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A Comparative Analysis of Groundwater Vulnerability and PFAS Contamination in Maine

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A Comparative Analysis of Groundwater Vulnerability and PFAS Contamination in Maine

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Abstract

As more information is learned regarding the long-term health effects of per- and polyfluoroalkyl substances (PFAS), increasing regulatory measures are being taken to protect the public from these chemicals. States like Maine are on the forefront of such legislation, banning land-applied biosolids in 2022 for fear of PFAS contamination, with plans to halt sales of all unnecessary PFAS products in the state by 2030. The state has conducted some testing of groundwater supplies, but the near-ubiquitous nature of PFAS in manufacturing indicates contamination may be widespread. To prioritize testing in Maine's most vulnerable aquifers, a groundwater susceptibility map has been developed using a modified form of the EPA's DRASTIC model. The model uses geological, atmospheric, and land use data to estimate the relative vulnerability of groundwater across the state. Additionally, a heatmap of potential PFAS sources was created, where each site was assigned a risk score based on the upper magnitude of PFAS contamination associated with its industry. These maps were compared with state PFAS test results to determine the validity of each method. Regional vulnerability trends were found which indicate karst features, coarse glacial/fluvial deposits, volcanic geology, and urban development are signs of high groundwater vulnerability. Density of potential PFAS sources was also found to be highest around urban centers, with PFAS test data affirming the relationship. Recommendations are made for best management practices guided by the models, such as protection of the most vulnerable aquifers via rezoning and building factories on impermeable geologies. Future model development is encouraged with more robust datasets and additional fine-tuning of the statewide Depth to Groundwater, Depth to Bedrock, and Hydraulic Conductivity maps.

Introduction

Water is an essential resource for humanity that is needed for bathing, agriculture, manufacturing, and drinking. Having a clean and abundant supply of water is essential for any community. However, due to urban development and the incorporation of toxic chemicals into many manufacturing processes, drinking water contamination is increasingly becoming a prominent concern[1]. Surface water contamination is a large concern, especially due to runoff from sewage systems, industry, and agriculture[2], but groundwater is only slightly less prone to contamination and supplies 38% of Americans with their drinking water[3].

Groundwater contamination differs from surface water contamination in that the effects are usually colorless and odorless, on top of which, purification of the aquifer is nearly impossible[4]. One family of chemicals in particular can be found in groundwater at concentrations up to tens of thousands of ng/L (ppt), contaminated via the soil or surface water[5]. These chemicals are per- and polyfluoroalkyl substances (PFAS), a class of chemicals known for its ubiquity in household goods like nonstick pans and raincoats[6]. PFAS are also known to impair reproductive systems, cause hormone-related developmental issues in children, decrease immune response to vaccines, and increase the risk of prostate, kidney, and testicular cancers[6][7]. Concern over PFAS has led to voluntary phase-outs of long-chain PFAS, such as Perfluorooctanesulfonic acid (PFOS) and Perfluorooctanoic acid (PFOA), in US manufacturing since the early 2000s, but they have largely been replaced with short-chain PFAS that have similar chemical structures[8].

Some states however have been more proactive, with Maine being one of the first states to sign legislation regulating PFAS usage in commercial products[9]. PFAS became a large concern in 2016[10], with the first investigation into contamination at farms being high PFOS levels at a dairy in Arundel, ME. Years of investigations and PFAS research culminated in a ban on land-applied sewage and biosolids in 2022[11], ending a decades-long practice of spreading waste treatment plant products on agricultural land. Extensive PFAS testing has since taken place surrounding the suspect agricultural fields, and the Maine Department of Environmental Protection (DEP) has developed a "Maine DEP PFAS Investigation" ESRI web app to track ongoing testing and investigations into historical spreading sites[Table 1]. Little effort has been made to map further sources of contamination, despite the prevalence of PFAS in facilities ranging from furniture factories to airports[12].

PFAS are found universally in manufacturing today[13], so narrowing the scope of PFAS investigation in Maine to a select few agricultural fields with relatively low contamination levels compared to other industries[14] is nonsensical. There is a clear need for a mapping project to assess groundwater vulnerability across the state. A modified version of the EPA's DRASTIC model[15] was used to estimate the relative groundwater vulnerability to surface contamination based on eight parameters. Using the EPA's Facility Registry Service[Table 1], a heatmap of potential PFAS sources was created, where each facility was assigned a risk score based on the upper magnitude of PFAS contamination associated with its industry (similar to Ojha et al, 2023)[12]. Both models were comparatively assessed and their accuracy was verified using PFAS test results from the state[Table 1]. The results of this project indicate areas of the state that are most vulnerable to general surface contamination, as well as areas with the highest PFAS contamination potential, visualizing where future groundwater testing and rezoning are needed most.

Background

Groundwater Vulnerability Maps

The idea of mapping groundwater's vulnerability to contamination has been around since the 1960s[16]. Originating in France, the central idea is that different areas of the landscape provide filtration to the underlying groundwater, based on varying hydrogeological qualities. Maps proved to be an effective means of visualization which are easy to interpret by administrators, politicians, and the public. Providing data in a visual format allows viewers to summarize findings faster than in numerical form[17], so presenting important concepts such as susceptibility to drinking water contamination in map format can be very useful.

Sources of contamination can be anthropogenic or natural, surface or subsurface, and point or diffuse. However, the purpose of these maps is often for land use planning, and the consideration of anthropogenic contamination sources is foremost. Factories, airports and wastewater treatment plants can be point source surface level polluters, while agricultural fields and landfills can be diffuse sources of contamination. Septic systems and discharge injection sites can be subsurface contamination points, bypassing vegetation, soil, and some surficial geology which would have served as natural filters. Many historical landfills and industrial sites would have been sited without the consideration of such maps because the required data were not available all in one place or in the necessary stage of completion[16], but today such maps are a valuable commodity when municipalities seek to site potential sources of contamination, or drill new boreholes for drinking water.

Ranging in size from small to large scale, groundwater vulnerability maps can have a wide range of objectives and uses. Small scale (covering a large geographic area in low detail) maps are general purpose and multi-use, but do not achieve high enough accuracy for local planning. These types of maps are used instead to visualize broad regional trends, and direct attention to areas of vulnerability which can then be explored and mapped in further detail. Large scale (covering a small geographic area in high detail) maps have to have a high density of data points with accurate data (high resolution spatial imaging or locally collected field measurements). However, with such large amounts of detailed data comes a higher degree of confidence, which can lead to site-level use maps, used for municipal zoning, conservation boundaries, and well placement.

Groundwater vulnerability maps can also be categorized into single- and multi-purpose assessment. Multi-purpose groundwater vulnerability maps are used for mapping general groundwater susceptibility (assessing two or more contaminants or groups of contaminants). There is debate on the efficacy of multi-purpose, or general groundwater vulnerability maps, as there is no such thing as a universal contaminant. Different contaminants come with their own physical and chemical properties which affect their attenuation in soils and surficial geology, affecting their rate of transmissivity into the groundwater system. However, creating a base vulnerability or susceptibility map using various hydrogeological metrics can serve as a valuable tool which can be overlaid with additional contaminant-specific layers or used alongside other maps which detail contamination sources and groundwater flow. Soluble chemicals do also share enough characteristics which make multi-use susceptibility maps valuable for general assumptions.

Single-purpose groundwater vulnerability maps are true to their name, created with the express purpose of gauging groundwater vulnerability to a particular contaminant. Single-purpose maps have the advantage of using tailored soil and surficial geology attenuation capacity layers to model the filtering capacity of surface materials towards certain contaminants. This is possible when considering the adsorption-desorption, oxidation-reduction, solution-precipitation, radioactive decay, gas transport, evaporation, and dispersion properties of a certain contaminant in a specific physico-chemical environment.

The usefulness of groundwater vulnerability maps can vary significantly based on their design and the user's objective, but with the proper disclaimers in place which allow the viewer to understand a given map's limitations, even the most data-limited and low-resolution maps can be used at the proper scale.

DRASTIC and DRASTICL

Since the first groundwater susceptibility maps were created in the mid-20th century, researchers and hydrogeologists have used many combinations of the same available parameters to model groundwater vulnerability. The common core categories are soil, unsaturated (vadose) zone, aquifer (saturated zone), recharge rate, topography, parent geology, surface water interactions, land use, and (human) population density. These hydrogeological parameters can be broken down further into specific measurements such as hydraulic conductivity, soil texture, percent slope, layer thickness, etc. By assigning index values to specific value ranges in the same units, and weighting each category based on predetermined hydrological importance, a standardized model can be constructed that is applicable to a wide range of environments and conditions.

A popular model which emerged in 1985 and has continued to weather the test of time is DRASTIC[18]. Developed by the United States Environmental Protection Agency, the DRASTIC model was tested and adapted for use anywhere within the United States. It is an index-based model, or point count system, which has inputs of multiple raster layers (gridded spatially referenced cells that are assigned values - often the product of spatial imagery) that are processed and standardized, weighted, and summed, to produce relative vulnerability values for each grid cell.

Each input parameter contains ratings between 1 and 10, based on vulnerability to surface contamination, where 10 is the most vulnerable. These ratings are multiplied by the parameter's assigned weight (determined by the EPA using expert knowledge of hydrogeology across the US) and then each parameter's weighted values are summed to create the overall DRASTIC model[18]. These values are not absolute quantitative vulnerability measurements, but rather a qualitative ranking system relative to other values within the map. Higher DRASTIC values indicate greater vulnerability, while lower values indicate lesser vulnerability, with all values being a relative comparison to other cells, rather than using a specific vulnerability unit.

DRASTIC is an acronym for the parameters in the model: depth to groundwater (D), net recharge (R), aquifer media (A), soil media (S), topography (T), impact of the vadose zone (I), and hydraulic conductivity (C). The DRASTIC index can be calculated using the following equation:

$$DI = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w \quad (1)$$

where, r = ratings allocated to each parameter; and w = weights allocated to each parameter.

In this project, the DRASTICL model will be used. The only difference is the addition of an eighth parameter, land use, to help characterize the effect of urbanization and development on groundwater vulnerability. Variations of this land use adapted model have been used in many DRASTIC studies[19], but the particular weights and ratings in this project come from Maqsoom et al. (2020)[20], who used a weight of 5 for the parameter, and ratings of 1, 2, 3, 5, 7, 8, and 9 for increasingly developed landcover[Table 12].

Limitations to this model include its generalization, interference between parameters in some areas, contamination is assumed to occur at ground level, the contamination travels at the same rate as water, and the method is not intended to be used for site-specific investigations less than 100 acres in size[16][18]. In recent decades it has been popular to modify the model to take land use urban population density into account, which has improved result accuracy, particularly in urban areas[19]. Other models have also been developed based off of the index-based general applicability and ease of use provided by DRASTIC, aiming to correct its limitations. None however have seemed to surpass its popularity to this day.

Understanding Maine's Surficial Geology

Imagining a cross-section of Maine, the geology below the surface can roughly be generalized into three components: soil, surficial geology, and bedrock. Bedrock forms through igneous, metamorphic, and sedimentary processes, and these consolidated materials form the base of the regolith (unconsolidated superficial deposits covering bedrock). Maine's bedrock formed over half a billion years, with the youngest bedrock in what is today Maine, forming 120 million years ago during the Cretaceous Period[21][22].

