The Subglacial Hydrology of the Laurentide Ice Sheet in Northern New Jersey

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ABSTRACT

During the last glacial maximum the Laurentide Ice Sheet covered much of Northern New Jersey. As the ice sheet began to melt, melt-water would have infiltrated the aquifers beneath the glacier and may have significantly affected hydraulic heads and gradients. Previous studies have suggested that the groundwater head distributions and thus flow velocities are significantly impacted by the presence of sub-glacial water drainage systems. The problem that I am addressing in this paper is whether or not the presence of a sub-glacial water film would have had an effect on the groundwater flow in the aquifers of New Jersey. To understand the effects the Laurentide Ice Sheet had on the aquifers of New Jersey, I used the groundwater modeling software MODFLOW to simulate the groundwater flow along a two-dimensional representation of the central flow line of a glacial lobe in North Eastern New Jersey. The groundwater model can be manipulated to evaluate the effects of various parameters such as water film thickness, glacier basal melt rate, and glacier thickness. The model results indicate that the presence of a sub-glacial water film reduced the hydraulic gradient in the aquifers whereas the absence of a sub-glacial film resulted in significantly higher gradients in hydraulic head within the aquifers. These results suggest that the presence of a sub-glacial water film had a significant effect on the groundwater flow regime in the sub-glacial aquifers.

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I. INTRODUCTION AND PREVIOUS WORKS

During the Last Glacial Maximum (LGM), the Laurentide Ice Sheet covered much of North America. The Laurentide Ice Sheet extended as far south as Missouri in the west and New Jersey in the east leaving prominent moraines situated in the North Central and North Eastern United States (Dyke and Prest, 1987). The Last Glacial Maximum extended from approximately 50,000 to 10,000 years ago with glacial declines beginning as early as 20,000 years ago (Clark et al. 2009). The Wisconsonian Glaciation was the last major glaciation event to occur in North America. During this period much of Northern New Jersey was covered by an ice sheet (Dyke and Prest, 1987). Approximately 16,000 years ago during this glacial period much of the South-Eastern Laurentide Ice Sheet rapidly began to recede (Dyke, 2004).

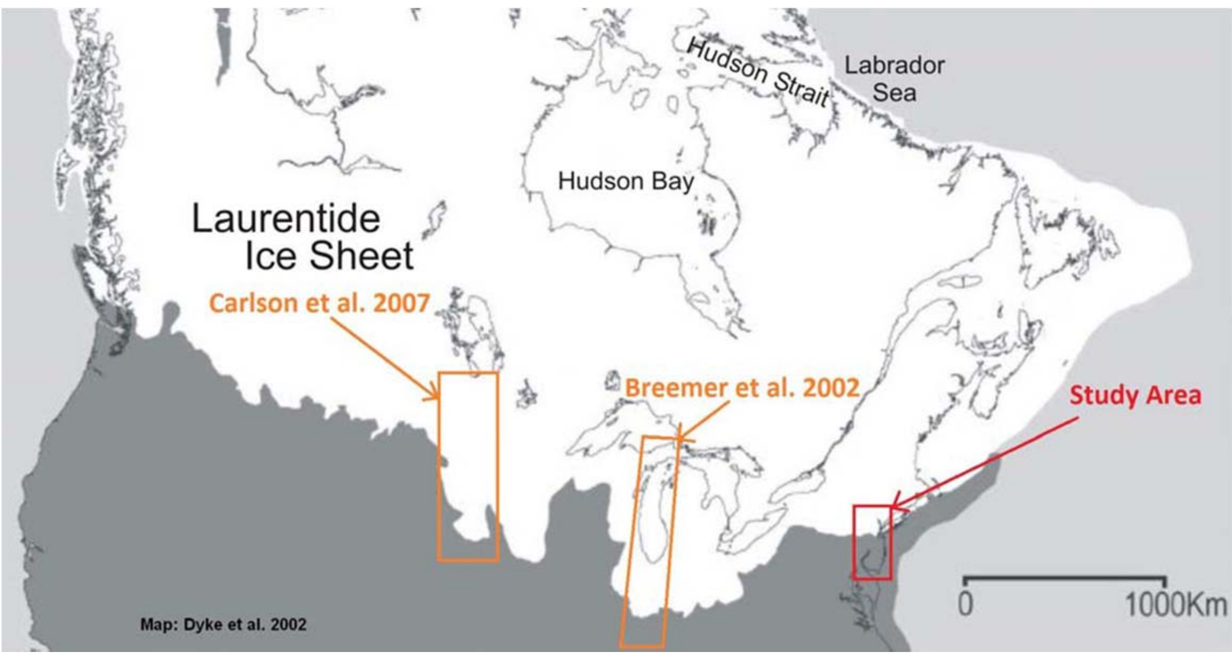


Figure 1. The previous studies (Carlson et al. 2007, Breemer et al. 2002) are outline in orange over a map of the Laurentide Ice Sheet provided by Dyke et al. 2002. Outlined in red is the area of study for this project.

The ice sheets covered much of North America, but little is known about the glacial mechanics at the base of these ice sheets. Previous studies have noted that glacial advance and melting phases of glaciers may have resulted in significant recharge of the aquifers (Breemer et al. 2002, Carlson et al. 2007). The amount of recharge would be influenced by head distributions in the aquifers, which in turn are affected by the presence or absence of water films at the base of the glacier. If the regional aquifer beneath the glacier cannot accommodate the meltwater then drainage systems may form at the ice-till interface (Alley, 1989). The formation of subglacial drainage systems would reduce the thickness of the subglacial water film, which would have affected basal sliding by the glacier (Alley, 1989).

Previous studies have shown that if the aquifer beneath of a glacier cannot accommodate all of the meltwater flowing into the system than other forms of drainage may form at the ice till interface to distribute water pressure (Alley 1989). The types of basal drainage systems that may develop are laminar films (Alley 1989, Breemer et al. 2002), channelized flow (Brown et al. 1987, Walder and Fowler 1994, Ng 2000), and channelized flow that may be associated with periodic outburst floods (Piotrowski 1997a,b., Shaw 1988). Laminar films are unstable under normal conditions as water tends to collect in channels (Breemer et al. 2002, Walder 1986). Due to lack of drumlin formations and streamlined till features in the New Jersey region, there is little evidence for subglacial floods. There are significant glacial outwash deposits found at the front of the glacial margin suggest subglacial drainage systems may have formed (Fig. 3). Therefore, the water under the ice sheets probably evolved from laminar films to basal drainage systems. Ice located between the basal drainage channels likely had thin laminar films that fed water into the channels. Therefore, most of the ice sheet that contributed to recharge of the subglacial aquifers would likely have thin laminar films.

This influx of water from the glacier would affect head distributions and water flow in the aquifers. Previous studies have shown that groundwater velocities in underlying aquifers were influenced by Pleistocene ice sheets (Carlson et al. 2007, Breemer et al. 2002, Boulton et al. 1995 a,b.) (Fig. 2).

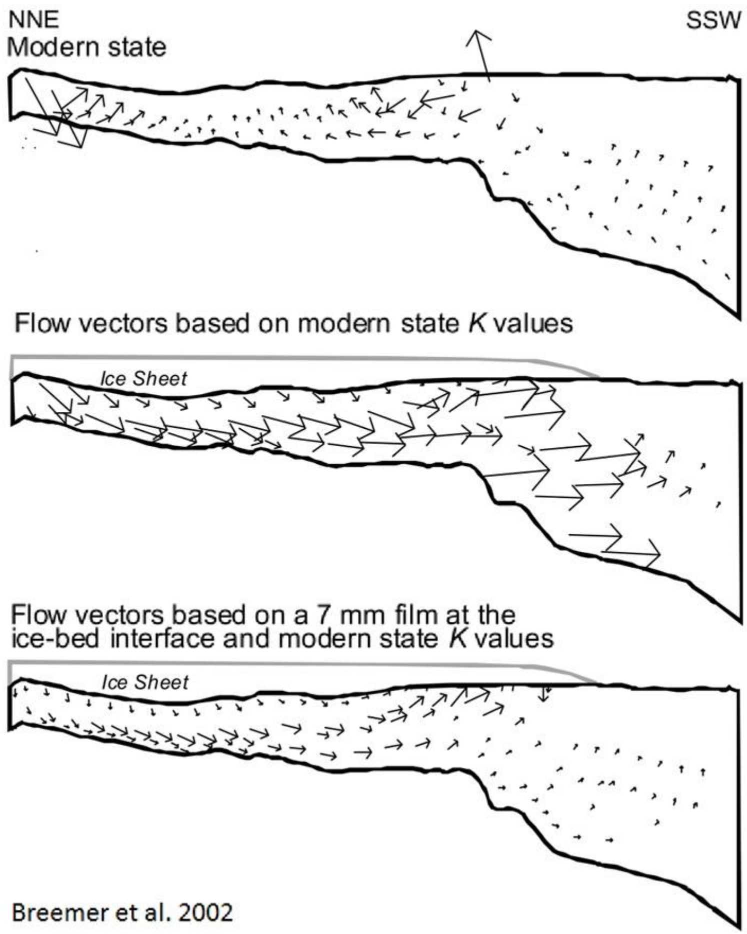


Figure 2. This figure from Breemer et al. 2002 shows the modeled groundwater flow vectors from three different model runs along a single flow line of the Lake Michigan lobe. The top model represents modern conditions. The middle model represents Pleistocene conditions with modern K values and no subglacial drainage systems. The bottom model represents Pleistocene conditions with modern K values and a 7 mm thick water film at the ice-bed interface.

During the Last Glacial Maximum the glacial margin of the Laurentide Ice Sheet was located in Northern New Jersey. As the ice sheet receded it left behind three distance moraines that overlie three distance geologic regions. The terminal moraine associated with each lobe has a distinct morphology that may be related to the basal water, the underlying geology the ability of the subglacial aquifer to transmit glacial meltwater. Therefore, the purpose of this study is to use groundwater flow models to explore the relationship between regional geology and glacier flow dynamics for a time period near the end of the Last Glacial Maximum. Although this study is similar to previous studies by Breemer et al. (2002) and Carlson et al. (2007), the configuration of the aquifer is significantly different. In particular the aquifer system underlying the glacier is in a basin, therefore the groundwater flow would move out of a basin rather than into a basin as it did near the mid-continent lobes.

