraphic order of the C2 values in Case H leads to the final lake deepening northward as opposed to southward. The high resistivity of the overlying Sonyea Group prevents erosion towards the south from proceeding to the less resistive layers below, all the while farther north in the domain where the Sonyea Group does not appear, erosion is able to progress without much hindrance.

Overall, the C2 sensitivity tests show that, as long as the Onondaga Limestone has a low C2 value, altering the C2 values of the bedrock layers mainly just alters the final dimensions of the lake, without affecting the general trend of the bathymetry too much. On the other hand, the bathymetry of the resultant lake is more sensitive to changes to the C2 of the Onondaga Limestone, as a more erodible Onondaga Limestone either leads to less southward deepening or reverses the trend to create a northward deepening lake. The C2 values used in the main paper, on the other hand, create lakes that have dimensions and bathymetric profiles that correspond to the real-life Finger Lakes while still maintaining consistency about the relative erodibility of different lithologies (e.g. shale should be more erodible than sandstone) and the facies change in the region (e.g. the Hamilton and Genesee Groups should be more resistive by Cayuga Lake than by Canandaigua Lake).

Supplementary Figures

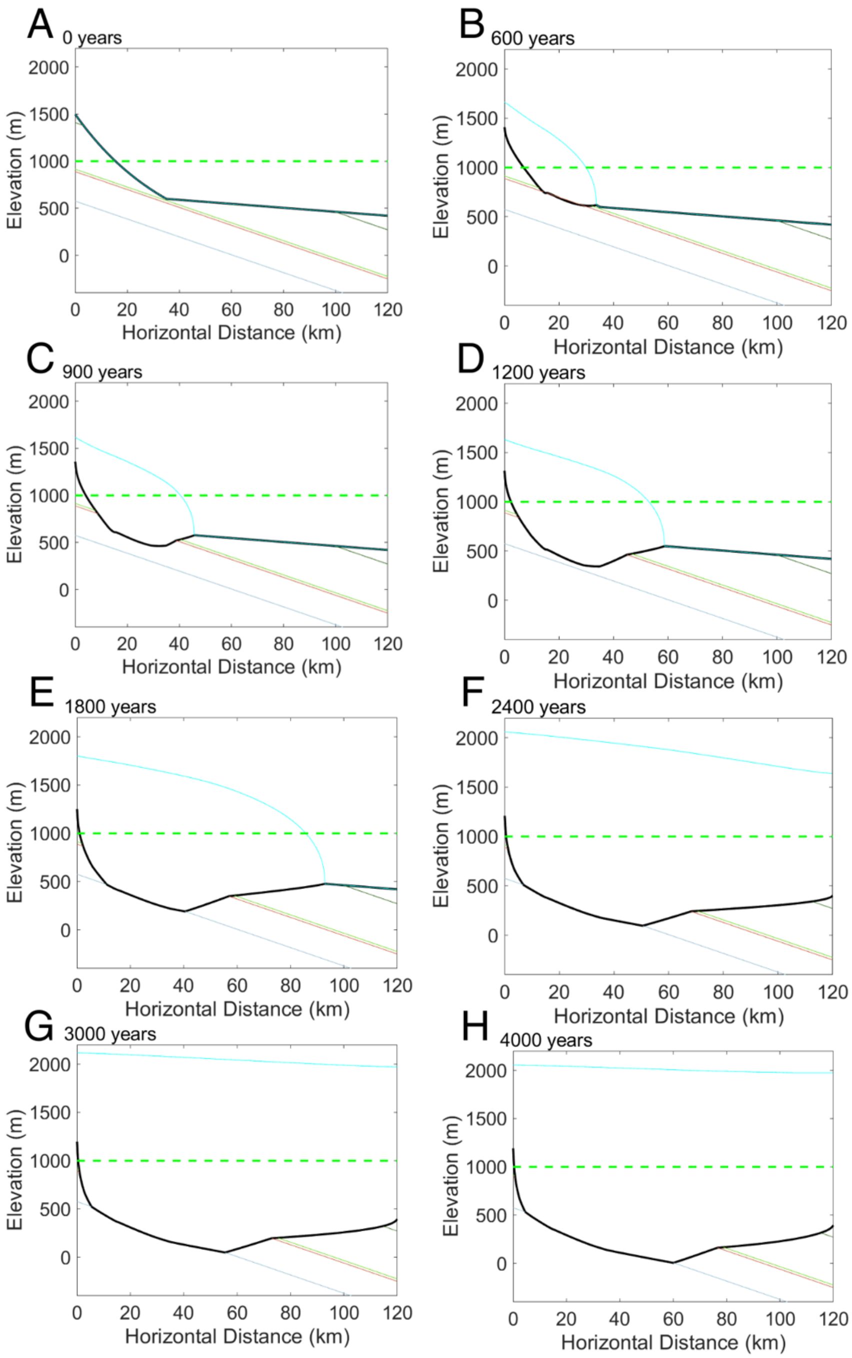

Figure S1.