The next layer that was deposited is composed primarily of glacial deposits. These were formed as glaciers scraped back and forth along the bedrock surface, advancing and receding during glacials and interglacials. They picked up a fair amount of rock, pulverizing some to sand, silt, and clay particles.

This layer is called overburden, or surficial deposits. The Laurentide Ice Sheet covered the whole state several times between 2.5 million years ago and 10,000 years ago[21]. As it receded, meltwater streams formed, carrying loose material, and blankets of unconsolidated sediment were left coating the bedrock surface. Depending on how they were deposited, these materials form different topographies, such as drumlins, eskers, and moraines (mounds and ridges of coarse sediment). Gravel, sand, and till (a combination of the former, clay, and rocks varying from cobbles to boulders) are common coarser overburden that are deposited in a heterogeneous manner, and are quite permeable (till varies based on clay content), forming some of the highest yielding surficial aquifers[21]. Silt and clay are often deposited as lacustrine or marine sediments, as the finest sediments it takes a long time in relatively stagnant water such as a lake or ocean for the particles to settle and layers to accumulate. Due to the fine particle sizes of these sediments, layers such as the Presumpscot Formation can act as confining layers to aquifers (also known as aquitards)[23].

Soils, the topmost layer, are a combination of the most weathered bedrock and surficial materials combined with organic matter from vegetation and other organisms. These can be divided into horizons, or distinct layers that differ in color, texture, and/or chemical composition. Often, soils are classified by their texture, determined by the ratio of sand, silt, and clay particles. This can be useful in determining permeability, as sand particles are the largest, then silt, then clay, decreasing in permeability in that order. Soils are the first filter for water that infiltrates the ground, which is why soil remediation is such an important field of environmental engineering, and why soil type has a large effect on groundwater purity[24].

The zones defined above are all found across the state, but bedrock is the only constant in the geological profile. Mountaintops and jagged coastlines are the first images which come to mind when thinking of exposed bedrock in Maine, but bedrock outcrops exist all across the state - areas where weather and erosion have prevented weathered materials from accumulating. So, some landscapes only consist of bedrock, while others are considered thin drift, with a few meters of surficial deposits. Other areas have bedrock, then tens to tens of meters of surficial deposits. Soil forms out of surficial deposits or bedrock if the right weathering conditions are met and enough time has passed since the deposits were formed. Unlike some western states, Maine does not have an overburden of hundreds of meters or more, but deposits can accumulate up to a few tens of meters[25].

This geologic profile can be further categorized hydrologically into the vadose zone and saturated zone, or aquifer. The vadose zone is all unsaturated materials between the land surface and the water table. This usually includes the soil horizons and some surficial deposits, but may include weathered bedrock with no or very little overlying sediments[16]. The saturated zone, or aquifer, consists of all materials below the water table which can hold water. These two zones are very important in terms of groundwater hydrology, as the vadose zone acts as a filter for water as it infiltrates to the aquifer, and the saturated zone materials determine both the yield of the aquifer and the further filtration of groundwater as it flows towards its terminus. The vadose zone is considered most important when it comes to groundwater contamination, as its ability to attenuate surface contaminants is the main factor in whether a groundwater source is contaminated from surface pollution[18]; once an aquifer is contaminated, there are very few steps that can be taken to remediate it[4].

Understanding Wells

In Maine, drinking water is acquired mainly via surface water or groundwater. In Lewiston and Auburn, where Bates College is located, the public water utility obtains its water from Lake Auburn (which is renowned for its purity, so much so that it has an EPA waiver to leave the water mostly unfiltered before distributing it to customers)[26]. Roughly, 40% of Maine citizens rely on a private well for their water supply[27].

To access Maine's groundwater, three types of wells are commonly used: drilled bedrock wells, drilled overburden wells, and dug wells/springs[28]. Starting with the least common, dug wells/springs are only able to be constructed in areas where the water table is within a meter of the surface, and there is sufficient unconsolidated sediment near the surface to hold enough water to continue refilling the well. In past centuries dug wells used to be more common, as they were the only well type that technology constraints allowed[24]. Due to contamination concerns (with less material to pass through before reaching groundwater, surface contamination is more likely to occur) and lower reliability in drought conditions, they are only estimated to make up 10-15% of private wells in the state today[24]. Dug wells can often be found around springs, as they are a constant source of water that is less likely to go dry during droughts. Springs are caused by groundwater being discharged to the surface via differences in pressure[29]. Most springs in Maine are gravity-fed, meaning that they occur at local low points of elevation, and where topography allows for the slope of the land to be more steep than the slope of the water table, causing water to come to the surface[29].

Drilled overburden wells are deeper versions of dug wells. In areas where the surficial overburden reaches more than 7 meters deep, it is easier to drill a well than excavate it by hand or excavator. The well's source is still a sand and gravel (or other unconsolidated material) aquifer, and if properly placed, should be able to yield more than a bedrock well due to the superior water storage capacity and permeability of coarse unconsolidated sediments[30]. The aquifer may be confined or unconfined - confined aquifers are made of permeable material which can store water, but have an impermeable layer above them (such as bedrock or clay) - whereas unconfined aquifers are made up of unconsolidated material up to the surface[30].

Drilled bedrock wells are usually the lowest yielding, but are the most common due to the prevalence of thin overburden in Maine[30]. Drilling allows for deeper penetration into the subsurface, potentially giving greater access to groundwater[28]. Unweathered bedrock cannot hold water - the structure of the rock has formed so there is minimal porosity (not very much space between particles) and what porespace there is will not be connected to other pores to allow for groundwater mobility and recharge. The reason why bedrock wells exist at all is because often the bedrock may be fractured through weathering and geomorphological processes such as tectonic plate movements and metamorphism. Surface weathering can cause pressure or erosion to wear away at weaker sections of bedrock over time, forming cracks and space which water can penetrate[27]. Tectonic plate shifts can cause crustal deformation, fracturing bedrock made brittle by metamorphic hardening[30]. Some of these fractures form where they are not open to the overlying surficial sediments or ground surface, so they are a poor place for bedrock wells (if the well cannot recharge with water from precipitation and groundwater infiltration, then it will not be useful), but bedrock fractures which extend to locations in contact with infiltrating water can store water. If a well passes through enough of these fractures, it can provide a stable source of drinking water.

In the construction of a drilled bedrock well, first a small-diameter hole is drilled through the overburden to bedrock. Steel casing is sealed in place to the bedrock, extending to the surface, to prevent contamination from the water contained in the surficial aquifer. The well is then drilled until there is deemed enough water inflow, and a mesh screen is installed along the fractured portion.

Interpolation

Creating a surface elevation map (one type is the digital elevation model or DEM) is easy and accurate enough with enough time and money, because the land surface can be readily observed. Most often done through aerial surveying missions nowadays[31], LIDAR (Light Detection and Ranging) data are collected by shining a laser to the land surface and calculating the distance by measuring the time it takes for light to be reflected back to the sensor array. Combining this distance data with the laser's angle and very precise Global Positioning System (GPS) data, a datum point with GPS coordinates and elevation is recorded. When many data points are collected, a LIDAR point cloud is formed, visualizing a topographic surface in three dimensions, with accurate elevation measurements. Converted to a raster image, a DEM can be made, where each pixel in the image holds an elevation value. The number of LIDAR points collected determines the resolution of the DEM, where the number of points is directly proportional to the size of each pixel or cell (1x1 m, 5x5 m, 10x10 m, etc).

Subsurface data are more often collected at discrete points, such as through boreholes or well points. Instead, in these cases, point data are collected selectively where conditions allow, providing discrete data points throughout an area. The sparse and sporadic nature of most of these data means that it cannot be converted directly to a raster, so a method is needed to estimate the values of the area in between the data points. This method is called interpolation, where mathematical and statistical formulas are used to predict values from the discrete data available[32]. The basis for predictions relies on Tobler's First Law of Geography, which states that "Everything is related to everything else, but near things are more related than distant things"[33].

Interpolation can be broadly placed into two categories: deterministic and geostatistical. Deterministic interpolation methods (inverse distance weighted, nearest neighbor, polynomial trend, radial-basis, and spline) are mathematically based formulas which assign predicted values based on surrounding measured values[32]. These models make predictions solely based on the values of nearby data points (going back to Tobler's First Law, where closer points are assigned higher weights, and farther away points are assigned lower weights)[33].

Geostatistical interpolation methods (mainly kriging, cokriging, and Empirical Bayesian kriging) generate value estimates via a statistical model[32]. The main concept is that for a set of point data, they are divided into subsets, and a semivariogram (line of best fit for the subset) is fitted to the data. For each point in the subset, a radius is drawn around it, and all points within the circle are included in the subset. The distance from the main point to each other point is measured and squared (to amplify the effect that closer things are more alike than those that are farther apart), then all the distance squares are plotted and a trendline is fit to the data, like in a regression analysis — this line is the semivariogram. For each data point, the differences in the distances to surrounding points (and the values of those points) will result in a unique slope and corresponding semivariogram depending on the degree of spatial correlation. Once the semivariogram model is created, the kriging algorithm uses a linear combination of the sample values weighted by the spatial correlation between the sample locations[32].

There are costs and benefits to each method. Deterministic models are simpler and thus faster to execute, which is good for either preliminary data exploration, or data with a simple relationship (like a linear slope between points). Geostatistical models can often be smoother, but require (much) more computing power. Most of this is due to the fact that deterministic models are often weighted averages of distances to the closest points, or similar mathematical models, whereas geostatistical models create a large number of fitted trends to try and match the slope of the data[34].

The Topo to Raster tool in ArcGIS Pro is a deterministic model that has been modified to be hydrologically correct. Inputs for the tool can be elevation data (points or contours), lake polygons, river/stream polygons or polylines, known sinks (points where water accumulates and leaves the system), and cliff polylines[35]. An interpolation raster is created from the elevation data by using the primary data (elevation points in the case of the Depth to Water interpolation) to create a coarse model of the terrain by connecting lines between points, and then iteratively refines the terrain model by modeling how natural valleys and streams would be eroded in the landscape over time. This model is best suited for applications such as modeling groundwater elevation, as a defining factor in the modeling process is the erosive power of water.

Methods

Depth to Water

The Minnesota Department of Natural Resources published a report in 2016[36] detailing their methods used in creating an updated statewide water table elevation map. The approach used in the report was adapted for the Maine groundwater elevation map and subsidiary depth-to-water table map.

Water level data are obtained from well data, gSSURGO soil water table data, surface water data, and seismic refraction profile data. The gSSURGO data were sampled at 100 m intervals, to obtain annual minimum depth to water values. Points which are considered a perched water table were excluded. Using data from the National Hydrography Dataset Best Resolution[Table 1], all bodies of water in the state were mapped, and points along their edges (or centerline in the case of streams and rivers) in 100 m intervals were assigned a value based off of the surface elevation (where the depth to water is assumed to be 0). The Maine Geological Survey has created seismic refraction profiles[Table 1] throughout the state, which depict depth to bedrock and depth to water level graphically in segments between 18.29 and 655.32 meters. Average values were assigned to the center point of each profile. To create a continuous depth to water raster from the discrete data, ArcGIS Pro's Topo to Raster interpolation tool was used, estimating a slope from the available data, and assigning values from along it to a raster. DRASTIC ratings were assigned according to Table 2, with shallower water table values associated with higher vulnerability ratings. The ratings tables are in imperial units, but this project will display all results in the metric equivalents.