Ice internal deformation is caused by ice crystals deforming and sliding past one another. This deformation rate is a function of temperature and is summarized by Glenn's Flow Law (Glenn 1958):

$$\text{Strain} = A\tau^{n} \quad (1),$$

where τ is the basal shear stress (kN m^{-2}) and both A and N are functions of temperature.

Glacier shear stresses are observed to be in a narrow range, 20 – 150 kN m^{-2} for internal deformation to occur. Glacial thickness reconstructions use evidence for the presence and absence of basal water and threshold shear stress values (e.g. 150 kN m^{-2}) to reconstruct ice sheet thickness. To calculate the thickness of the glacier above the aquifer the Orowan and Perutz (1949) equation is used:

$$H^2 = \frac{2\tau}{\rho_i g}x \quad (2),$$

where x is the distance from the glacial margin.

When liquid water is present, glaciers can also move by basal sliding, which the sliding of the glaciers along the base and represents movement in addition to internal deformation. A mountain glacier for example, moves by internal deformation during the winter months and then by basal sliding as meltwater accumulates at the glacier base.

Therefore, we can determine the thickness of the glacier by estimating the critical shear stress and position from the glacier snout (thickness = 0) and other known points of the glacier thickness. The ice thickness produces that overburden stress that the glacier exerts on the aquifer. Therefore, the local ice sheet thickness is used to determine hydrostatic pressure:

$$P_i = \rho_i g H_i \quad (3),$$

where P_i is the overburden stress, ρ_i is the density of ice (900 kg m^{-3}), g is the acceleration from gravity (9.81 m s-^{2}), and H_i is the glacier thickness above a given point within the aquifer. The presence of water beneath the ice sheet affects two important parameters, the critical shear stress of the glacier and the recharge rate of the aquifers beneath the glacier. Observations of basal melt rates of modern ice sheets in Greenland and Antarctica range from 1 to 7 mm yr^{-1} (Bell 2008).

Given these melt rates the water could accumulate at the base of the glaciers. The basal water layer is likely to be thin, but given the basal water layer is to be included in a groundwater flow model, it needs to be thin enough to still act as a laminar flow layer. Groundwater flow velocities in fractures or gaps are proportional to the gap or fracture diameter (D) squared. Fractures with diameters below 1 cm in thickness maintain laminar flow and thus meet the criterion for Darcian flow:

$$V = aD^2 \quad (4).$$

Therefore, the basal water later is modeled with a thickness less than 10 mm (Breemer et al. 2002).

Hypotheses

1. The presence of a subglacial water film would create a low hydraulic gradient in New Jersey aquifers near the LGM glacial margin in New Jersey, whereas absence of a subglacial water film in the same New Jersey aquifer system would result in a high hydraulic gradient localized beneath the ice sheet.
2. Thicker overlying ice sheets will produce a steeper hydraulic gradient, but this effect will be less significant than the presence of a basal water film.

3. Therefore, the lowest hydraulic gradient in the aquifer would be associated with a thin ice sheet thickness and the presence of a subglacial water film; conditions that would be associated with warm, wet ice streams prior to glacial retreat.

These hypotheses can be evaluated with the MODFLOW groundwater flow model applied to the hydrostratigraphic characteristics of the New Jersey aquifers.

Study Site: The Quaternary and Bedrock Geology of the LGM New Jersey Lobe

The study site is located in Northern New Jersey. The glacial moraines of the New Jersey lobe show three distinctive surface profiles (Fig. 3). These moraines establish the glacial margins of the three major glacial lobes in Northern New Jersey. The eastern sub-lobe has a prominent moraine and significant glacial meltwater deposits parallel to the Hudson River. To the west the moraines front is located further north and there is also evidence of glacial meltwater in front of the terminal moraine. The western lobe has less well-defined moraines and more localized glacial meltwater deposits.

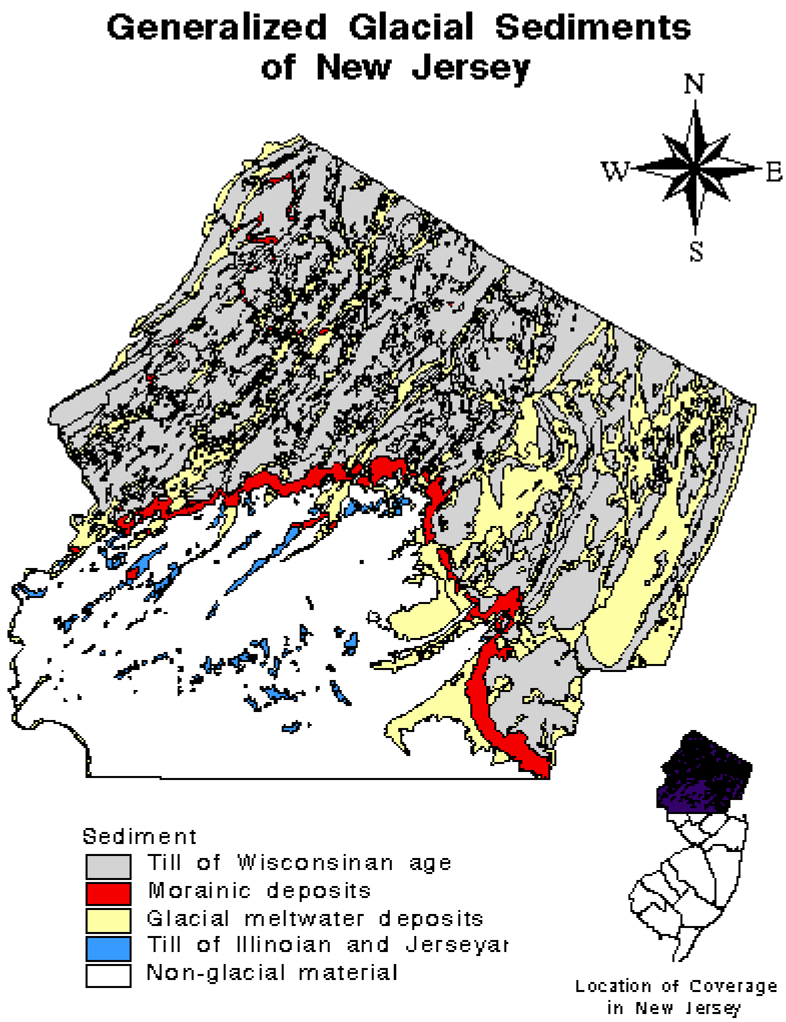


Figure 3. Generalized map of glacial sediments (New Jersey Department of Environmental Protection and the New Jersey Geological Survey; 2002). Terminal moraines (red) define the margin of the Laurentide Ice Sheet during the Wisconsonian glacial period.

Pre-Pleistocene Geology

The aquifer systems of New Jersey occupy three distinct geologic regions separated by faults and distinctive changes of lithology. These three regions are the Atlantic Coastal Plain, the Piedmont and the New Jersey Highlands (Fig. 4). The Atlantic Coastal Plain forms the eastern margin of the North Atlantic United States. The formations in the Atlantic Coastal Plain dip gently to the east and achieve maximum depths of about 2000m. The lithologies consist mostly of Tertiary and Cretaceous sandstones and unconsolidated sands, silts, and clays (Owens et al. 1998). In contrast to its neighboring aquifers, the Atlantic Coastal Plain has the most permeable aquifers of the surrounding regions (Mannel et al. 2012).

The Piedmont region forms the boundary between the Highlands and the Atlantic Coastal Plain. The units dip towards the west and is separated by two normal faults along the eastern and western boundaries (Drake et al. 1997, Owens et al. 1998). The most prominent geologic feature of the Piedmont region in New Jersey is the Newark Basin which consists mostly of Mesozoic claystone and siltstone to the east and basaltic sills to the west. Many of the aquifers in the Piedmont have poor hydraulic conductivity and much of the fluid is transmitted through fractured rock (Serfes 1994).

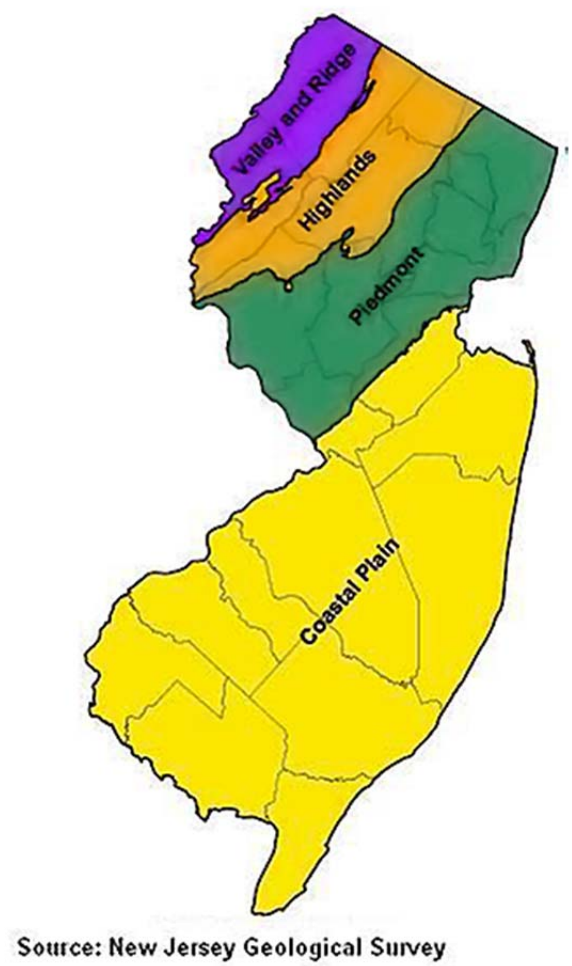


Figure 4. The three geological provinces of New Jersey: The Coastal Plain, Piedmont, and Highlands/Valley and Ridge Provinces New Jersey Department of Environmental Protection and the New Jersey Geological Survey (2002).