Time-lapse of the glacier growing over and eroding the bedrock at select time-intervals in the Skaneateles Lake Case. The cyan line is the top of the glacier. For the bedrock layers, the blue line is the bottom of the Hamilton Group, the red line is the bottom of the Tully Limestone, the light green line is the bottom of the Genesee Group, and the dark green line is the bottom of the Sonyea Group.

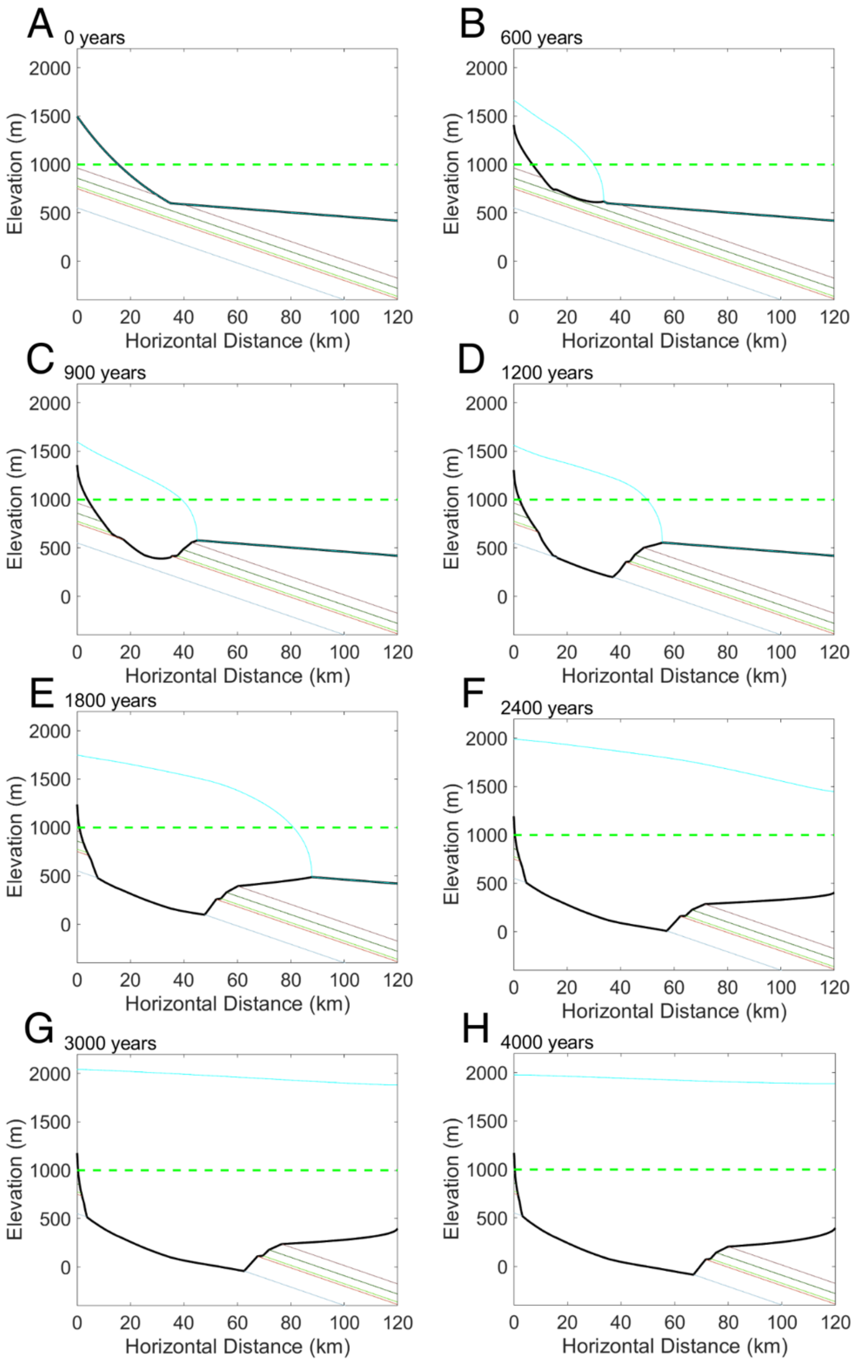

Figure S2

Time-lapse of the glacier growing over and eroding the bedrock at select time-intervals in the Canandaigua Lake Case. The cyan line is the top of the glacier. For the bedrock layers, the blue line is the bottom of the Hamilton Group, the red line is the bottom of the Tully Limestone, the light green line is the bottom of the Genesee Group, the dark green line is the bottom of the Sonyea Group, and the purple line is the bottom of the West Falls Group.