Net Recharge

Nielsen and Westenbroek (2019)[Table 1] simulated annual net recharge values for Maine from precipitation data collected between 1981 and 2015. This data was used directly for the DRASTIC model, with the median value dataset chosen as the best representation of typical Maine net recharge. DRASTIC ratings were assigned according to Table 3, with higher net recharge values associated with higher vulnerability ratings.

Aquifer Media

Surficial geology, surficial materials, bedrock geology, karst features, and significant sand and gravel aquifer maps exist for Maine[Table 1], but they do not specify the geology of aquifers beyond those that yield 10 or more gallons of water per minute to wells. Discussed in the background section, *Understanding Maine's Surficial Geology,* aquifers are water bearing geologic materials that can store or transmit groundwater. Aquifers are found below the vadose zone, and their upper boundary is defined by the local water table.

To determine which geology map to use, the depth to water map was used, along with a Quaternary sediment thickness map from Soller and Garrity (2018)[Table 1]. Comparing the depth which surficial sediments extend to the local water table depth, if the upper boundary of the water table was within surficial sediments, that material was used, but if the water table only appeared in the bedrock layer, then bedrock geology was used. These values were amended according to the karst features and significant sand and gravel aquifers maps[Table 1], with the latter two taking precedence (wherever those features occur) as they are more permeable, resulting in higher vulnerability.

The geology maps are specific, with detailed descriptions of the interbedded layers within them, and particle sizes for surficial materials. In order to use the DRASTIC ratings, the aquifer geologies need to be generalized according to Table 4, so the majority component was matched with an existing DRASTIC category, simplifying the materials to 31 categories[Table 5]. DRASTIC values were assigned according to Table 5, with higher permeability materials being assigned higher vulnerability ratings.

Soil Media

Using the gSSURGO dataset[Table 1], the surface texture was determined, and assigned a DRASTIC rating according to Table 7, adapted from the original DRASTIC ratings in Table 6. Coarser and thus more permeable soils are more vulnerable to surface contamination, receiving a higher DRASTIC rating.

Topography

Using several 1/9 arc second digital elevation models (DEMs)[Table 1], a statewide elevation map was created and the ArcGIS Pro Slope tool was used to calculate the percent slope. Flatter topography is more apt to absorb precipitation due to lower runoff, so it is more vulnerable to surface contamination and receives a higher DRASTIC rating according to Table 7.

Impact of the Vadose Zone Media

Similar to the methods for aquifer media, vadose zone media was determined from existing bedrock geology, surficial geology, surficial materials, significant sand and gravel aquifers, and karst features[Table 1]. The vadose zone however is above the water table, consisting of surficial geology wherever present, with bedrock geology as a substitution where no Quaternary sediments existed. Karst features and significant sand and gravel aquifer materials were again substituted where present. DRASTIC ratings were assigned from the same table as aquifer media, Table 5.

Hydraulic Conductivity

Hydraulic Conductivity is determined by aquifer media. Using the geology types determined in the aquifer media parameter, DRASTIC ratings were assigned according to Table 11, which was adapted from the original DRASTIC ratings in Table 10, using hydraulic conductivity values pulled from the literature.

Land Use

Using land use data from NOAA[Table 1], DRASTIC ratings were assigned to land uses according to Table 12, derived from values used in Maqsoom et al. (2020)[20]. Generally, more developed land has a higher vulnerability and likelihood of contamination, receiving a higher DRASTIC rating.

DRASTICL

The DRASTIC model is a weighted sum of the parameters depth to water, net recharge, aquifer media, soil media, topography, impact of the vadose zone media, and hydraulic conductivity. DRASTICL is a modified DRASTIC model which also uses land use data. Each parameter consists of cells rated between 1 and 10, described in the previous methods. All parameters are multiplied by their respective weights (according to Table 13) and summed to create the DRASTICL model.

Potential PFAS Sources

Using data from the EPA Facility Registry Service[Table 1], Maine facilities were downloaded. The facilities were then assigned risk scores by industry according to Table 14, derived from Ojha et al (2023)[12]. Facilities were mapped as point data, and symbolized as a heat map weighted by risk score, where hotspots are multiple high risk facilities and lighter shades are standalone lower risk facilities (no shading represents a lack of PFAS-associated facilities).

PFAS Test Results Overlay

The DRASTICL map was overlaid with the Potential PFAS Source Heatmap. To validate the accuracy of both models in comparison to real-world test results, state groundwater PFAS test data[Table 1] was overlaid as data points corresponding in color (yellow to red) to the magnitude of the concentration. The concentration is the sum of Maine's six regulated PFAS chemicals: perfluorooctanoic acid (PFOA), perfluorooctane sulfonic acid (PFOS), perfluorohexane sulfonic acid (PFHxS), perfluorononanoic acid (PFNA), perfluoroheptanoic acid (PFHpA) and perfluorodecanoic acid (PFDA).

Results

Depth to Water

As expected from literature review[27], depth to the water table across the state is for the most part under 10 meters (Figure 1). In Maine, there is considerable seasonal variation in the water table, where spring thaws raise the elevation up and then as water reserves are slowly depleted throughout the summer, the water table drops to a few meters below the surface, or around thirty at the most[30]. 84.96% of the Depth to Water data points are from gSSURGO soil data, which use annual minimum depth to water table values. The effect is that this map is on the conservative (low) side of depth values, more representative of the summer dry season than spring or winter.

60.33% of the state has a water table between 0 and 1.524 meters (5 feet) from the surface, 24.64% is between 1.524 - 4.572 m (5 and 15 feet), and 8.82% is between 4.572 - 9.144 m (15 and 30 feet) (Table 2). The maximum water table depth value from the soil data is 2.01 m, which explains the steep dropoff in cells after the 1.524 - 4.572 m class. The other depths make up 6.20% of the area, many of which overlap with mountainous terrain (refer to the Topography section), indicating an erroneously large value caused by a steep slope and mismatched resolution between terrain rasters being subtracted from one another.

If a raster with 50 m cells is subtracted from a raster with 10 meter cells in mountainous terrain, the single value of the 50 m cell (representing some elevation value in that area, whether it is a representative value and the resolution is chosen to be low due to storage capacity, or it is a somewhat random elevation value obtained for a such a large area due to low surveying accuracy), the same value contained in the one 50 m cell will be used with each of the twenty-five 10 m cells, giving a wide range of differences.

There are at least several cases however where the Depth to Water value is verily 30 or more meters, such as to the east of St-Georges, where there is no corresponding steep terrain. These truly deep water tables are probably also in effect in the region to the west of Augusta, in the area around 45°, -68°, and along the northern border with Canada from 46°30’, -70° to 47°, -68°30’. Such regions are likely due to eskers or ice-contact deposits, which form small drumlins at various points along the retreat of the Laurentide Ice Sheet, and cause local increases in surface elevation without affecting the regional water table elevation.

Net Annual Recharge

As a coastal state, Maine has a moist climate, characterized by moderate precipitation, and within the past decade the average precipitation has only risen[37]. Unsurprisingly, the median annual net recharge (the amount of precipitation that makes its way into the groundwater) across much of the state is over 25.4 cm (10 inches), equivalent to a DRASTIC parameter rating of 9 (Figure 2). With such a homogenous rating across the state, only a few small areas in the northeast of the state have ratings of 1, with a slightly larger region across the central north with 10.16 - 17.78 cm (4 - 7 inches) carrying a rating of 6. Across most of the northwest border however, lies a significantly sized region with no data, removing the area from the final DRASTICL model.

Aquifer Media

The map of Aquifer Media is largely classified as till, giving it a rating of 5, but by no means does it take up a majority of the map (Figure 3). There are several large regions which have high parameter ratings, across alluvial deposits, eskers, coarse glaciomarine deposits, volcanic and karst features. The dark pink regions from 46°, -69° to 47°, -69° are composed of basalt and other volcanic bedrock. Being quite porous, it is a high permeability aquifer media, hence the high rating. Along the northeast border from 46° to 47° N, the dark pink is due to a large region of karst limestone, an especially vulnerable material due to the fissures and caves which form, connecting water bearing fractures to the surface. The mid-pink regions throughout the state are eskers, coarse glaciomarine deposits, stagnation moraines and other types of coarse sediment that was deposited during the Laurentide ice sheet’s glacial retreat. The lighter pink describes alluvial deposits along current and historic river plains, as well as fine grained glaciomarine deposits. The lightest pink media found throughout the state is mostly sedimentary rocks (massive sandstone and interbedded sequences of sandstone, limestone and shale), with some finer grained moraines mixed in. The end result is an interesting tapestry of variable permeability till (due to different mixtures of clay, silt, gravel and sand) with higher permeability streaks of coarse sediment in many regions.

Soil Media

Most of Maine can be categorized as some type of forest or woodland (see Land Use). This is particularly true however in the northwestern region of the state, from the upper section of the Appalachians (44°30’, -71°), through the 100 mile wilderness (45°30’, -69°30’), until the agricultural region of the northeast (47°, -68°). Due to the forest canopy, this region is largely made up of organic matter in various states of decomposition as the O horizon of the soil media (Figure 4). All of the state associated with the medium yellow of soil media rating 8 is composed of this layer in fact. The darker section bounded by Portland, Bangor (44°45’, -68°45’) and the Blue Mountains (44°30’, -70°30’), and another dark section stretching along the northeast border (45°30’, -68° to 47°, -68°) are composed of various loams ranging from mucky to sandy, which make these regions the state’s most productive agricultural sectors[38]. The forest floor humus is more vulnerable to surface contamination than the agricultural loam, as it is usually very thin, and is made up of coarse particles and chunks, compared to the silty and clayey loams of the northeast and southwest. The bright yellow outcrops in the north (46°, -68°45’) and east (45°15’, -68°30’) are gravelly soils and exposed bedrock, associated with mountains and less weathered terrain.

Topography

Slope plays an important role in groundwater susceptibility, as surface pollution will run off a steep slope rather than infiltrating the soil. On a floodplain however, there is nowhere else for water to go besides being evaporated, so a much larger fraction will make its way into the subsurface. In Figure 5, the topography of the state is characterized by percent slope, clearly showing the Appalachian range cutting through the center of the state in the form of the White Mountains (44°, -71° to 45°30’, -69°30’) and Boundary Mountains (45°, -71° to 45°30’, -70°), ending in Mount Katahdin (46°, -69°). Lake regions along the southern edge of the mountain ranges have flatter topography, along with plains in the northeast (46°30’, -68°30’) and northwest (46°, -69°30’), and Downeast (45°, -67°30’). There is a slight rise in incline northwest of Acadia (44°30’, -69°) into the lakes region to its northeast (45°30’, -68°).