II. METHOD OF ANALYSIS

Numerical Groundwater Flow Modeling

Steady-state groundwater flow beneath the Laurentide Ice Sheet is modeled with the USGS ground water modeling program MODFLOW (Harbaugh, 2005). MODFLOW is a three-dimensional finite-difference groundwater modeling program (Harbaugh 2005). To calculate the hydraulic gradient, MODFLOW uses a modified version of Laplace's partial differential equation, which is a combination of Darcy's Law and the continuity equation. MODFLOW modifies Laplace's original equation by accounting for the recharge and pumping rates and storativity of the aquifer:

$$\frac{\delta}{\delta x}\left(-K_{xx}\frac{\delta h}{\delta x}\right)+\frac{\delta}{\delta y}\left(-K_{yy}\frac{\delta h}{\delta y}\right)+\frac{\delta}{\delta z}\left(-K_{zz}\frac{\delta h}{\delta z}\right)+W=S_s\frac{\delta h}{\delta t} \quad (5),$$

where $K_{xx,yy,zz}$ is the directional hydraulic conductivity (m yr^{-1}), h is the hydraulic head (m), W is the volumetric flux (yr^{-1}) where W>0 represents a recharge event and W<0 represents a drawdown event, S_s is the specific storage of an aquifer (m^{-1}), and t is the time interval (yr). MODFLOW applies this equation over a three-dimensional aquifer system with the finite-difference equation:

$$\sum Q_i = S_s\frac{\Delta h}{\Delta t}\Delta V \quad (6),$$

where Q_i is the flowrate of the cell (m^3 yr^{-1}), ΔV is the volume of the cell (m^3), Δh is the change in head (m), and Δt is the time interval (yr) (Harbaugh 2005).

Modeling Groundwater Flow

Applying this model to the subglacial aquifers will involve a series of steps of data compilation and establishment of boundary conditions to develop a functional model that can be run for the sets of conditions that will test the hypotheses (Fig. 5). For each glacial lobe modeled, I created a hydrostratigraphic model, defined the boundary conditions, and built a numerical model. The model is a two-dimensional representation of the aquifers along the central flow line of the glacier. The hydrostratigraphic model was developed by compiling relevant field data to establish hydraulic conductivities (K), unit thicknesses (z) and boundary conditions in and around the aquifers. The numerical model is designed around the hydrostratigraphic model with the addition of known head boundaries and recharge rates provided by the overlying glacier.

The purpose of the conceptual model is to establish the boundary conditions and aquifer properties used by the numerical model. I have developed several scenarios of glacier thickness to constrain the hydraulic head values in the top of the aquifer. Simulations from the numerical model provide quantitative values of head along the glacier flow line for different scenarios of glacial thickness and water film thickness.

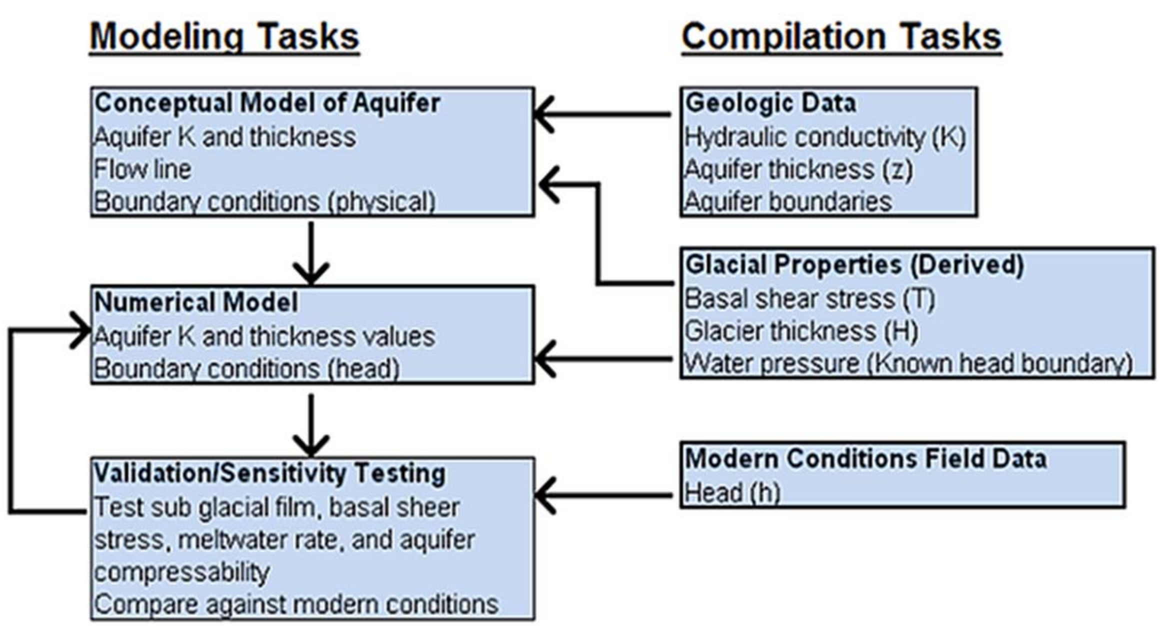


Figure 5. The flow chart outlines the processes involved for modeling subglacial hydrology. On the right side there are the compilation tasks of data collection, establishing boundary conditions, and ice sheet reconstruction. To the left are modeling tasks that use the compiled data.

The model is run with multiple sets of parameters designed to test the original hypotheses. Model runs are designed to evaluate different combinations of glacial thickness and water film thickness. These combinations are outlined below:

Table I: Parameters used in model runs

Variables	Film Thickness (mm)	Basal Shear Stress (kN m^{-2})	Basal Melt Rate (mm yr^{-1})
Series 1			
Trial 1	7 mm	20 kN m^{-2}	1 mm yr^{-1}
Trial 2	7 mm	150 kN m^{-2}	1 mm yr^{-1}
Trial 3	7 mm	20 kN m^{-2}	7 mm yr^{-1}
Trial 4	7 mm	150 kN m^{-2}	7 mm yr^{-1}
Series 2			
Trial 1	0 mm	20 kN m^{-2}	1 mm yr^{-1}
Trial 2	0 mm	150 kN m^{-2}	1 mm yr^{-1}
Trial 3	0 mm	20 kN m^{-2}	7 mm yr^{-1}
Trial 4	0 mm	150 kN m^{-2}	7 mm yr^{-1}

Model Domain

Northern New Jersey has three terminal moraines that establish the margins of the glacial lobes. These terminal moraines were deposited between the Hudson and Delaware Rivers during the Wisconsonian glacial period (Stone et al. 2002). During the Wisconsonian glacial period the glacial lobes flowed approximately 45^0 SW based on the assumptions made on the geomorphology of the moraines. For identification purposes the glacial lobes are labeled Lobe #1, #2, and #3 (Fig. 6).

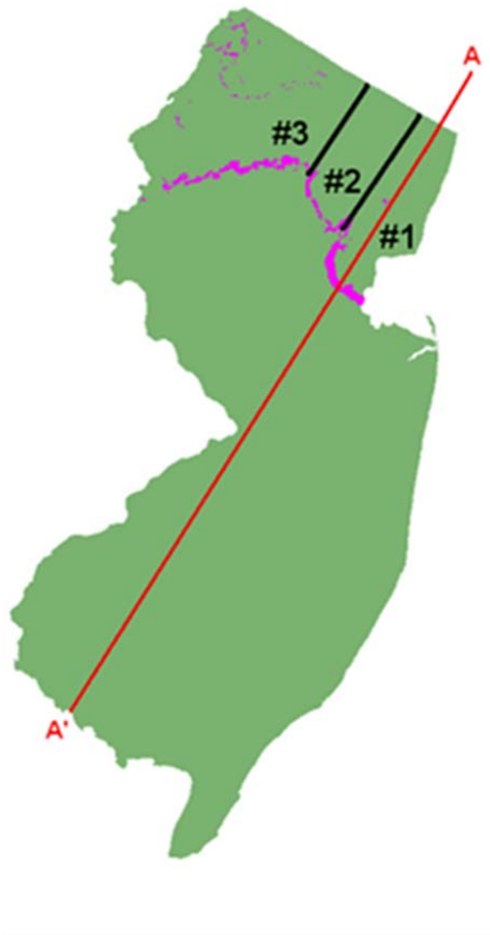


Figure 6. The pink corresponds to the terminal moraines, #1, #2, and #3 correspond to the different lobe of Northern New Jersey separated by black lines. The red A – A' line represents the central flow line profile for Lobe #1 and the boundary for the first hydrostratigraphic model.

Lobe #1 is the easternmost lobe bounded by the Hudson River. The moraine formed by Lobe #1 has the furthest southern extend among all of the moraines which suggests that it was the fastest moving glacier relative to the other neighboring lobes at the time. It rests above the Piedmont Provinces on a formation known as the Newark Basin and stops at about 8 km over the Coastal Plain Province. The moraine of Lobe #1 the most arcuate and best defined of the three lobes which suggests that it was the most erosive among the three glaciers and may have had basal water films (Boulton et al. 1995b).

Similarly Lobe #2 has a well-defined arcuate moraine that overlies the columnar basalts of the Piedmont Provinces. The moraine does not extend as far south as its eastern neighbor and is not as well defined. This suggests that the glacier was moving slower and was less erosive than Lobe #1 (Boulton et al. 1995b).

In contrast Lobe #3 is the least defined and has the least arcuate moraine among the three lobes in the study area. Unlike Lobes #1 and #2, the underlying aquifers offer very poor conditions for groundwater accommodation and flow. In this region much of the flow is accommodated through fractured bedrock which loses permeability with increased overburden stress that can close fractures. Therefore, using modern fractured rock aquifer properties would likely be an overestimate of groundwater flow conditions during the Late Wisconsonian Glacial period without considering the fracture compression at a depth determined by the ice sheet.

Hydrostratigraphic Model and Boundary Conditions

The hydrostratigraphic model is a two-dimensional representation of the aquifer along the central flow line of the glacier. To construct the hydrostratigraphic model, a combination of geological cross sections, hydrological databases, and previous groundwater hydrology studies are compiled (Drake et al. 1997, Owens et al. 1999, Martin 1998, Mannel et al. 2012, Vyas et al. 2004).