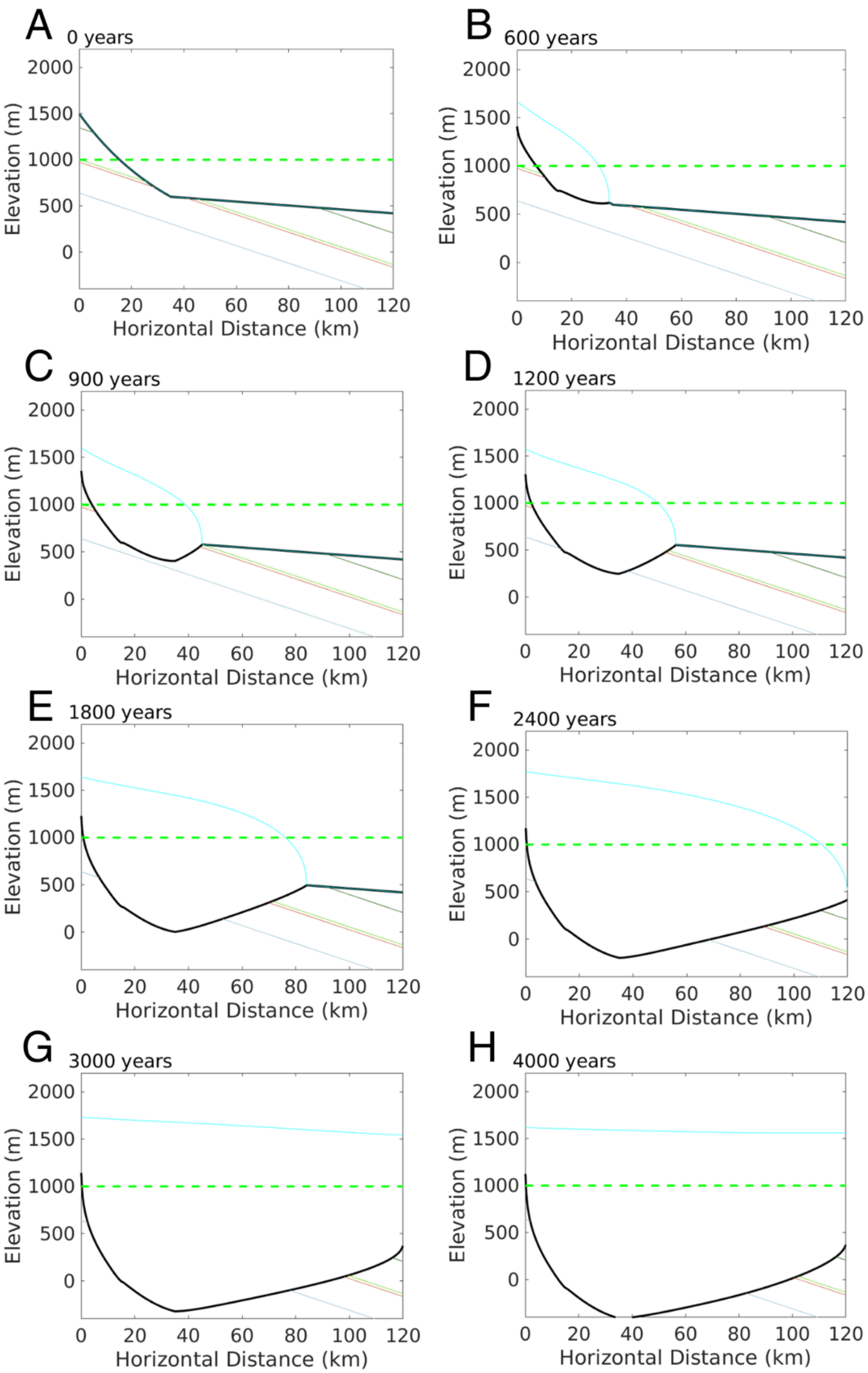

Figure S3

Timelapse of uniform erodibility case

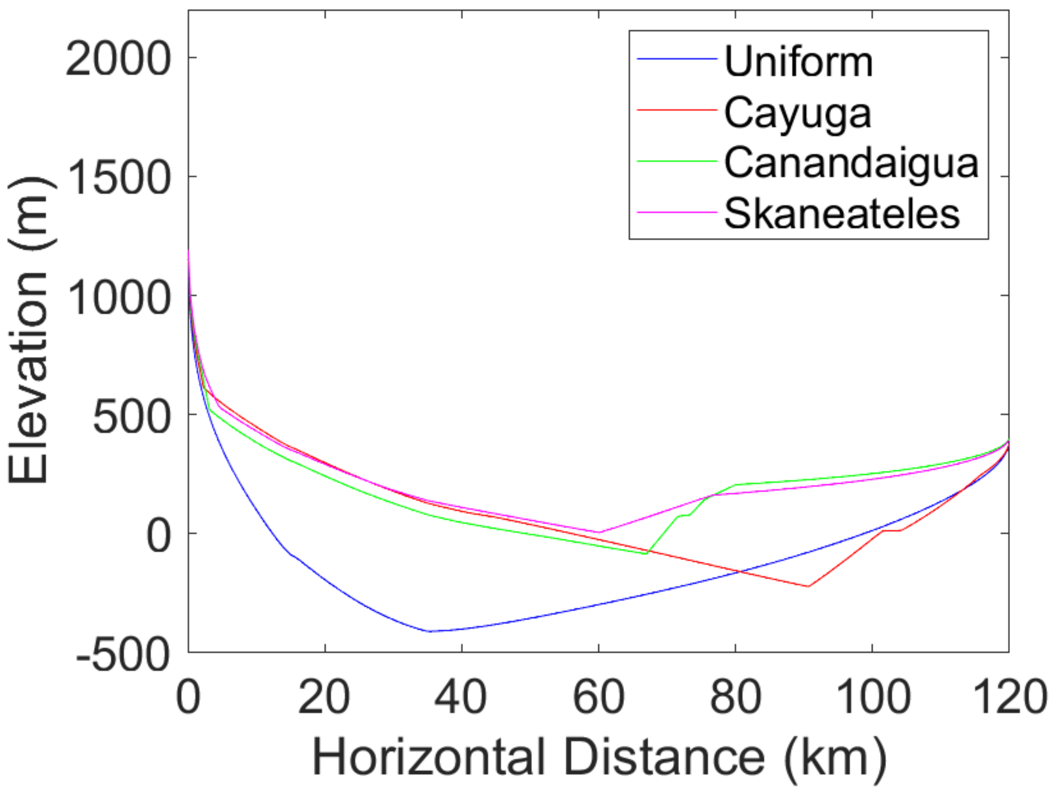

Figure S4

Comparison of final bedrock topography for uniform erodibility with 3 lake runs from main manuscript