Impact of the Vadose Zone Media

The Vadose Zone is the most important factor in determining groundwater vulnerability along with depth to the water table, according to the DRASTIC model. Both are given weights of 5, because they are deemed to be primary determinants of an underlying aquifer’s susceptibility. Depth to Water is important, because it determines the thickness of the Vadose Zone, and how much material has a chance to filter contaminants before they reach groundwater. The Vadose Zone is equally important however due to its role in the filtering process. The type of geologic media that the Vadose Zone is composed of is a key factor in the attenuation capacity of the layer. Loose, coarse particles like sand and gravel, coarse glaciomarine deposits, or volcanic rocks will filter any surface contaminants less than fine particle layers like silt and clay, or impenetrable layers like unfractured granite. The Vadose Media map in Figure 6 is similar to the

Aquifer Media map, but with seemingly less high vulnerability regions. The pink region in the north central portion of the state (46°, -69° to 46°30’, -69°) is the same volcanic and basaltic bedrock, which is clearly exposed to the surface, or covered with very thin till. The nearby pink areas are additionally still stagnation moraines, but the karst limestone features in the northeast (46°, -68° to 47°, -68°) and southwest (43°30’ to 45°30’, -69°) in the Aquifer Media map (Figure 3) appear to be buried (below the vadose zone), along with volcanic bedrock along the coast.

Hydraulic Conductivity

Hydraulic Conductivity is an elusive parameter that can only be accurately described in a local map with sufficient pump tests to measure transmissivity of the aquifer media. However, it has been generalized in this project and mapped statewide in Figure 7 according to literature values for the Aquifer Media map. Much of the state has a rating of 1, with a fairly significant portion rated at 2. The only outliers are karst features and significant sand and gravel aquifers along the northeast border (46°, -68° to 47°, -68°), as well as in south central Maine (44°15’, -70° to 44°45’, -69°30’). This parameter can vary widely at a local scale due to fractured bedrock having a much higher hydraulic conductivity than unfractured (consider the hypothetical scenario of water trying to infiltrate solid granite, vs a block of granite with a large fracture through the middle), but is hard to map at a regional or statewide scale without additional data collection. The trends in karst limestone and significant aquifers are regionally important anyhow, as they present a clear contrast in increased hydraulic conductivity compared to the rest of the state.

Land Cover

As previously mentioned, a majority of the state is forested, as can be seen in Figure 8 (sage green). This presents a reduced vulnerability scenario in terms of human impact, because forested areas are much less likely to have the type of industry which would cause significant surface contamination, compared to developed areas. The one land use type with a lower rating than forested land is the pale green-yellow symbolized wetland habitat, where it is assigned a rating of 1, as it is one of the least desirable land use types in terms of development. Agriculture is symbolized in dark green and is rated 5, due to its moderate risk of groundwater contamination. In pink, purple and dark blue are light, medium, and heavy development, respectively, noticeable around cities such as Portland, Lewiston (43°45', -70°30'), Brunswick (44°, -70°), Augusta, Waterville (44°30', -69°30'), and Bangor (44°45', -68°45').

DRASTICL

Combining the eight parameters according to Eq. 2, the DRASTICL map is produced in Figure 9. With hotspots in the southwest (43°30', -70°45'), northwest (47°, -69°30'), north central (46°30', -69°), northeast (46°30', -68°), Downeast (44°45', -67°45'), and cities, there are vulnerable aquifers across the state. Brunswick (44°, -70°) stands out as the darkest visible orange, with a rating around 200, meaning the city is highly vulnerable to surface groundwater contamination. Other spider web-like patterns appear in the southeast (44°45', -67°45') and southwest (43°30', -70°45') due to coarse glacial and alluvial deposits. In the center of the state (45°45', -68°45'), neon green moderate-to-high vulnerability is caused by moraines, volcanic bedrock, and karst features. The northwest (47°, -69°30') and northeast (46°30', -68°) face similar geological patterns, with stagnation moraines, but the northeast has opposite ratings in different parameters which cancel out, such as karst features (high vulnerability), loamy soil (lower vulnerability), till (lower vulnerability), agriculture (higher vulnerability), and high hydraulic conductivity (high vulnerability). All of the large areas of vulnerability are enabled by flat topography and shallow depth to groundwater, in addition to their geological vulnerabilities.

Half the state has a DRASTICL value between 140 and 160[Table 14], representing a medium groundwater vulnerability. The data (not including water or No Data values) does not seem to be substantially skewed towards either side, appearing visually to be a normal distribution.

Potential PFAS Sources

Potential PFAS Sources are characterized by the heatmap in Figure 10, which shows hotspots where several high risk facilities are located close together, blue where one or a couple low risk facilities are located, and no color where no facilities are located. The map provides logical results as hotspots are located near population centers such as Portland, Lewiston (43°45’, -70°30’), Brunswick (44°, -70°), Augusta, Waterville (44°30’, -69°30’), Bangor (44°45’, -68°45’), the northeast agriculture corridor (46°, -68° to 47°, -68°), and broadly along the coastal half of the state (minus most of Downeast (44°45’, -67°45’)). Several readers have asked about the singular points to the west and northwest of Baxter State Park (46°, -69°), due to the area’s low population density. The facilities are mostly remote airports, with several landfills and land-applied biosolid fields. Although they are remote, the facilities are not insignificant in terms of PFAS potential however as they have risk scores of 75, 100, and 25, respectively, out of 100[Table 16].

PFAS Test Results Overlay

To determine the validity of the models, statewide PFAS test data from groundwater and drinking water systems were mapped on top of each model in Figure 11. Testing locations are largely centered around Potential PFAS Source hotspots (logically this makes sense, as PFAS tests are still too expensive for wide scale testing to take place, rather facilities which expect to have PFAS contamination, and buffer zones around them, are the ones testing for PFAS). In the southwest (43°30’, -70°30’), many PFAS detections appear to take place along mid-to-high vulnerability DRASTICL regions, although an equal number of Non-Detect tests appear in the same regions. In the rest of the map it is harder to discern the DRASTICL rating underlying PFAS tests, but it appears that more are on or close to the 140-160 medium vulnerability classification. When PFAS Test data are compared to their underlying DRASTICL ratings (Table 15), the percent of tests with PFAS detected decreases from 73.86% at the 120-140 DRASTICL classification until 56.95% at the 180-200 classification, which is the opposite of one would expect with higher vulnerability, but then sharply increases to 78.57% and 81.25% at the 200-220 and 220+ DRASTICL classifications, respectively. For the 1,537 samples categorized as in water by the DRASTICL model (due to low spatial resolution – when the DRASTICL model layer was turned off, the samples appeared close to water bodies, but not within), 72.54% detected PFAS.

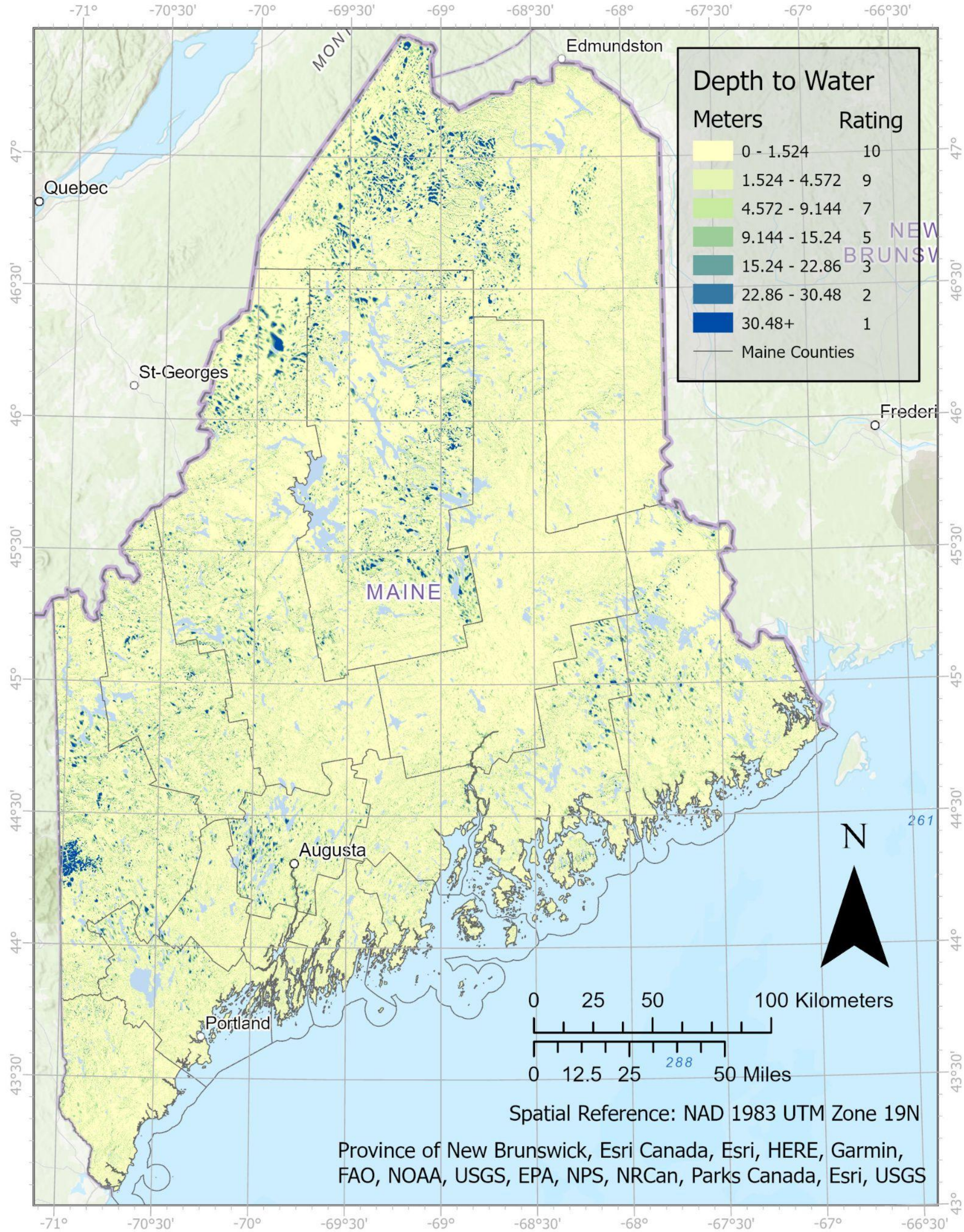

Figure 1: Depth to Water

This map depicts depth to the water table in meters, interpolated from soil, seismic refraction, surface water, and well data points. Some high depth pixels are distortions caused by steep sloping terrain, which causes discrepancies between the water table elevation data and surface elevation. Lower depth to the water table corresponds to a greater vulnerability to surface contamination, represented as a higher DRASTIC rating.