The Delaware River forms the southern boundary as a boundary of a known hydraulic head of zero. The presence of glacial striae suggests a decrease in basal water pressure that establishes the northern boundary as a no-flow boundary (Dyke and Prest 1987) (Fig.7). The rationale is that the glacial striations from where basal pore-water pressure is low, which implies that this is part of the accumulation zone of the glacier, north of the equilibrium line (Glasser and Bennett 2004). The glacial profile forms a known head boundary based on ice thickness. The ice sheet itself is treated as an impermeable boundary at the top of the hydrostratigraphic units that comprise of the model. Finally, the Precambrian basement rocks forms a near-impermeable boundary at the base of the aquifer.

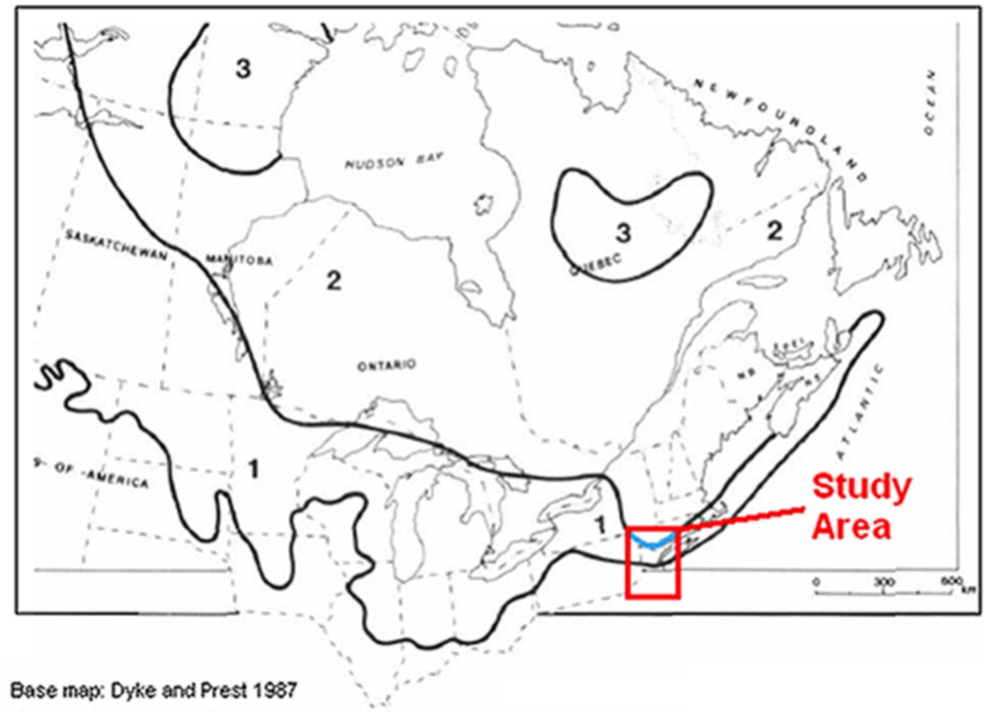


Figure 7. A map compiled by Dyke and Prest (1987) showing the profile of the Laurentide Ice Sheet. Zone 1 is characterized by terminal moraines and hummocky terrain and Zone 2 is characterized by glacial striae and esker formation. The study area is outlined in red with the blue line highlighting the Zone 2 boundary which forms the northern no-flow boundary condition.

GIS Compilation of Glacial and Subglacial Geological Maps

To produce a map and a cross section of the study area I compiled geologic and hydrostratigraphic data from Drake et al. 1997, Owens et al. 1998, Martin 1998 , and Stone et al. 2002. The map displayed in Figure 8 is a compilation of surface geology (Drake et al. 1997, Owens et al. 1998) and sediments (Stone et al. 2002). This map outlines the glacier margin and the boundaries of the regional geology which provides the upper boundary for the conceptual model.

To produce a hydrostratigraphic model of the Coastal Plain aquifer along the A – A’ flow line I use hydrostratigraphic cross section data from Martin 1998 (Fig. 9). For modeling purposes the Coastal Plain aquifer is grouped into a series of a top and bottom aquifers and a central aquitard. The K values of these aquifers are the mean K values for all of the grouped aquifers/aquitards. The data processed in Figures 8 and 9 is used along with geologic cross sections by Owens et al. 1998 to produce a two dimensional cross section of the hydrostratigraphy of the A – A’ flow line (Fig. 10).

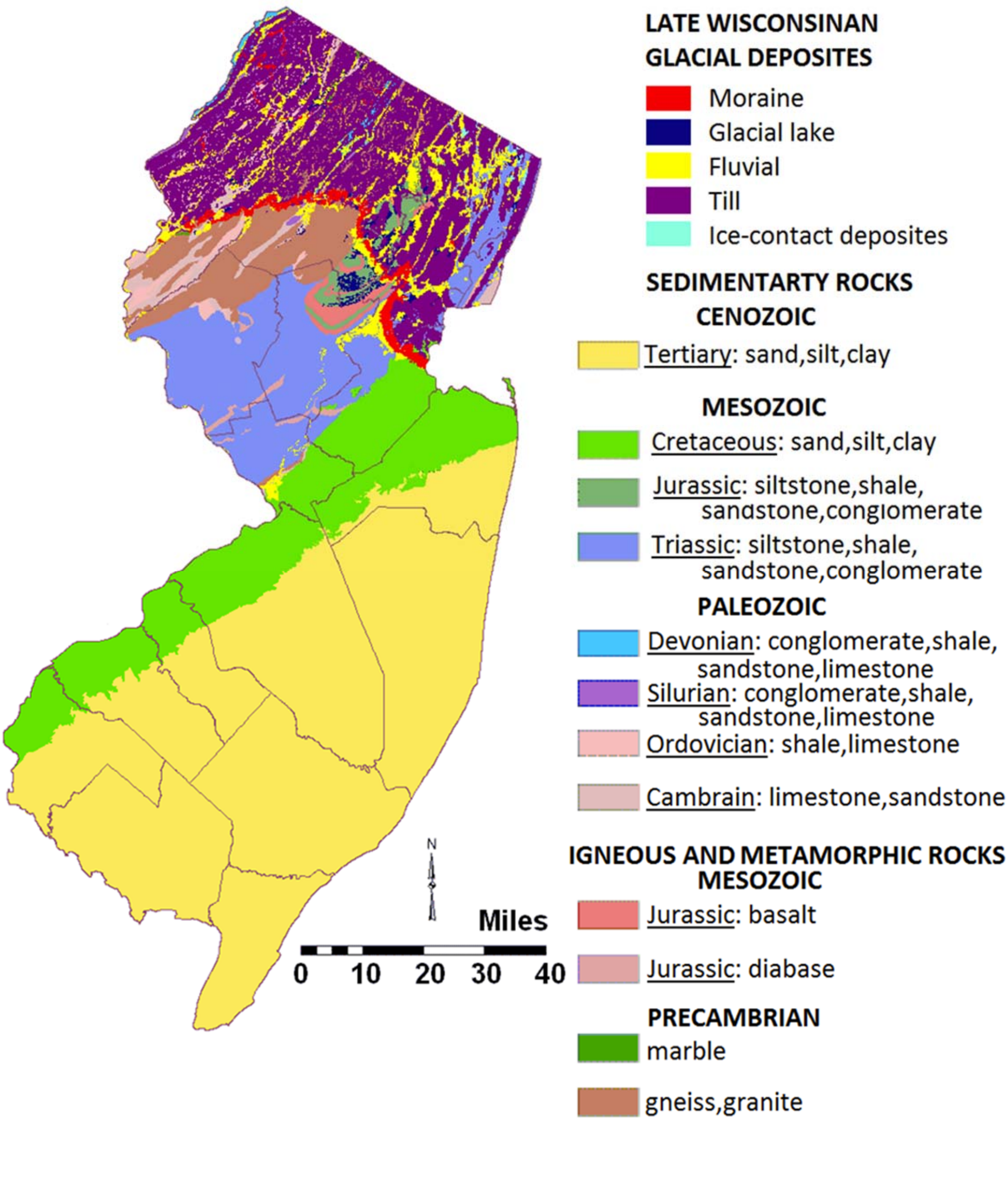


Figure 8. Map compiled from GIS data from Drake et al. (1997), Owens et al. (1998), and Stone et al. (2002) showing the surface glacial deposits and related bedrock geology.