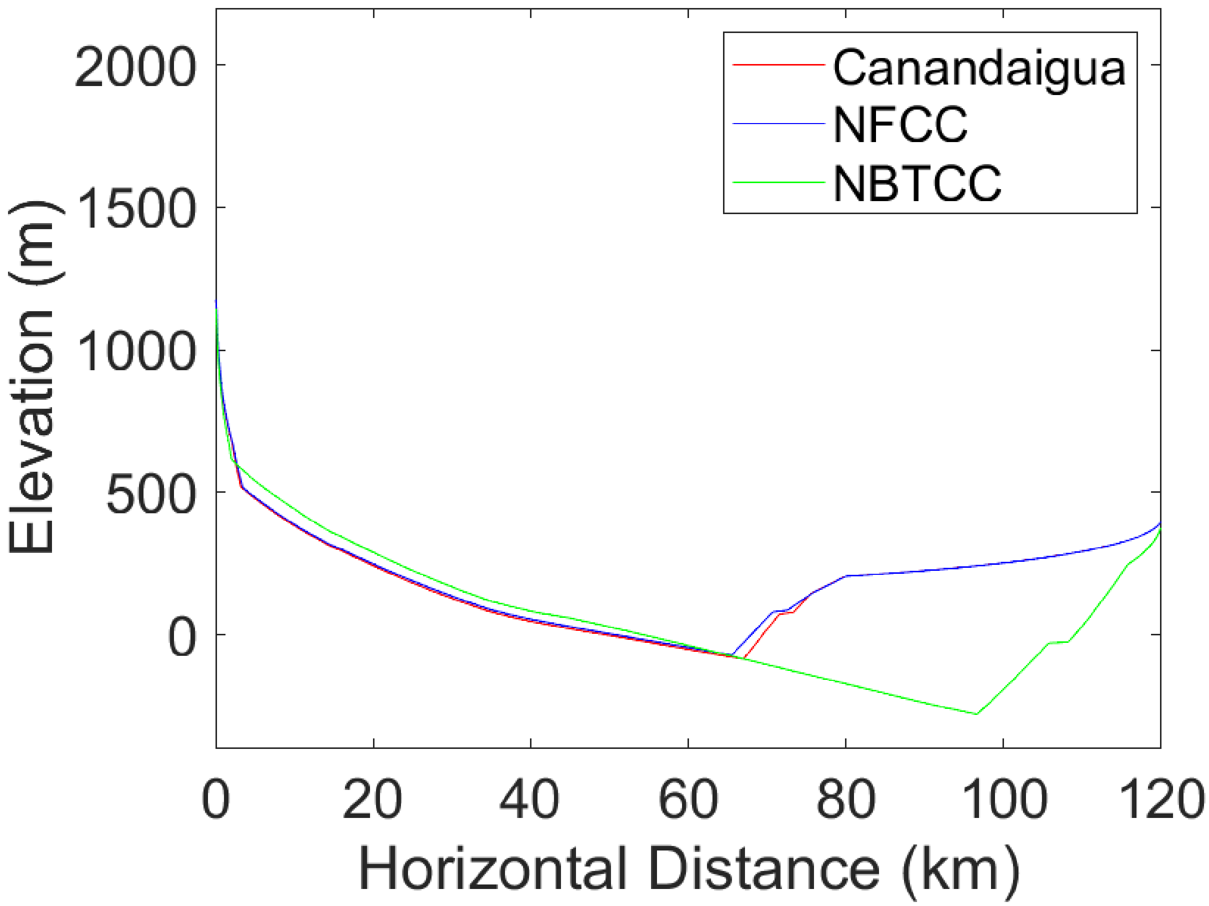

Figure S5

The final elevation profiles from the Canandaigua Lake Case (red), the No Facies Change Case using Cayuga Lake facies on bedrock layers with the thicknesses of those in Canandaigua Lake (blue), and the No Bedrock Thickness Change Case using Canandaigua Lake facies on bedrock layers with the thicknesses of those in Cayuga Lake (green).