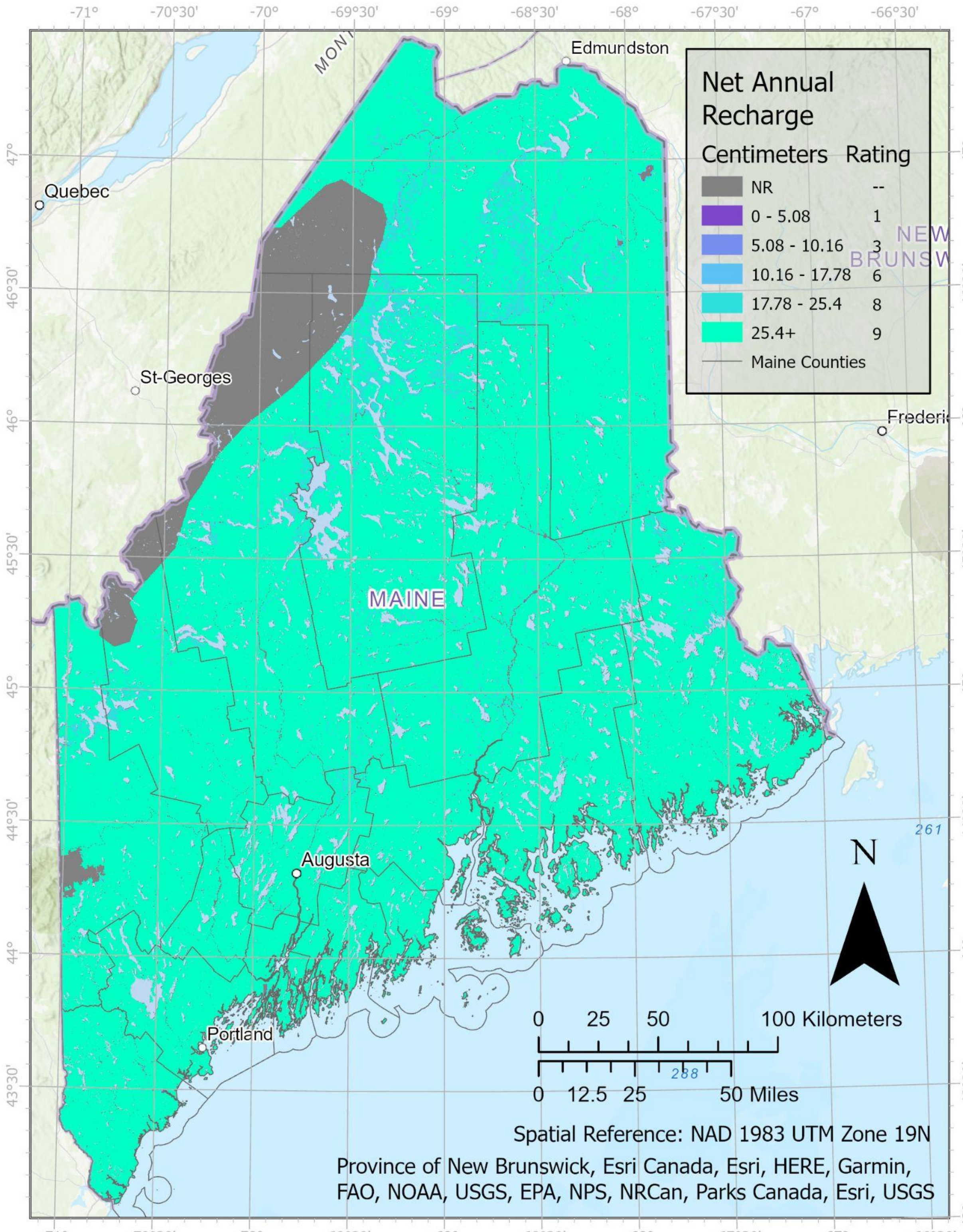

Figure 2: Net Recharge

Net Annual Recharge was simulated for Maine by Nielsen and Westenbroek for the period 1981-2015. The median dataset was chosen for this project to reduce the weight of outlying drought years. A significant area along the northwest border did not have enough data to simulate net recharge, so it was excluded from the model. Lower net recharge values correspond to less vulnerability to surface contamination, represented as a lower DRASTIC rating.

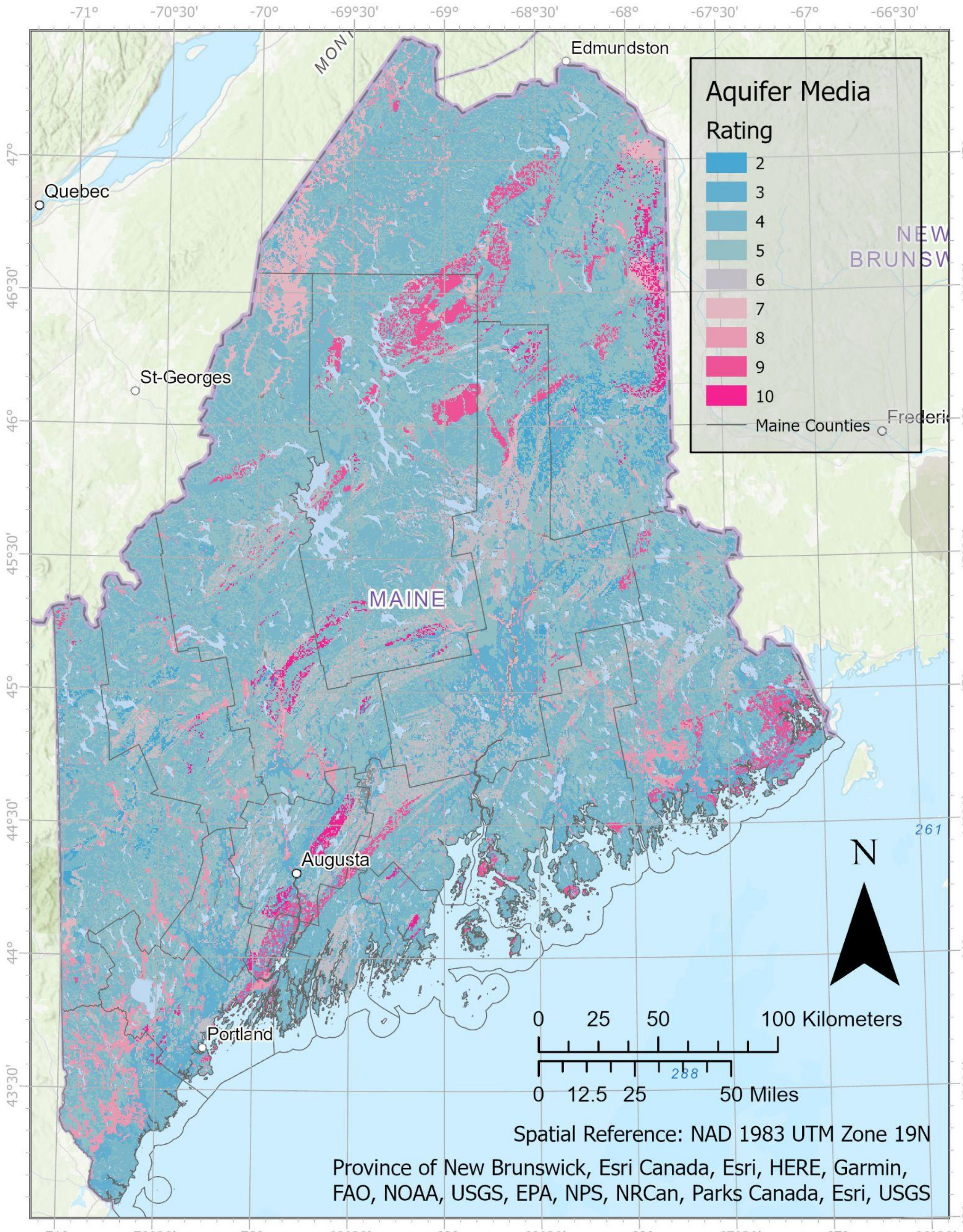

Figure 3: Aquifer Media

Using statewide bedrock and surficial geology data, a DEM, water table elevation data, and overburden thickness data, Aquifer Media were determined. DRASTIC ratings correspond to material permeability, with higher permeability associated with higher vulnerability and a higher rating. Unconsolidated sediments like sand and gravel have higher ratings, while unfractured bedrock has a lower rating.

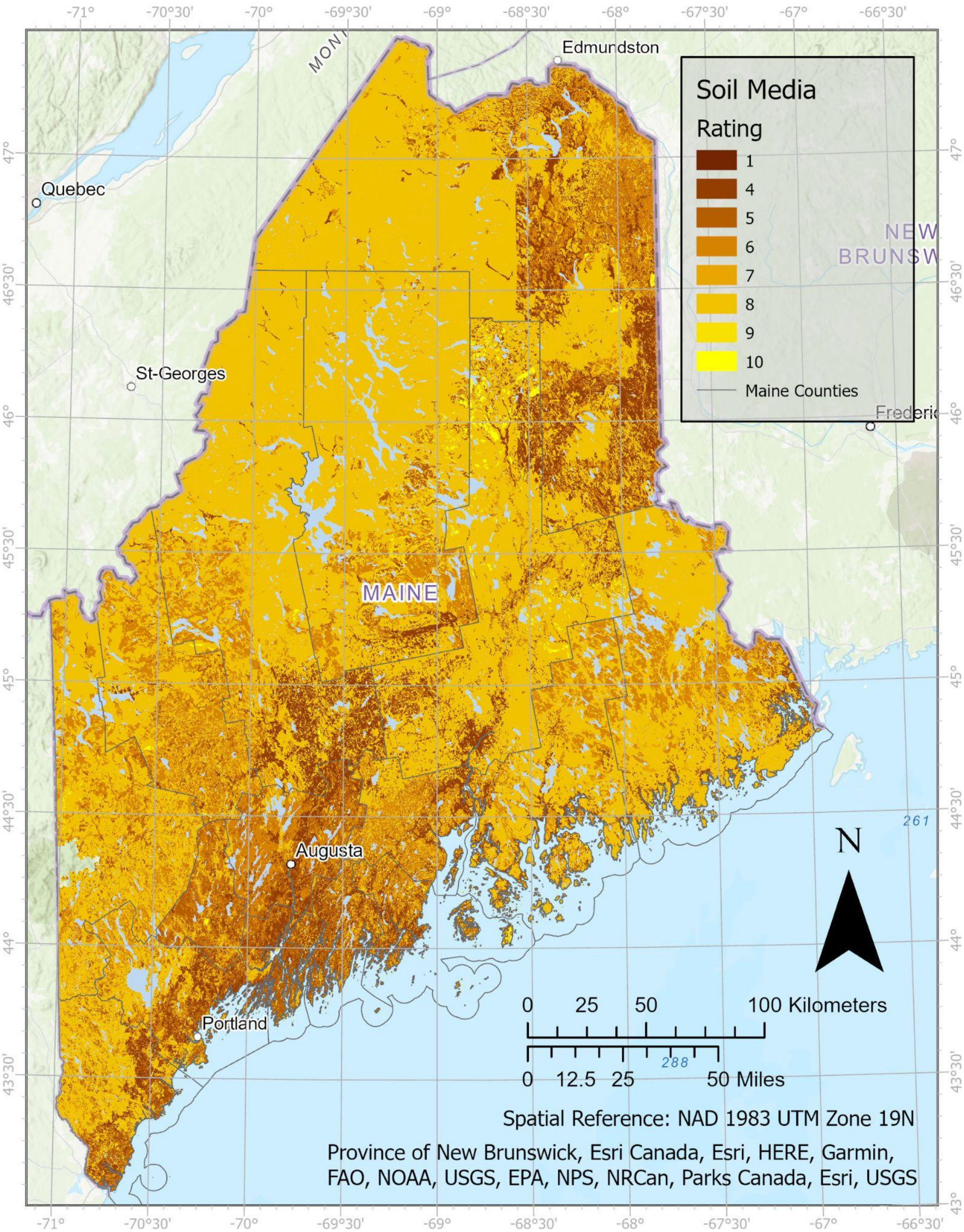

Figure 4: Soil Media

Surface soil texture data were used to assign ratings based on permeability, with coarser materials having higher ratings and finer particles having lower ratings. Higher permeability is associated with higher vulnerability and a higher rating. The soil textures were derived from gSSURGO gridded soil data.