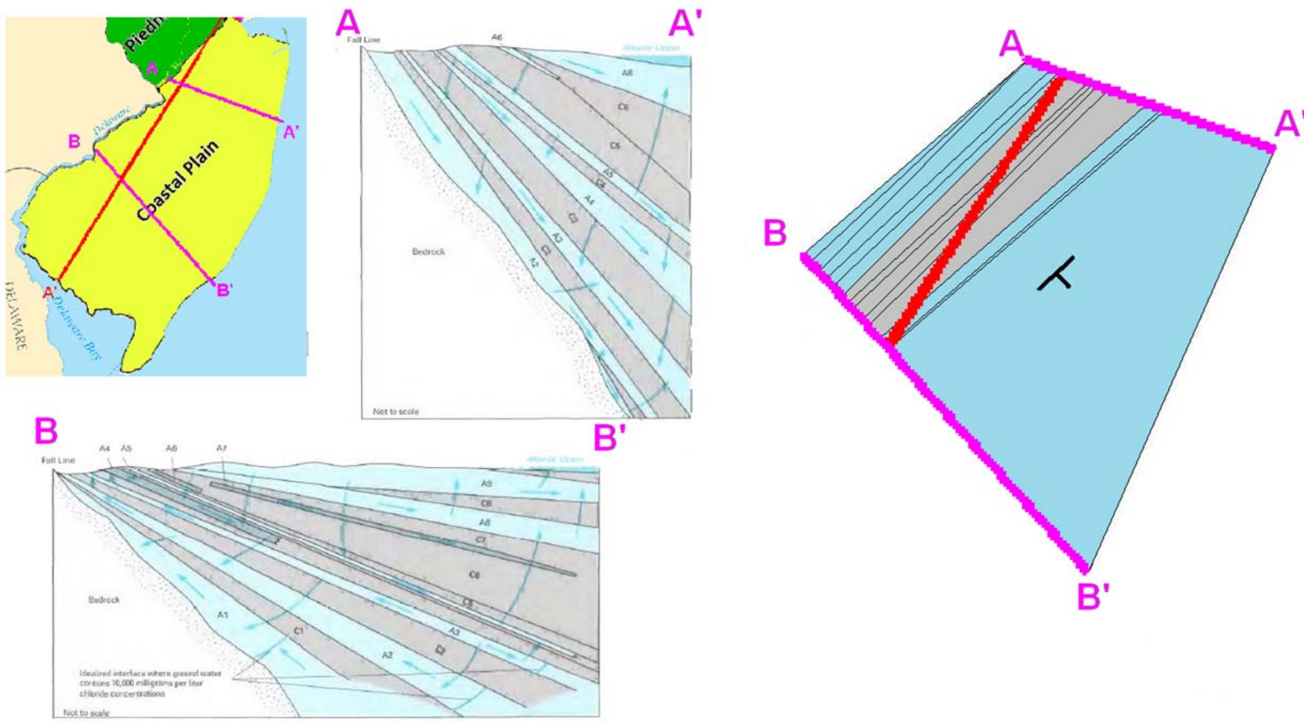


Figure 9. Using hydrostratigraphic data from Martin 1998 I modeled the Coastal Plain hydrostratigraphy along the A-A' flow line shown in Figure 6 to produce the image on the right. Aquifers are shown in blue and aquitards are shown in gray. To simplify the model aquitards were grouped together where they are at high abundance in the middle of the model and the average hydraulic conductivity of the grouped units are used.

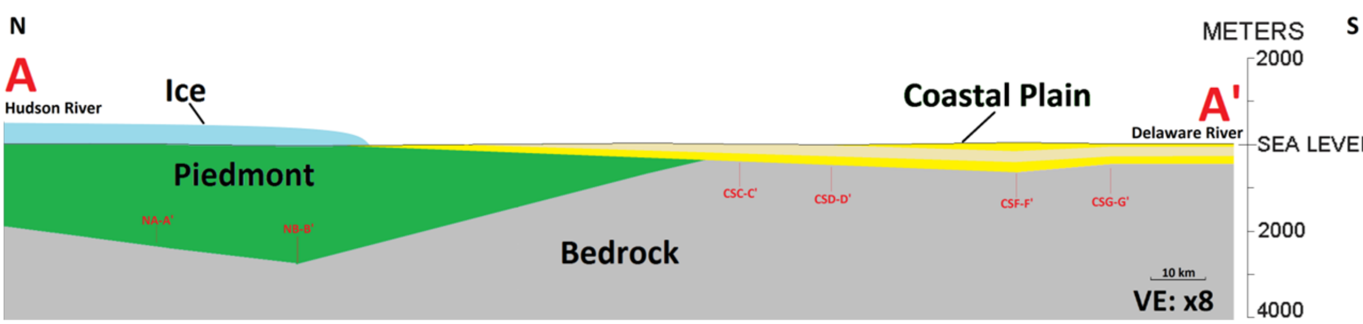


Figure 10. Two-dimensional cross section compiled with hydrostratigraphic data from Martin 1998 and Geologic data from Owens et al. 1998. This model corresponds to the flow line shown in figure 6. The cross section forms the boundary conditions of the conceptual model and subsequently the numerical model. The green represents the Piedmont aquifers with K values from Mennel (2002) (Appendix D). The yellow and light brown represents the Coastal Plain aquifers and aquitards respectively with K values from

Martin (1998) (Appendix A-C). The gray represents bedrock with K values of 3.16E-5 that extends 1 km below the the Piedmont and Coastal Plain.

Glacial Parameters that Constrain the Hydraulic Boundary Conditions

The purpose of the numerical model is to provide quantitative values of hydraulic head along the glacial flow line. The numerical model uses MODFLOW to calculate the groundwater flow. MODFLOW fundamentally relies on solving equation (5), therefore, the values for hydraulic conductivity ($K_{xx,yy,zz}$) and storativity (S_s) become essential variables required for solving the flow equations.

The boundaries and aquifer properties of the numerical models are based on the conceptual hydrostratigraphic models of the Atlantic Coastal Plain, and Piedmont aquifers. A two-dimensional rectangular grid is fit to the hydrostratigraphic model along the central flow line of the glacier. To calculate the overburden stress, the ice sheet thickness is determined from the shear stress-distance relationship (2), where τ is the basal shear stress (kN m^{-2}) and x is the distance from the glacial margin. The values for shear stresses are 20 and 150 kN m^{-2} which model a wet and relatively dry glacier. The values for shear stresses is constrained between 20 and 150 kN m^{-2} as a range of shear stress values based on observed in modern environments for a glacier sliding at its base. values based on observed in modern environments for a glacier sliding at its base. The recharge rate beneath the glacier is also varied, and the minimum and maximum values of basal melt, based on the basal melt rates of modern observations of ice sheets in Greenland and Antarctica of 1 to 7 mm yr^{-1} (Bell 2008). This calculation will be used in a series of horizontal cells relative to the length and position of the glacier to establish a known head domain boundary.

Directly beneath the known head domain established by the glacier is the subglacial drainage layer which acts as a source of recharge for the system. This layer is simulated by the Romm (1966) fluid in fracture flow equation:

$$K = \rho_w gb^2 / 12\mu \ (7),$$

where ρ_w is the density of water at 0^oc (1000 kg m^{-3}), μ is the viscosity of water at 0^oc (5.67 E+4 m^2 yr^{-1}) b is the subglacial film width (0 – 7 mm).

Sensitivity Analysis and Hypothesis Testing

To test the hypotheses, I evaluate the response of the model to three different parameters in various combinations (Table. I). The parameters are subglacial film thickness (mm) which relates to the amount of water at the glacier base, basal shear stress (kNm^{-2}) which relates to the ice sheet thickness, and the basal melt rate ($mm\ yr^{-1}$). To test the first hypothesis, all of the variables are initially set to their lowest reasonable values and each variable is tested individually. To test the second hypothesis, all of the variables are initially set to their highest reasonable values and each variable is tested individually. To test the hypothesis, the models are compared using the Wilcoxon rank-sum test.

III. RESULTS AND ANALYSIS OF UNCERTAINTY

Model Results

I ran the model to simulate eight different scenarios, which model basal shear stresses of 20 to 150 $kN\ m^{-2}$, subglacial water film thickness from 0 to 7 mm, and a basal melt rate of 0 to 7 $mm\ yr^{-1}$. The model runs are designed to simulate steady state conditions beneath the glacier over a one year period. I also ran the model to simulate modern non-glaciated conditions (fig. 11) by deactivating the top two layers that were used to simulate the thickness of the glacier and the thickness of the subglacial water film and by setting a constant infiltration rate of 0.13 $m\ yr^{-1}$ for the Piedmont and 0.228 $m\ yr^{-1}$ for the Coastal Plain based on assumptions made by Daniel 2002 using the methods outlined by Charles et al. 1993.

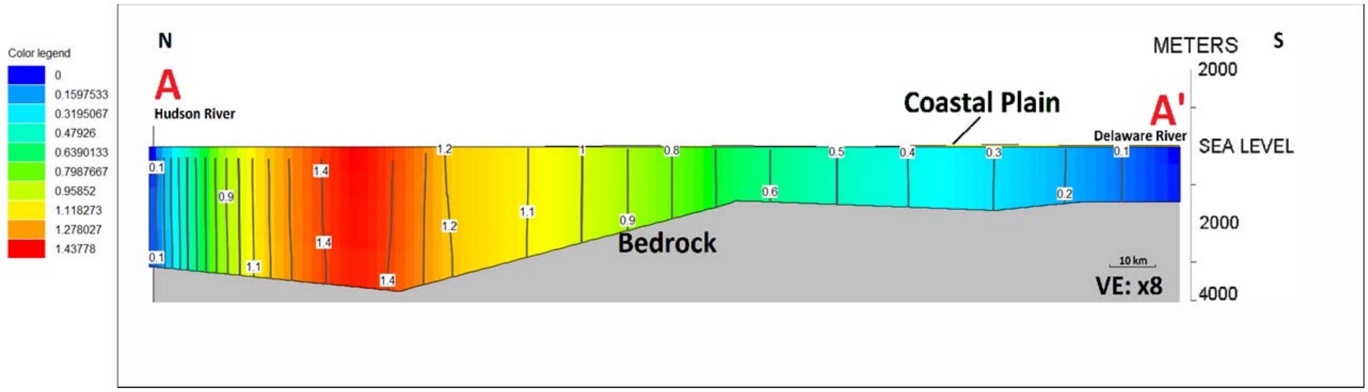
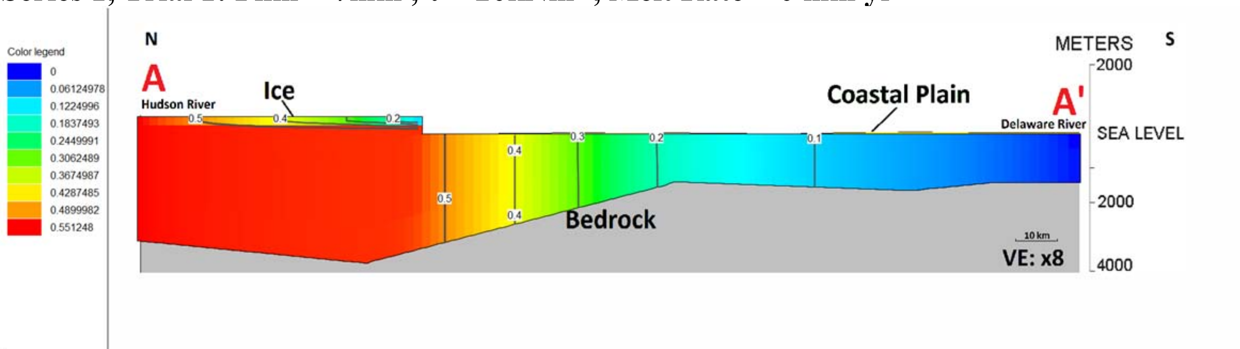