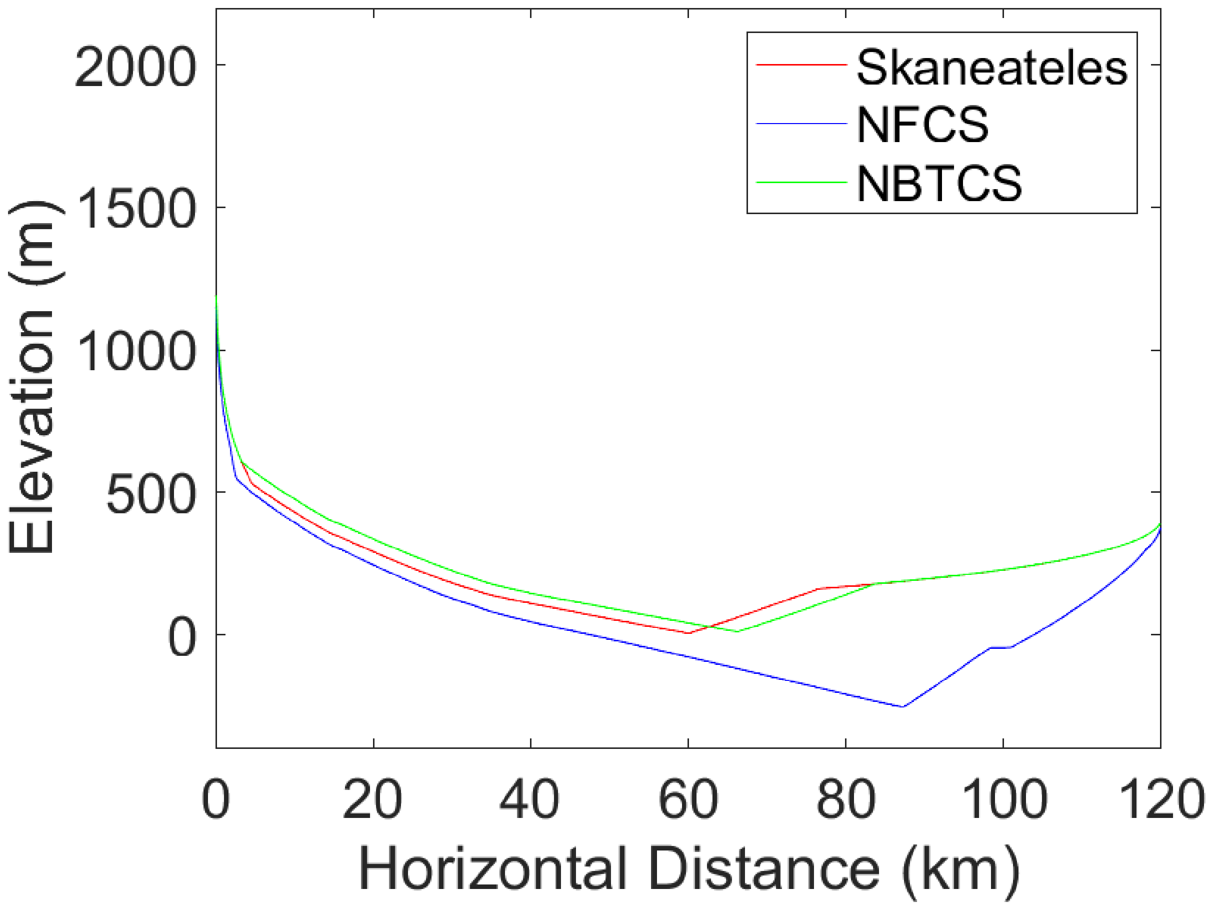

Figure S6

The final elevation profiles from the Skaneateles Lake Case (red), the No Facies Change Case using Cayuga Lake facies on bedrock layers with the thicknesses of those in Skaneateles Lake (blue), and the No Bedrock Thickness Change Case using Skaneateles Lake facies on bedrock layers with the thicknesses of those in Cayuga Lake (green).