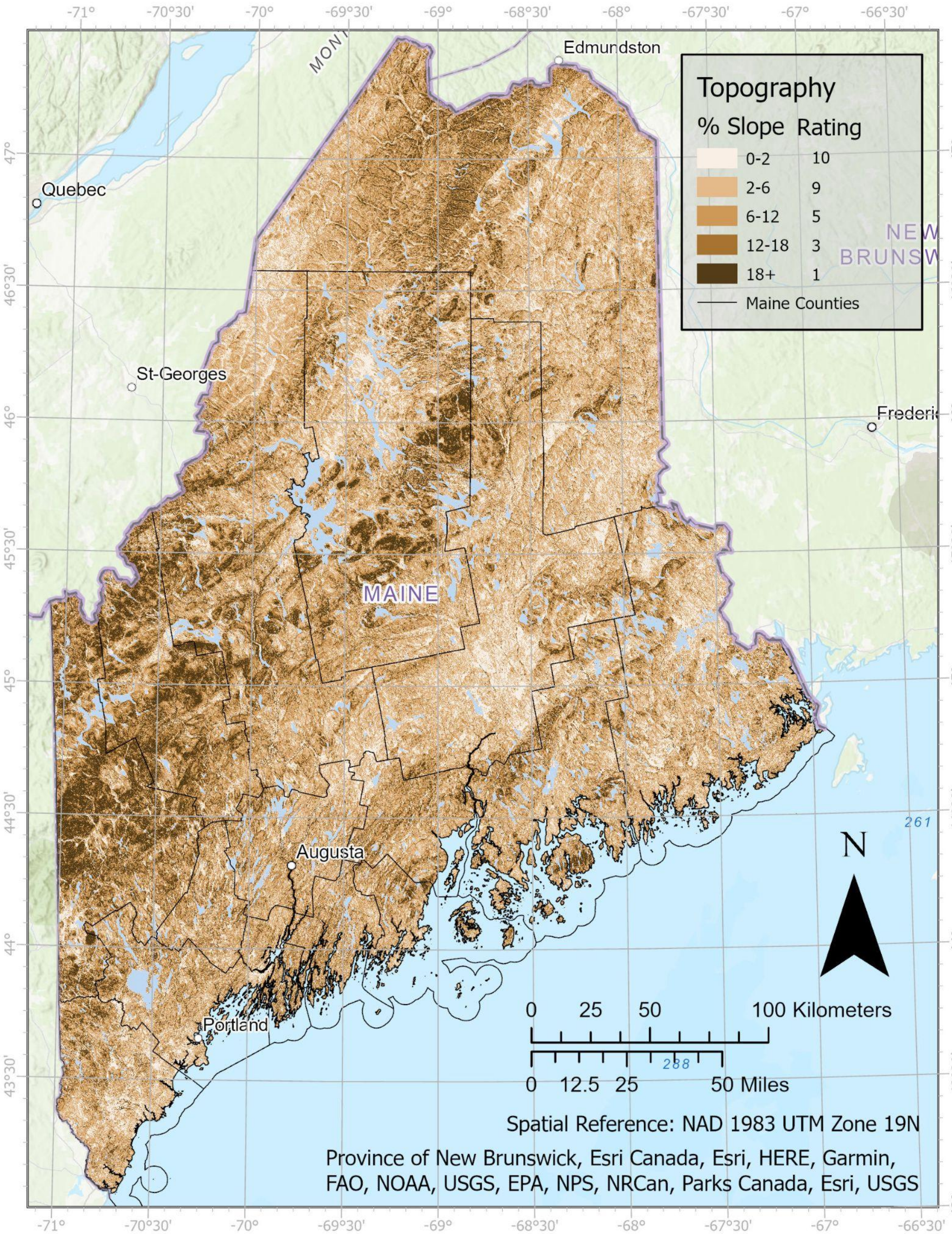

Figure 5: Topography

A 1/3 Arc Second DEM was used to derive percent slope across the state. Steeper slopes are less vulnerable to surface contamination, as most pollution will runoff, making mountain ranges low vulnerability, and floodplains or other low lying topography more vulnerable. Higher vulnerability is associated with a higher DRASTIC rating.

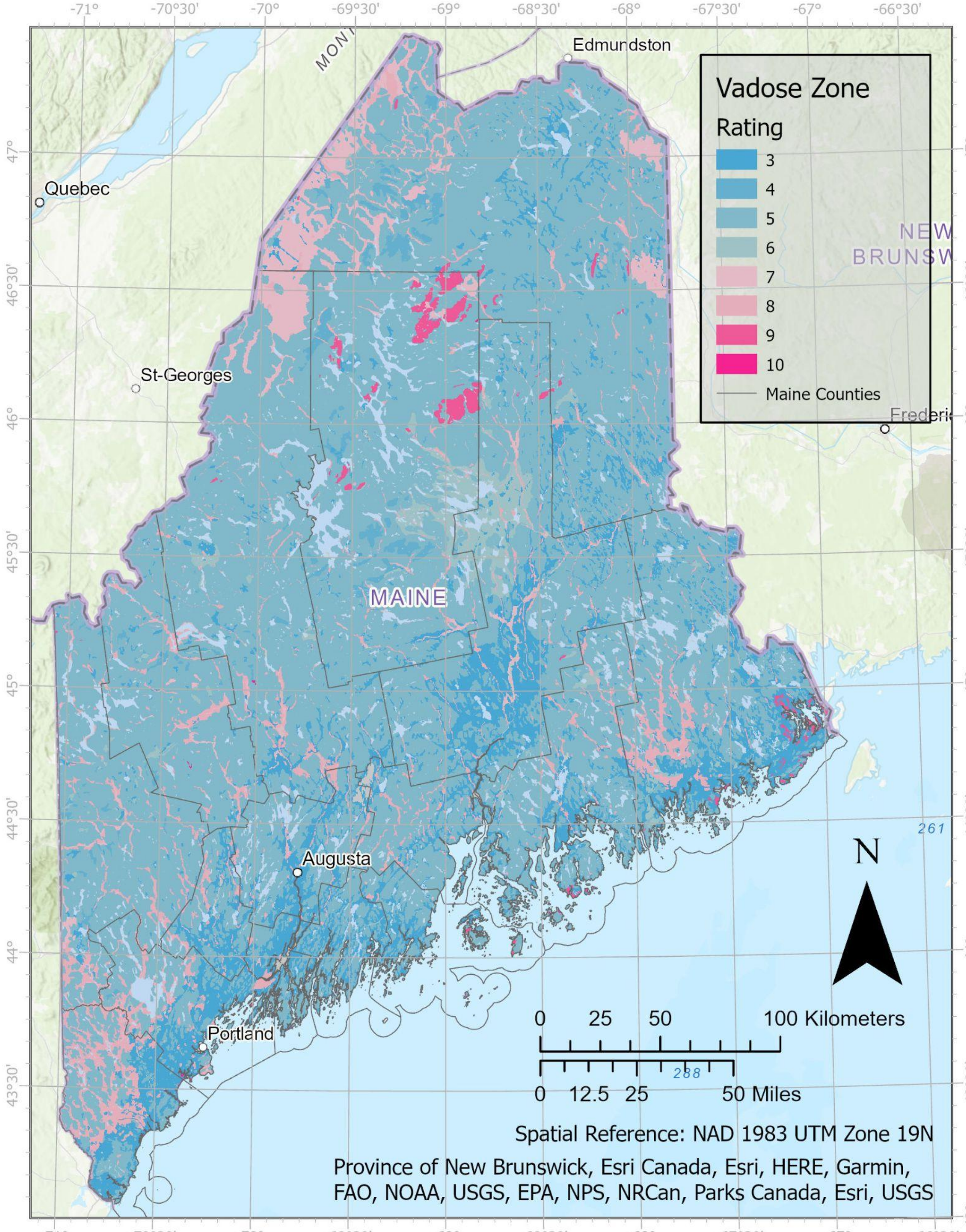

Figure 6: Impact of the Vadose Zone Media

Using the same data sources as the Aquifer Media map, Vadose Zone Media is the geologic material between the water table and the soil. This unsaturated zone is one of the most important factors in determining groundwater vulnerability, as it is the largest filter layer between the surface and the aquifer. DRASTIC ratings correspond to material permeability, with higher permeability associated with higher vulnerability and a higher rating.

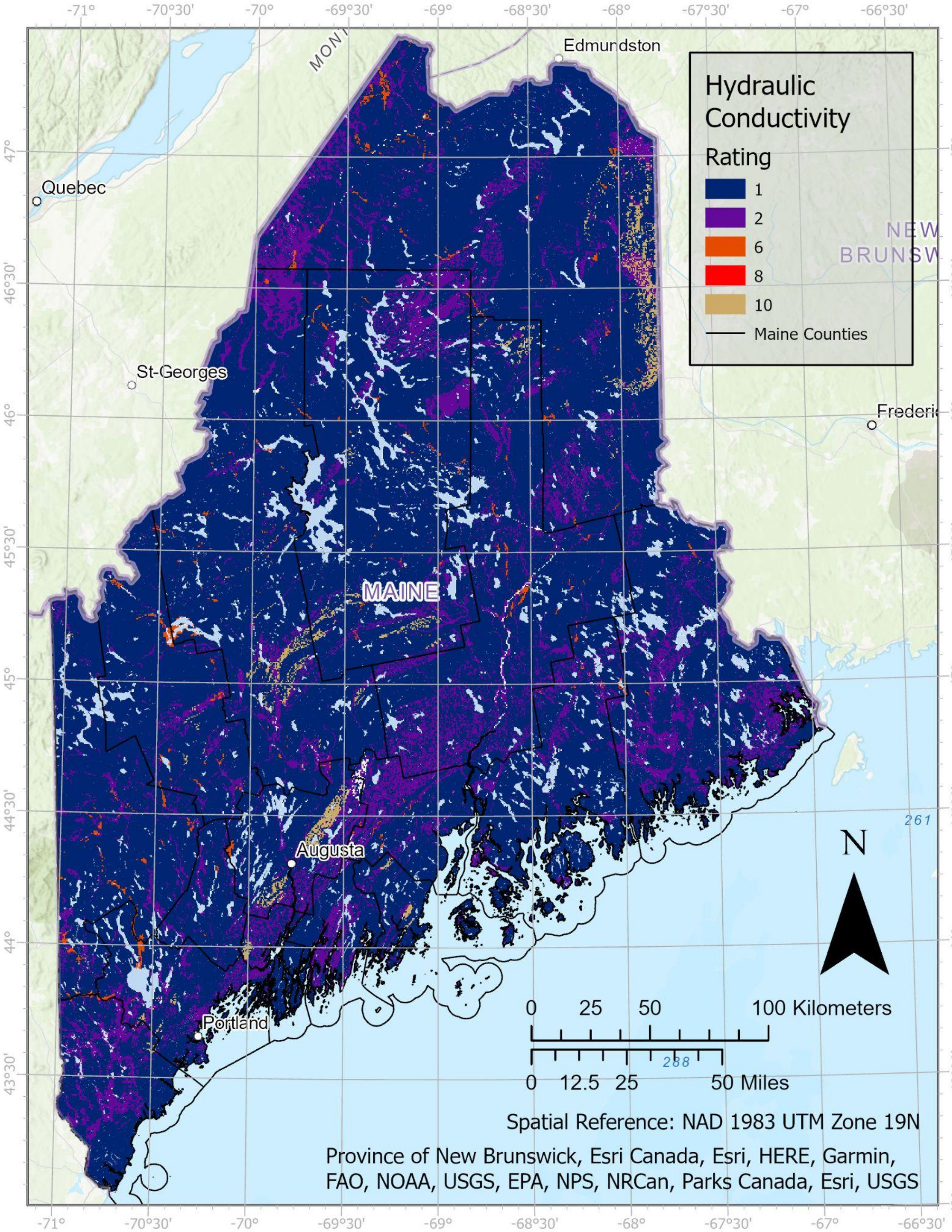

Figure 7: Hydraulic Conductivity

Permeability describes how well a material can transmit a fluid, tied to the material's porosity. Hydraulic conductivity describes how well water can pass through a material. The hydraulic conductivity was estimated for each Aquifer Medium based on values from the literature. Higher hydraulic conductivity values are associated with higher vulnerability and a higher DRASTIC rating.