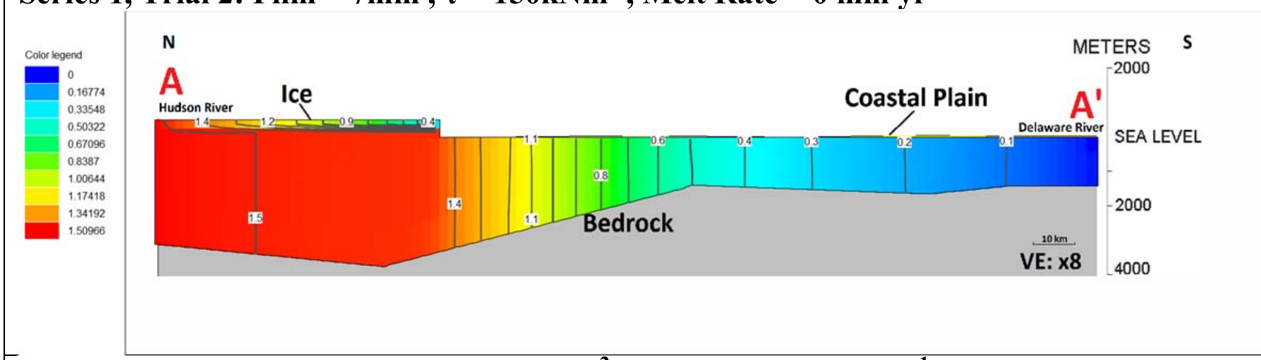
Figure 11. A model run of present, non-glaciated conditions (no overlying glacier or subglacial water film). This model was given a constant recharge rate of 0.13 m yr^{-1} for the Piedmont and 0.228 m yr^{-1} for the Coastal Plain at the surface. The model has the highest head measurements in the center of the.

The present day simulation produced the largest head values at the center of the basin (Fig. 11). The highest head values were only slightly larger than the thick glacier (150 kN m^{-2}) simulations. The model runs which had 150 kN m^{-2} for the basal shear stress produced higher overall heads with a proportionally increasing hydraulic gradient compared to the model runs with 20 kN m^{-2} as the basal shear stress value. Basal melt rates between 0 and 7 mm had no apparent effect on the hydrology of the model. The presence of a 7 mm subglacial water film produced lower hydraulic gradients than models run without the presence of a subglacial water film (Fig. 12).

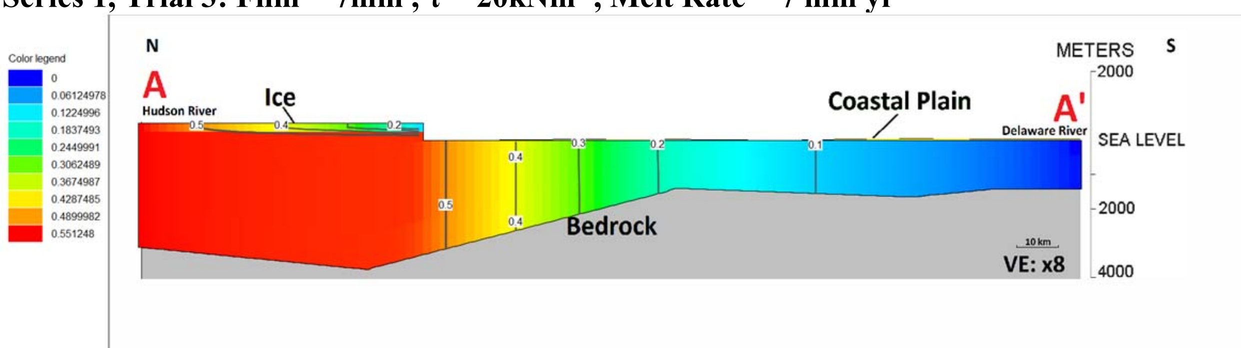
Series 1, Trial 1: Film = 7mm , τ = 20kNm^{-2}, Melt Rate = 0 mm yr^{-1}



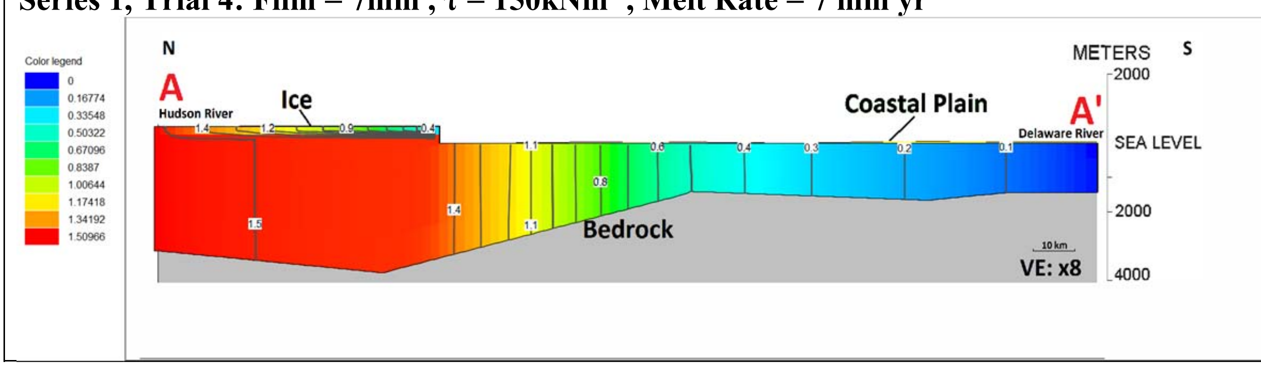
Series 1, Trial 2: Film = 7mm , τ = 150kNm^{-2}, Melt Rate = 0 mm yr^{-1}



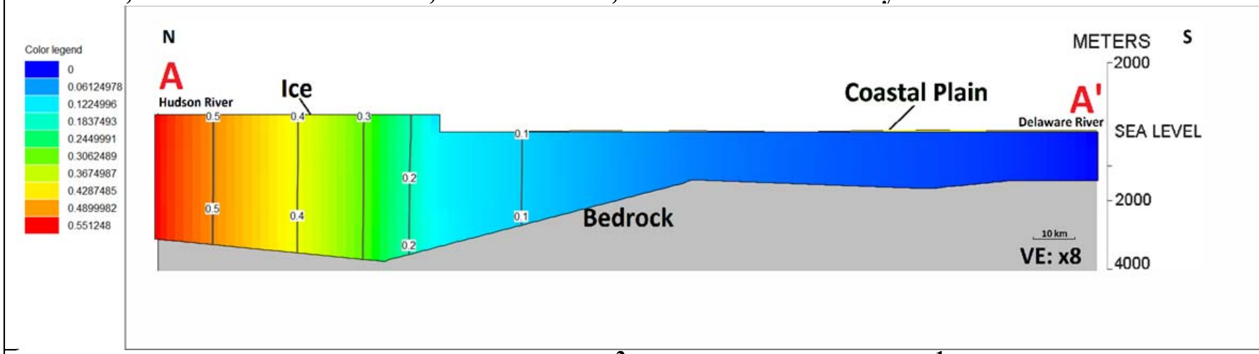
Series 1, Trial 3: Film = 7mm , τ = 20kNm^{-2}, Melt Rate = 7 mm yr^{-1}



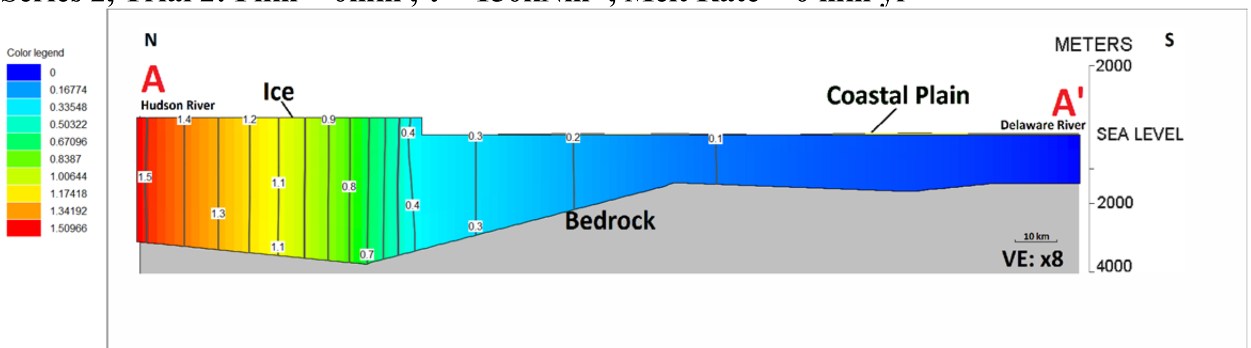
Series 1, Trial 4: Film = 7mm , τ = 150kNm^{-2}, Melt Rate = 7 mm yr^{-1}



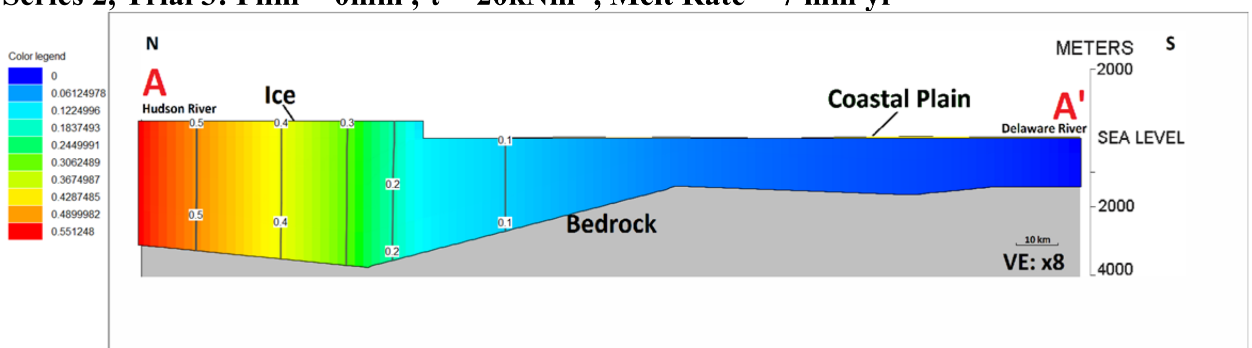
Series 2, Trial 1: Film = 0mm , τ = 20kNm^{-2}, Melt Rate = 0 mm yr^{-1}