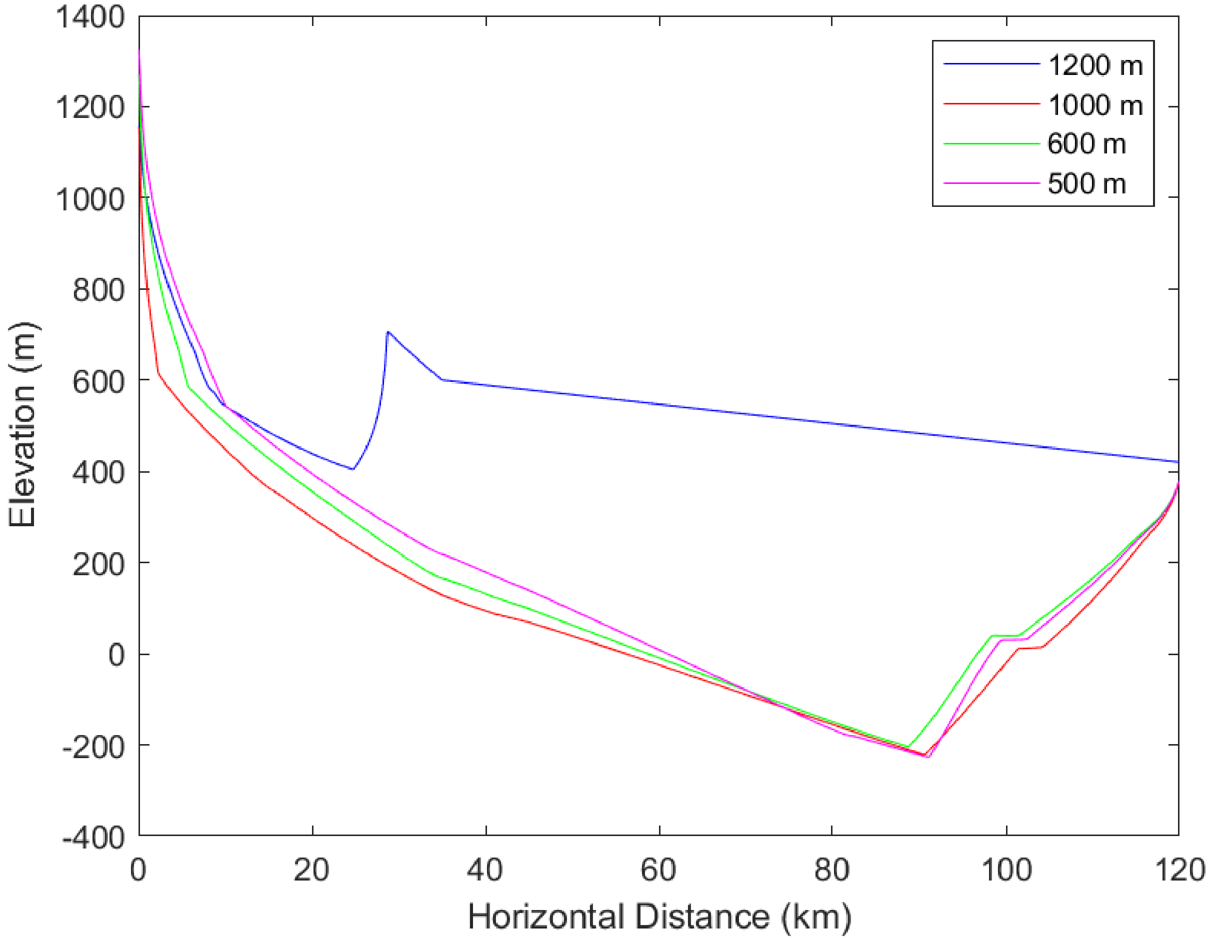

Figure S7

The final elevation profiles from the Cayuga Lake Cases with the ELA set to: 1200 m (blue), 1000 m (red), 600 m (green), and 500 m (pink).