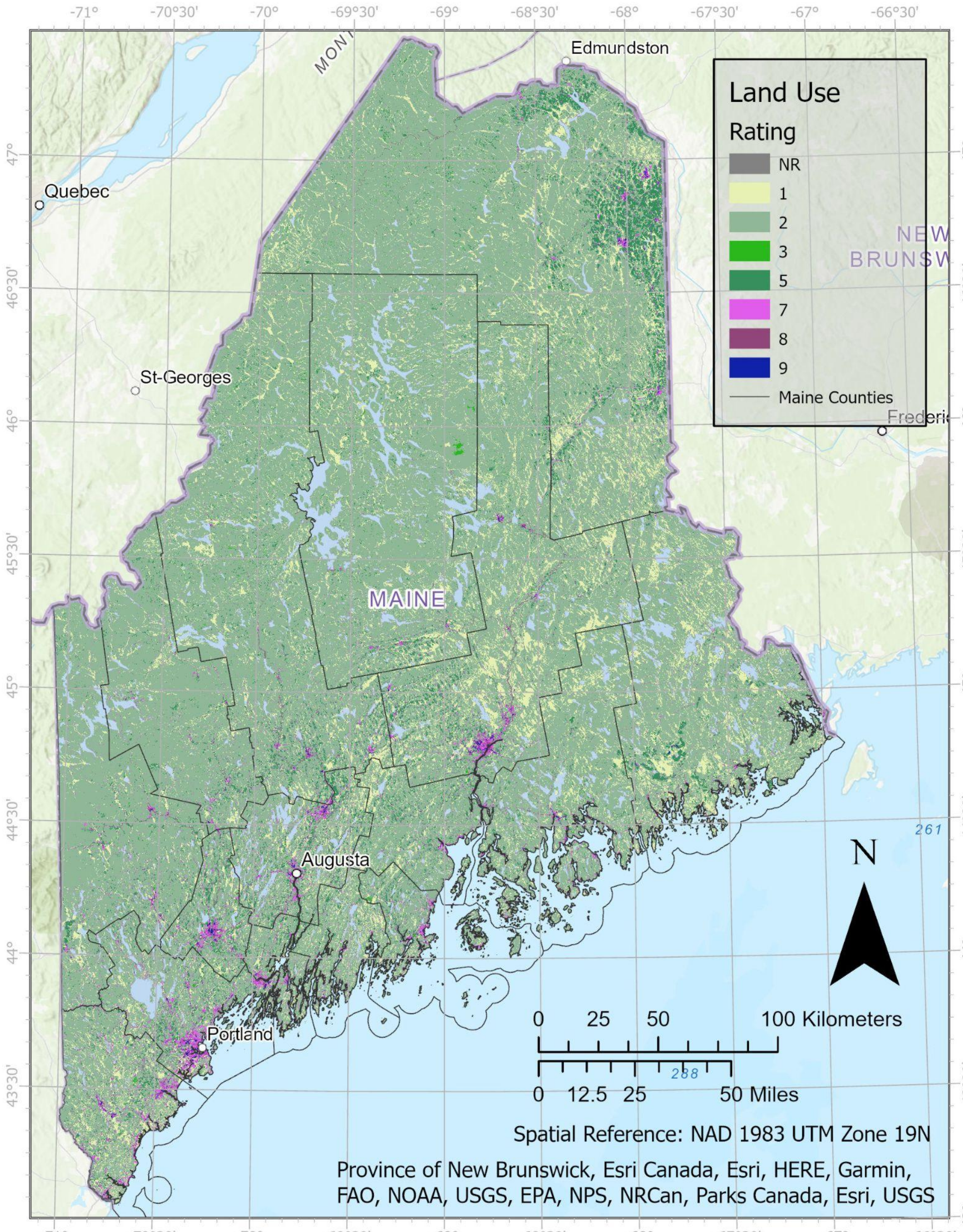

Figure 8: Land Cover

Using NOAA's 2016 C-CAP Regional Land Cover data, each land use type was categorized into a general groundwater vulnerability category, with undeveloped land being less vulnerable than populous developed land. Higher vulnerability is associated with a higher DRASTICL rating.

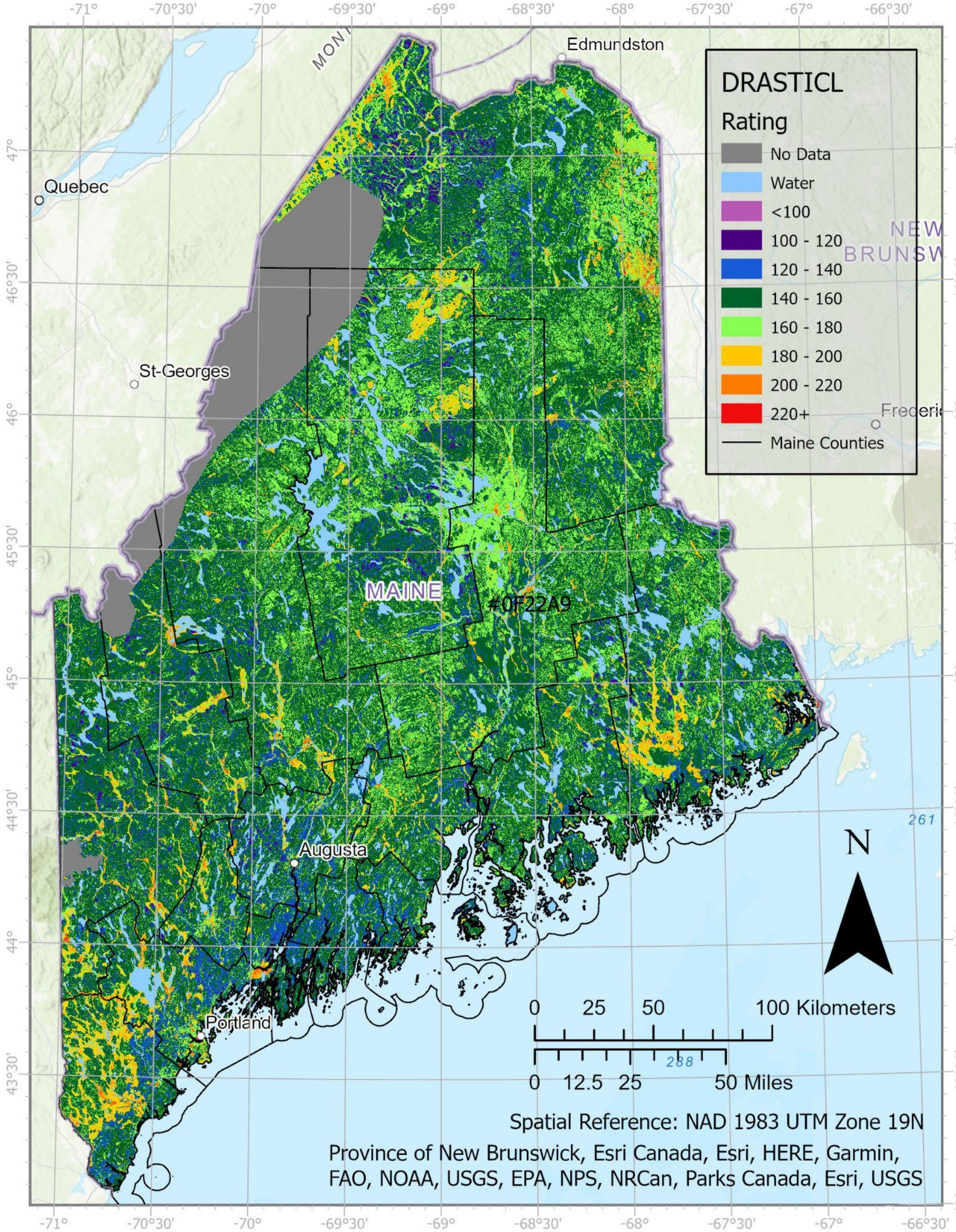

Figure 9: DRASTICL

Unitless DRASTICL ratings represent the relative groundwater susceptibility to surface contamination. Higher values represent a greater vulnerability. The ratings are a weighted sum (Eq. 2) of the eight parameters, with each parameter being assigned a weight between 1 and 5[Table 13], and parameter ratings ranging from 1 to 10[Tables 2-12].