Series 2, Trial 2: Film = 0mm , τ = 150kNm^{-2}, Melt Rate = 0 mm yr^{-1}



Series 2, Trial 3: Film = 0mm , τ = 20kNm^{-2}, Melt Rate = 7 mm yr^{-1}



Series 2, Trial 4: Film = 0mm , τ = 150kNm^{-2}, Melt Rate = 7 mm yr^{-1}

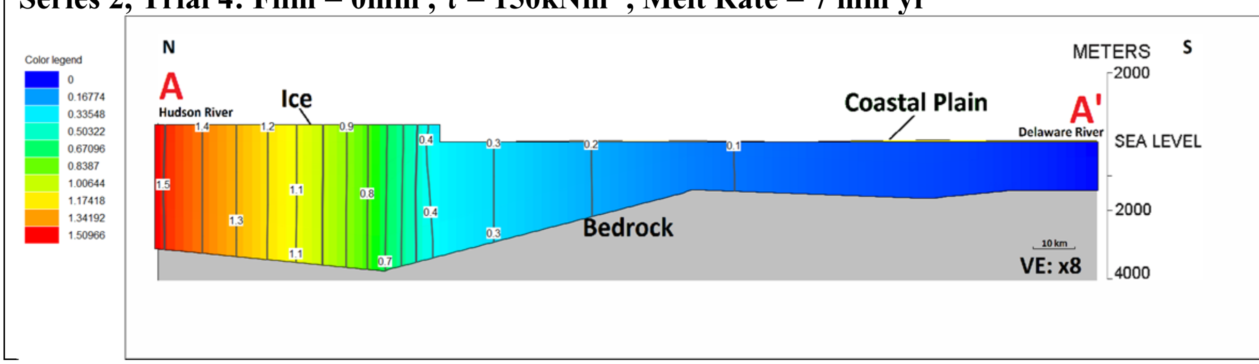


Figure 12. The model results from Trials 1 – 4 of both Series 1 and 2 (Table I). The scale of the model is relative to the modeled results and each contour represents hydraulic head increments of 0.1 m. All of these models are modeling steady state conditions of the New Jersey aquifers along the A – A' flowline under the effects of a glacier over a one year period of time.

Uncertainty Analysis

Uncertainty is assessed through the data collected and the sensitivity analysis of the model. All of the aquifer property data is the result of field testing and therefore has quantifiable error associated with it. In addition, hydraulic conductivity values are highly variable in both fractured rock and sedimentary rocks. Some reports also do not report error and only provide the mean values. In these cases, the error associated with similar aquifers is used.

The numerical model constructed in MODFLOW also has error associated with fitting and truncation. Generally with longer time-steps and larger grid spacing the more truncation error will be introduced. Fitting cells to the geologic bedding also induces error since a cubic grid will not fully conform to the slope of the geologic unit. Fitted grid lines may not follow the fundamental equations that MODFLOW uses which may result in misaligned hydraulic conductivities (Harbaugh 2005).

MODFLOW has a feature for calculating discrepancy between in-flow and out-flow of the model given by the equation:

$$D = \frac{200(IN - OUT)}{(IN + OUT)} \quad (8)$$

where D is the percent discrepancy, IN is the volume of flow into the model, and OUT is the volume of flow out of the model. If the volume of in-flow does not match the volume of out-flow then the mass balance requirements of a steady state model is not met and the amount of discrepancy can be reported as a feature of the model test.

To evaluate the response of the numerical model to input variables, various sensitivity tests are performed. The variables that are tested are: the hydraulic conductivity of subglacial till, the basal shear stress of the glacier for values between 20 and 150 (kN m^{-2}), and the meltwater discharge rates for values between 1 to 7 mm yr^{-1}. Values greater than 7 mm yr^{-1} may be possible but that would produce a layer of water that would violate the assumptions of Darcian flow.

For further validation the model is applied to modern boundary conditions. Therefore the glacier properties and confining unit on the top layer are replaced with a constant recharge along the entire top of the model based on modern infiltration rates of the aquifer.

Model Limitations

This model is a two-dimensional representation of what is essentially a three-dimensional problem. This model runs almost parallel to the general strike direction of the aquifers (Fig. 9). Therefore, some of the water pressure may be driven out of the system as gravity should drive flows towards the dip direction which this model does not account for. This could result in lower than expected head values especially near the glacial margin.

As noted in Figure 9, the geology of this region is very complex with many heterogeneous aquifers stacked in rapid succession over a relatively shallow depth of approximately 500 m. This model does not take into account the heterogeneity of the aquifers and simplifies the numerous aquifer-aquitard bands into three distinct bands with averaged K values. The model also does not take into account the effects on aquifer compression from the glacier and the effects of permafrost which would decrease present day measurements of hydraulic conductivity and alter the available pore space of the aquifers.

Another limitation of this model is the lack of modern analogs. The only comparable ice sheets in terms of mass are the Greenland and Antarctic ice sheets. However, these ice sheets overlay impermeable bed rock and flow directly out to sea. Therefore, the only potentially comparable analog to this system in the present day is the southwestern tongue of the Vatnajökull glacier in Iceland.

IV. DISCUSSION AND CONCLUSIONS

Discussion and Conclusions

The presence of a subglacial water film decreases the hydraulic gradient which supports the first hypothesis. However the thickness of the ice sheet does have a greater effect on the hydraulic gradient than expected in hypothesis two. This could be because the relatively short distance from the glacial margin to the Delaware River and the shallow depth of the Coastal Plain aquifer are not enough to accommodate the heads produced by a thick glacier.

Basal melt rate seemed to have an insignificant role in determining head distribution for the glaciated systems. However, surface recharge rate of the present non-glaciated system had a significant role in determining head magnitude and distribution of the system. This suggests that the thickness of the glacier and the subglacial water film thickness are the determining variables for the subglacial hydrology of New Jersey.

With the presence of a subglacial water film, the aquifers are able to distribute water pressures more evenly throughout the system beneath the glacier (Fig. 13). This produces higher heads directly beneath the glacier but allow for a shallower hydraulic gradient whereras the lack of a subglacial water film produces a high hydraulic gradient especially beneath the glacial margin.

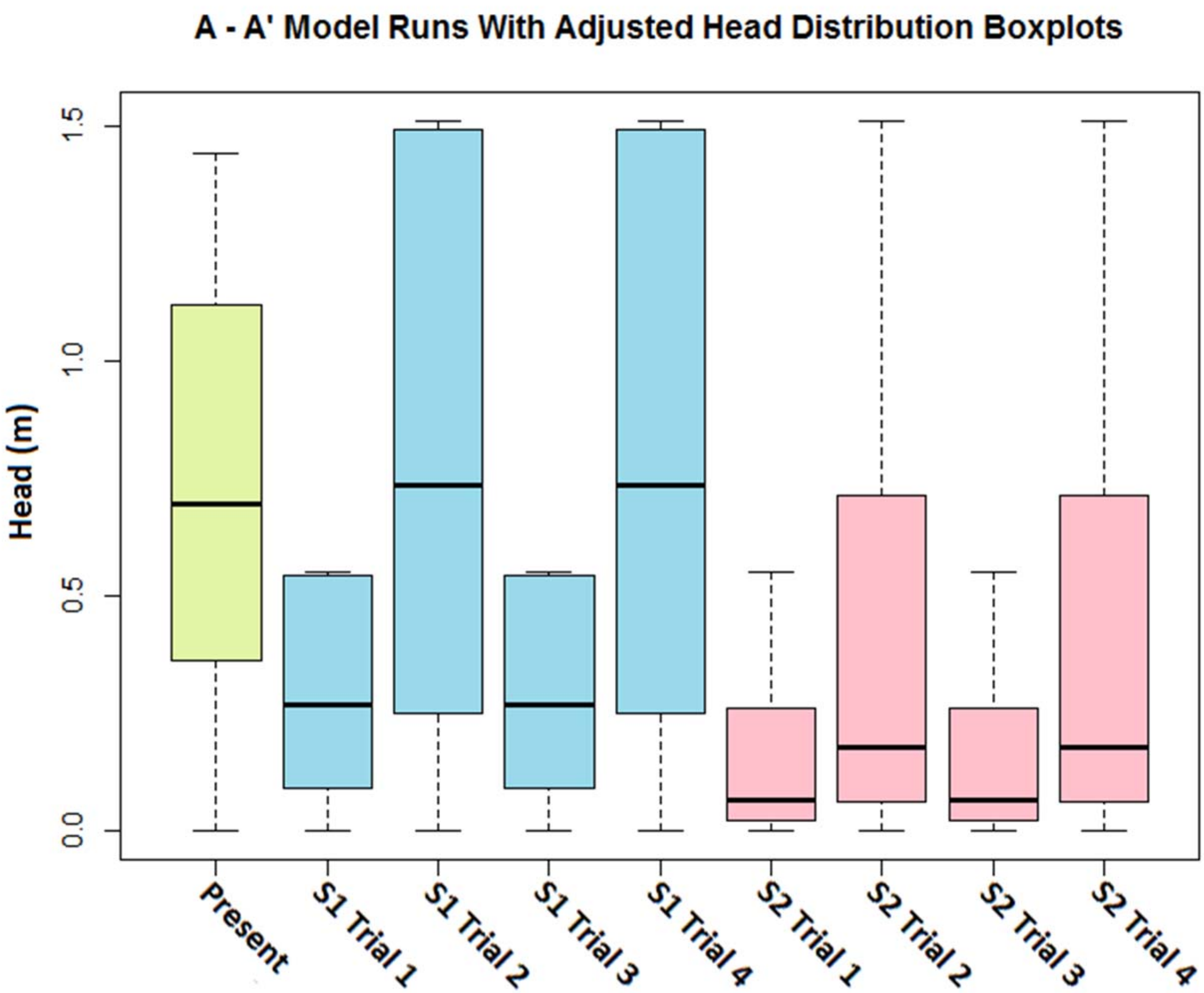


Figure 13. A series of boxplots representing each model trial using the variables outlined on Table I. Series 1 (S1) shown in blue features a 7 mm subglacial water film whereas Series 2 (S2) shown in red has no subglacial water film. Trial 1 of both series models a glacier with a shear stress of 20 kN m^{-2} while trial 2 of both series models a glacier with a shear stress of 150 kN m^{-2}. Trials 1 through 4 of their respective series share the same distribution geometry but on a different scale which suggests a linear relationship between head distribution and glacial thickness. Series 2 however is highly positively skewed while series 1 is more negatively skewed with trials 2 and 3 more resembling present conditions.