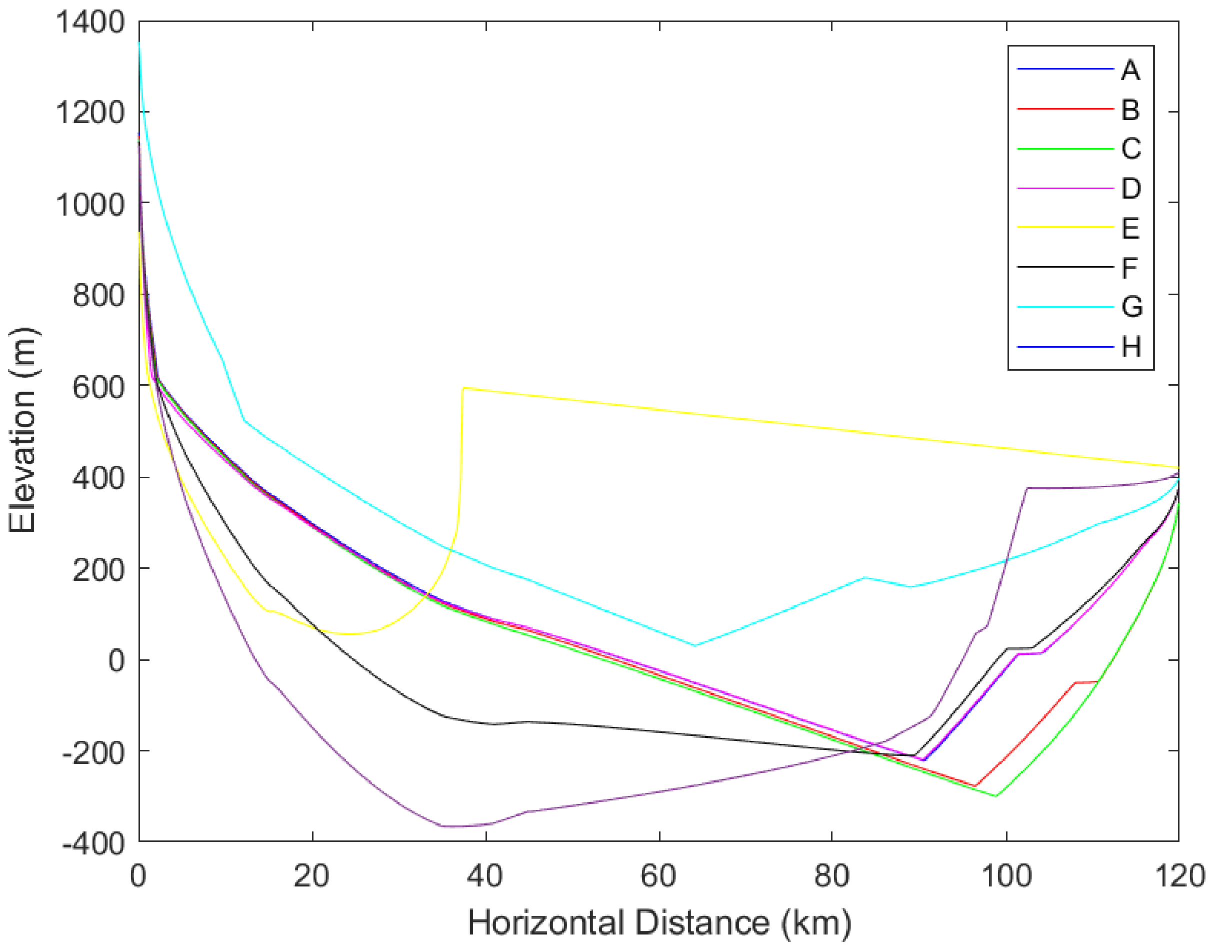

Figure S8

The final elevation profiles of the C_2 sensitivity testing cases. The case letters in the key correspond to the case letters in Table S5.

Supplementary Tables

Supplementary tables present additional information in support of the conclusions of your paper.

Table S1

List of parameters in the numerical model

Symbol	Description	Units	Value(s)
x	Horizontal distance	m	
dx	Horizontal grid spacing	m	100
zb	Bedrock elevation	m	
H	Thickness of glacier in cell centres	m	
H_{edge}	Thickness of glacier at cell edges	m	
z	Ice surface elevation (zb+H)	m	
t	Time	yr	
dt	Model timestep	yr	0.0001
ELA	Equilibrium line altitude	m	1,000
b	Local mass balance	$m\ yr^{-1}$	
db/dz	Gradient of mass balance with elevation	yr^{-1}	0.01
A	Flow law parameter	$Pa^{-3}\ yr^{-1}$	2.1×10^{-16}
n	Flow law power	-	3
ρ_i	Density of ice	$kg\ m^{-3}$	917
g	Gravity	$m\ s^{-2}$	9.81
S	Slope of the ice surface	-	

τ_b	Basal shear stress of the glacier	Pa	
u_{def}	Deformational velocity of the glacier	$m\ yr^{-1}$	
u_{slide}	Sliding velocity of the glacier	$m\ yr^{-1}$	
m	Sliding exponent	-	1
C_1	Sliding constant	$m^2\ s^2\ kg^{-1}\ yr^{-1}$	5.1×10^{-6}
Q	Ice discharge	$m^2\ s$	
$\dot{\varepsilon}$	Erosion rate	$m\ yr^{-1}$	
C_2	Erosion constant	-	

Layer	Thickness (m)	Elevation of the bottom of the layer at the northern shore (m)	C_2 value
Onondaga Limestone	-	-	0.2
Hamilton Group	335	213	1.5
Tully Limestone	30	548	0.5
Genesee Group	342	578	1.1
Sonyea Group	-	920	0.9

Table S2

Data for the bedrock layers used in the Cayuga Lake case. The full thickness of the Sonyea Group doesn't appear in the Cayuga Lake case since it goes beyond the domain, hence the thickness of the Sonyea Group is left blank.

Layer	Thickness (m)	Elevation of the bottom of the layer at the northern shore (m)	C_2 value
Onondaga Limestone	-	-	0.2
Hamilton Group	199	126	1.7
Tully Limestone	25	325	0.5
Genesee Group	83	350	1.5
Sonyea Group	105	433	0.9
West Falls Group	624*	538	0.45

Table S3

Data for the bedrock layers used in the Canandaigua Lake case. *The West Falls Group layer, as defined in the model, includes the Java Group and part of the Canadaway Group in its thickness due to them all having a similar sandstone-rich lithology. This is the reason for the supposed large thickness of the West Falls Group in the model.

Layer	Thickness (m)	Elevation of the bottom of the layer at the northern shore (m)	C_2 value
Onondaga Limestone	-	-	0.2
Hamilton Group	313	149	0.8
Tully Limestone	26	462	0.5
Genesee Group	495	488	0.5
Sonyea Group	-	983	0.5

Table S4

Data for the bedrock layers used in the Skaneateles Lake case. The full thickness of the Sonyea Group doesn't appear in the Skaneateles Lake case since it goes beyond the domain, hence the thickness of the Sonyea Group is left blank.

Case	Onondaga	Hamilton	Tully	Genesee	Sonyea	Exponential Region
A (base Cayuga Case)	0.2	1.5	0.5	1.1	0.9	1
B	0.2	1.5	0.5	1.5	1.5	1
C	0.2	1.5	1.5	1.5	1.5	1
D	0.2	1.5	0.5	1.1	0.9	-
E	1.2	2.5	1.5	2.1	1.9	2
F	0.5	1.5	0.5	1.1	0.9	1
G	0.1	0.75	0.25	0.55	0.45	0.5
H	0.9	1.1	0.5	1.5	0.2	1

Table S5

C_2 sensitivity testing cases. Each row shows the C_2 values for the bedrock layers in the corresponding columns. The C_2 value assigned to the exponential region in the first 35 km of the domain is also shown in the final column. A '-' in that column indicates that the exponential region was not defined as a separate region with its own distinct C_2 value in the case in that row.

Captions for other materials that are not included in this integrated PDF

Movie S1.
Movie of Cayuga Lake model.

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