As the glacier forms and melts, the groundwater response would have most likely followed a specific series of head distributions over time as depicted in figure 14 where prior to glaciation the groundwater system would most have likely resembled the model of the present day conditions (Fig. 11) with the highest heads near the center of the basin and the lowest heads at the Hudson and Delaware Rivers. The most likely system that would have existed during the Last Glacial Maximum may have been a thick glacier, dry at the base glacier similar to what is modeled in Series 2 Trial 2 (Fig. 12). During the melting period of the glacier the likely system that existed may have been a low profile glacier which was wet at the base such as the system modeled in Series 1 Trial 3 (Fig. 12).

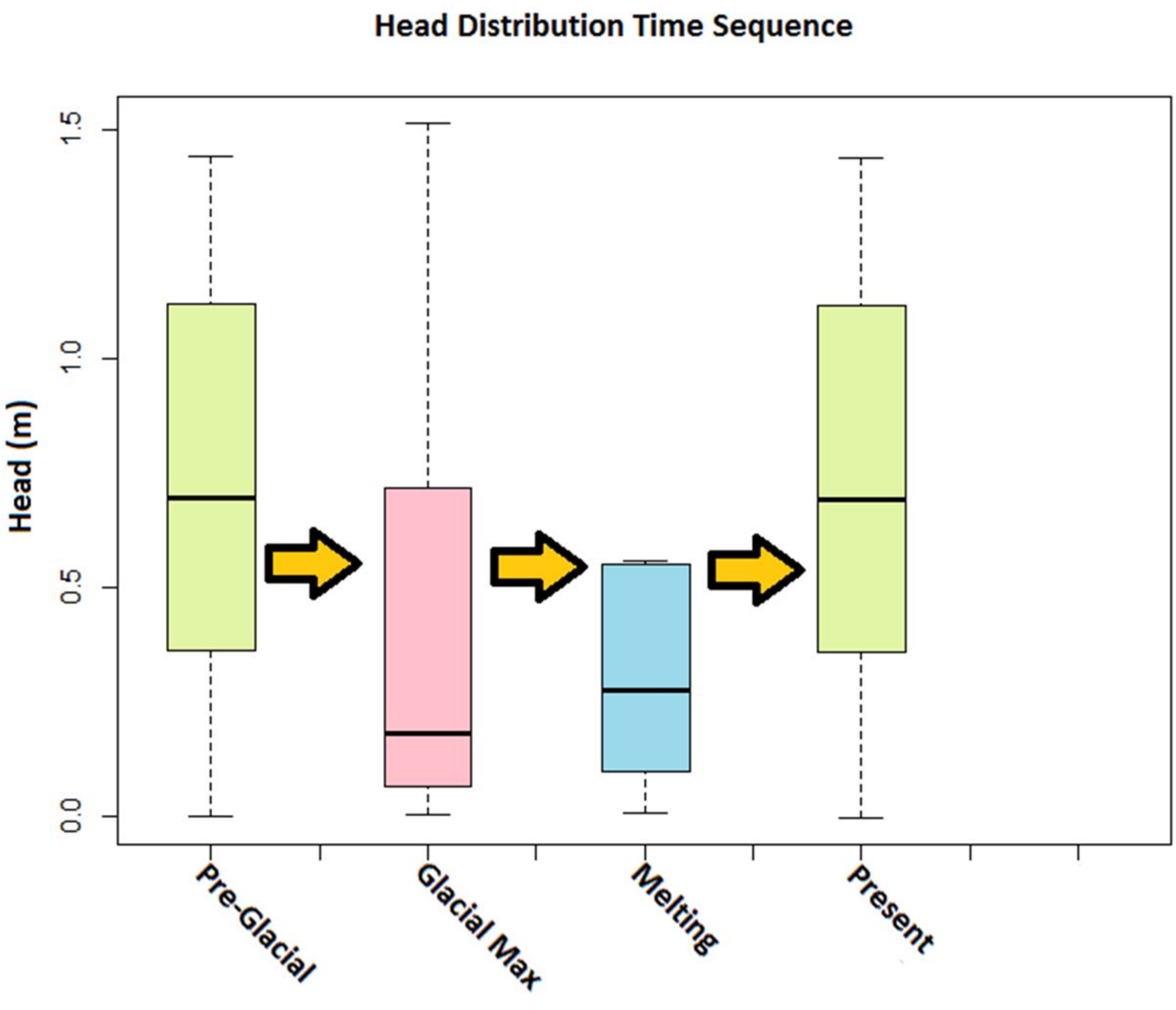


Figure 14. The significant trial boxplots from figure 13 placed in a time series resembling pre-glacial conditions (Present), glacial maximum conditions (Series 2 Trial 2), melting conditions (Series 1 Trial 3), and present day conditions (Present). However, present day conditions may be altered by glaciated conditions where transient flow models are required to model such a response.

V. ACKNOWLEDGMENTS

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VII. APPENDIX

Appendix A

Coastal Plain K Measurments

	Avg K (ft/d)	SD	K (ft/d) ----->													
A1	230	89.81462	350	240	140	190										
A2	305.7143	495.7688	130	270	200	217	290	200	200	350	2000	79	119	32	88	105
A3	240	0	240													
A4	33.2	22.91724	27	45	67	12	15									
A5	16.2	3.03315	17	13	19	13	19									
A6	21	0	21													
A7	23	0	23													
A8	83.375	45.58489	42	48	120	150	108	120	38	41						
A9	128.2857	48.35196	130	130	120	86	130	53	67	170	130	250	90	140	150	150
Avg A	120.0861															

	Avg Ky (ft/d)	SD	Ky (ft/d) ----->											
C1	0.305444	0												
C2	0.040003	0.042139	3.60E-02	8.60E-06	8.40E-02									
C3	0.002699	0.008611	1.00E-04	4.00E-04	3.70E-06	6.00E-05	3.60E-06	1.40E-05	4.30E-06	8.60E-07	1.70E-03	1.00E-04	3.00E-02	1.90E-06
C4	0.021799	0.053008	2.60E-04	1.30E-01	4.90E-04	5.70E-06	2.40E-05	1.50E-05						
C5	1.462682	2.792111	2.00E+00	5.00E-04	1.30E-01	9.00E+00	1.30E-01	3.00E-03	2.00E-02	8.00E-02	6.70E-01	4.00E+00	5.60E-02	
C6	0.305444	0												
C7	0.000036	2.26E-05	2.00E-05	5.20E-05										
Avg C	0.305444													

Appendix B

Coastal Plain Depth Range

	Med z (ft)	Min z (ft)	Max z (ft)
A1	1000	600	1400
A2	650	100	1200
A3	400	0	800
A4	300	0	600
A5	400	0	800
A6	50	0	100
A7	200	100	300
A8	25	0	50
A9	25	0	50
Sum A	3050		

	Med z (ft)	Min z (ft)	Max z (ft)
C1	150	0	300
C2	175	0	350
C3	125	100	150
C4	30	0	60
C5	30	0	60
C6	200	0	400
C7	50	0	100
Sum C	760		

Appendix C

Coastal Plain Aquifer		Avg Aq K	Avg K	Avg Thick	Aq Thick	Thickness Ratio	Weighted K	Avg K (ft / d)	Avg K (m / yr)
	A1	230		509.1269		0.37136	85.41276		
Aq 1	**C1**	0.305443766		150		0.109411	0.033419		
	A2	305.7142857	155.2119	329.2323	1370.98	0.240144	73.41537	195.2122	**21717.75**
	C2	0.040002867		175		0.127646	0.005106		
	A3	240		207.6208		0.15144	36.34553		
	C3	0.00269903		125		0.108071	0.000292		
	A4	33.2		154.3283		0.133427	4.429778		
	C4	0.021799117		30		0.025937	0.000565		
At 1	**A5**	16.2	10.57696	338.1767	1156.649	0.292376	4.736493	13.69077	**1523.126**
	C5	1.462681818		30		0.025937	0.037938		
	A6	21		71.51111		0.061826	1.298348		
	C6	0.305443766		200		0.172913	0.052815		
	A7	23		157.6333		0.136284	3.134542		
	C7	0.000036		50		0.043228	1.56E-06		
	A8	83.375		61.15		0.582473	48.56372		
Aq 2	**C8**					0	0		
	A9	128.2857143	105.8304	43.83333	104.9833	0.417527	53.5627	102.1264	**11361.77**
	C9					0	0		

Appendix D

Piedmont Aquifers

	Avg K (ft/d)	SD	Avg K (m/yr)
Brunswick Group	1.12	0.82	124.6849

Appendix E

Subglacial Film K

Symbol	Value	Unit		
p	1000	kg / m^3	K =	pgb^2
g	9.77E+15	m / yr^2		12u
b	7	mm (m)	**K =**	**7.03E+08**
u	5.67E+04	m^2 / yr		

p	1000	kg / m^3	K =	pgb^2
g	9.77E+15	m / yr^2		12u
b	0	mm (m)	**K =**	**1.25E+02**
u	5.67E+04	m^2 / yr		