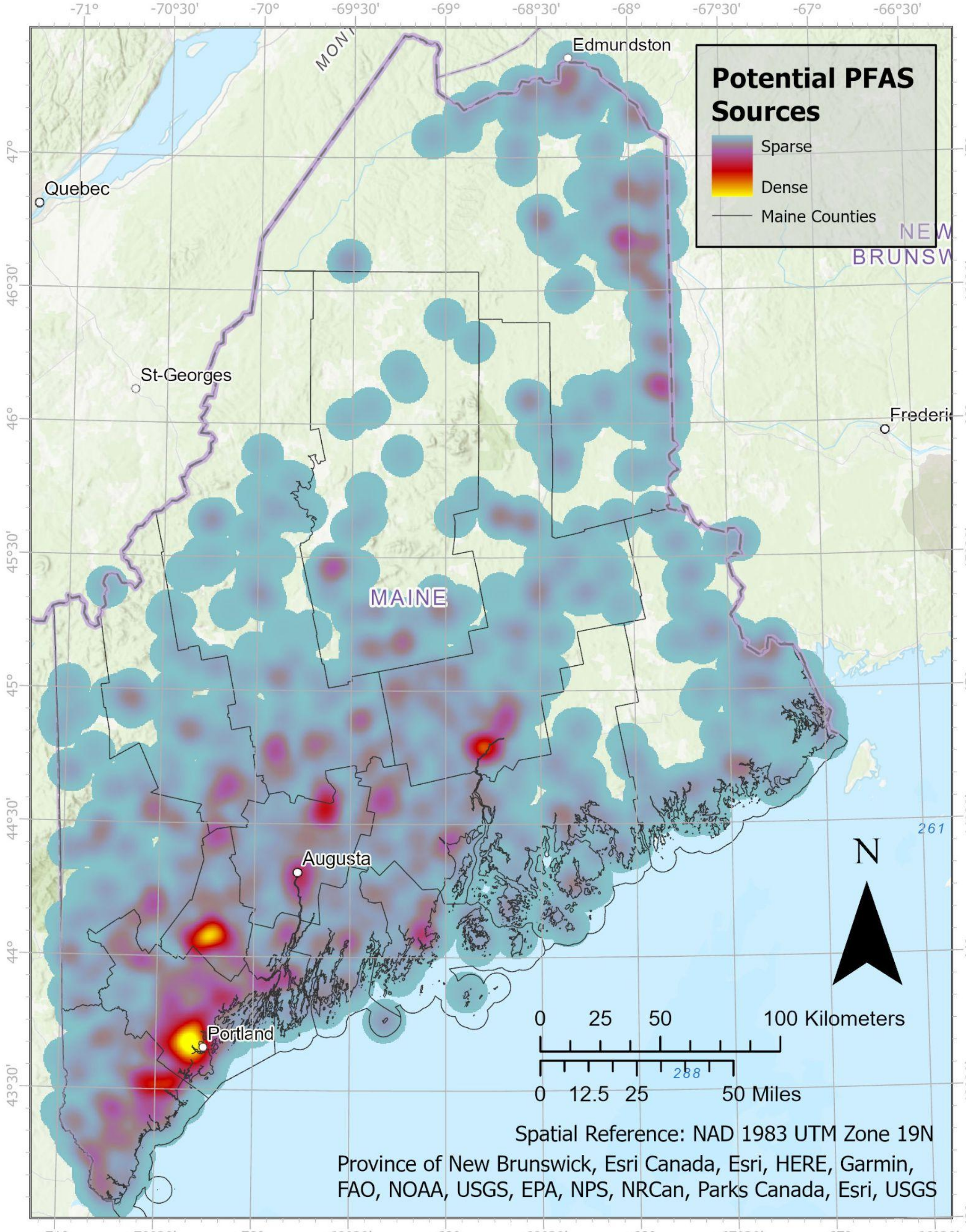

Figure 10: Potential PFAS Sources

Using data from the EPA's Facility Registry Service, facilities associated with industries that are known to use PFAS chemicals were selected. Each facility was assigned a risk score between 25 and 100 based on its industry, and a weighted density heatmap was created. Higher risk scores correspond to higher potential for PFAS contamination in groundwater around the facility, and hotspots represent multiple high risk facilities in close proximity.

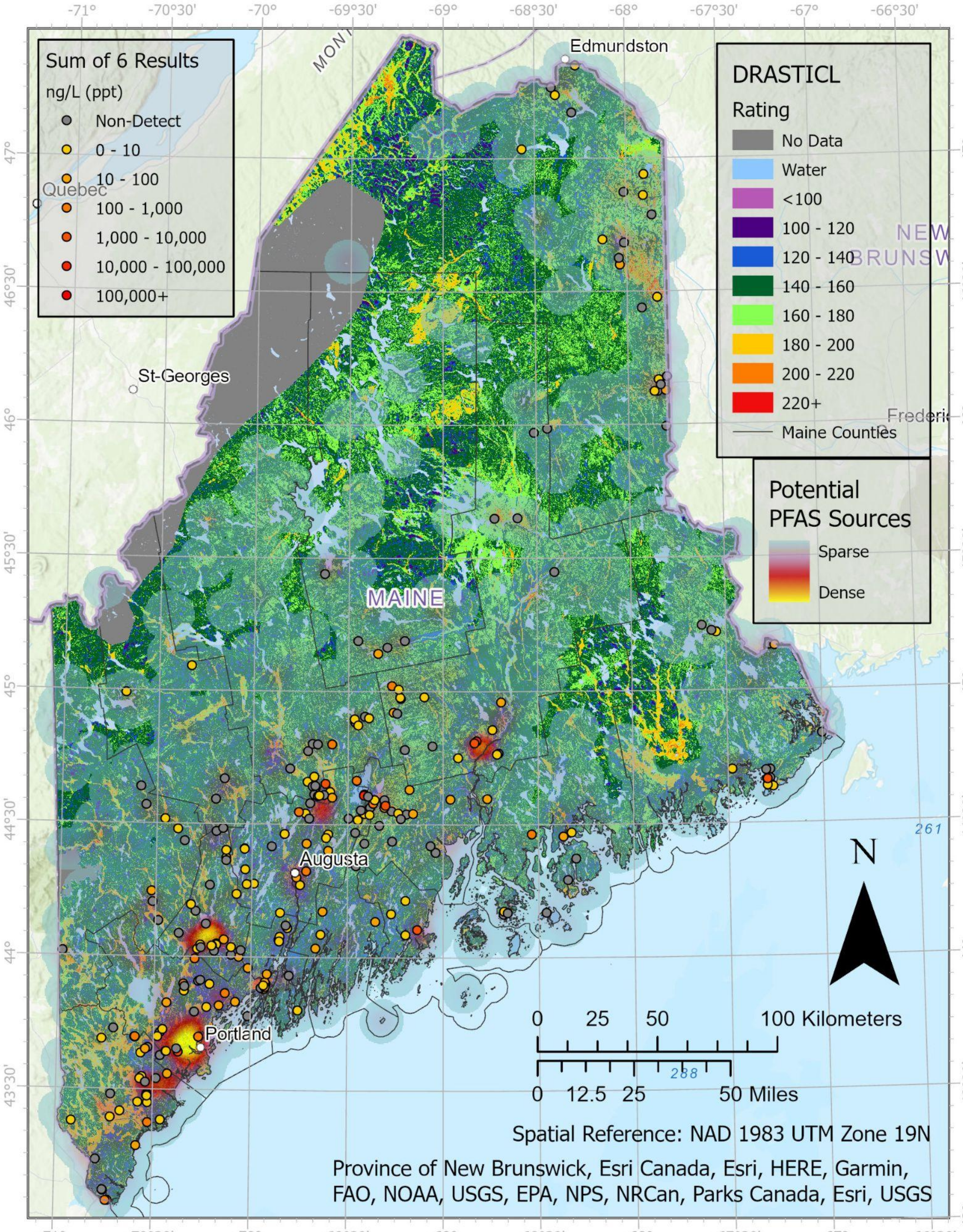

Figure 11: PFAS Test Results Overlay

Combining DRASTICL model ratings with the Potential PFAS Source Heatmap and public PFAS test results, the two maps' validity can be visually analyzed. Displayed PFAS test results were selected from groundwater and drinking water samples, and converted to ng/L (ppt).

Discussion:

There are clear pros and cons when using the DRASTIC model at a statewide scale with the data that is currently available. The model is capable of establishing regional vulnerability patterns such as karst features, glacial deposits, alluvial deposits, sand and gravel aquifers, land use, topography, and soil data. These topographical and geological features are rated as high vulnerability, and the underlying logic supports their case. Unconsolidated surficial overburden is more permeable and thus, less able to filter out surface contaminants, or slow their passage for long enough to allow them to naturally degrade before reaching groundwater. Fractured or karst consolidated sediments have the same vulnerability to contamination, as surface fractures allow contaminants to flow directly from the surface into subsurface fractured bedrock aquifers. Unfractured bedrock is not susceptible to contamination, as no or little water can infiltrate, but if the bedrock is fractured sufficiently to accommodate drilled wells, then there must be a point of vulnerability. Unlike regions with primarily surficial overburden aquifers, Maine's underlying bedrock geology is complex and hard to model. Unfortunately, there is a lack of data surrounding bedrock fractures and transmissivity, other than where specialized pump tests and transmissivity studies have been performed, so it is difficult to differentiate weathered and unweathered bedrock at a regional scale.

The general trends of groundwater vulnerability shown in the DRASTICL model are similar to a lower resolution Maine DRASTIC model made by Li Wang at Tufts University in 2008[39]. Wang's model shows the same regional vulnerabilities in the northeast corridor of the state (46°45', -70° to 47°30', -69°), Downeast (44°45', -67°45'), the southwest (43°45', -70°30'), and glacial/fluvial deposits throughout the center (45°30', -68°45' to 46°30', -69°). Despite using single data sources for each parameter and no land use data, simplified hydraulic conductivity, soil data for the vadose zone, simplified aquifer media, and low resolution national data for the net annual recharge and depth to water table, achieving the same trends indicates that the shared regions of vulnerability highlighted above are particularly susceptible, and efforts should be made to protect them specifically.

Although regional trends may be accurate, the DRASTICL model's lack of more specific accuracy can be observed in the PFAS Test Results Overlay in Figure 11 and Table 15. The pattern of decreasing percentages of PFAS detection in samples as DRASTICL ratings increased, is proof of a poorly weighted model and/or inaccurate data. A good model would produce a positive relationship between PFAS concentrations in groundwater and DRASTICL rating, or at least a positive correlation between DRASTICL rating and the percentage of samples where PFAS is detected. However, the increase in PFAS detection rate for the highest two DRASTICL classifications shows that the high vulnerability ratings may be accurate, especially if they are in areas with especially vulnerable aquifers, such as karst limestone, sand and gravel, or other coarse glacial deposits.

These inaccuracies most likely stem from the Depth to Water map, depth to bedrock map, and the Hydraulic Conductivity map. With such sparse data in many regions, gSSURGO data was used for 84.96% of points (a highly accurate data repository, but generalized to conform to the scale it is used at). Since soil data makes up such a large portion of the data, the depth to water map is biased towards minimum depth to water values (the highest water level throughout the year), rather than average, contributing a higher vulnerability rating to the DRASTICL map than is probably representative of typical conditions. The depth to bedrock map is based on a 1:5,000,000 scale map which should have enough data added to match the scale of the surface DEM being used (500 m cells compared to 10 m cells). Lastly, as mentioned above, the

Hydraulic Conductivity map is far too generalized, as local bedrock fractures have a large effect on groundwater vulnerability, possibly making an area highly vulnerable that was assumed to be unfractured and low vulnerability.

Due to the role of land cover in the DRASTIC model and the assignment of ratings between 7 and 10 to urban areas[20], it is unsurprising that the metropolitan areas are modeled as having higher groundwater vulnerability. An implication of this effect is that urban areas have a certain degree of PFAS vulnerability inherently, whether or not there are PFAS-related industries. PFAS is mostly ubiquitous in the environment, as studies of background levels have shown[13], but in urban environments where more household products and people occur, there should be a greater groundwater vulnerability to PFAS contamination[20]. Even smaller towns like Brunswick (44°, -70°) or Waterville (44°30', -69°30') have high land use ratings (Figure 8), so the effect of any development on groundwater vulnerability should not be underestimated.

The model indicates that the areas least susceptible to groundwater contamination are regions with more mountainous terrain, undeveloped wilderness (particularly forests and wetlands), and impermeable layers such as fine particles or confining layers (assuming the groundwater is coming from below the confining layers). This should indicate that drinking water sources be located as far away from development as possible, such as is the case for New York City's water supply in the Adirondacks. Where significant sand and gravel aquifers are used as the primary water source, local regulatory action should be taken to prevent industry from being zoned on or uphill from the aquifer. Any industry with potential to pollute PFAS into the environment should be located downhill from wellheads, and on confining geology such as clay or unfractured bedrock.

It is very clear that there is a link between the facilities in the Potential PFAS Source heatmap and PFAS contamination, as the test data are clustered around Potential PFAS hotspots. It seems that this less complex model may be a better predictor of PFAS contamination, which simply posits that areas where large amounts of PFAS are used or produced are most likely to have groundwater contamination.

When comparing the overlap between the Potential PFAS Sources heatmap and the DRASTICL model, it should be noted that in areas with high potential for PFAS contamination due to multiple high risk PFAS facilities in close proximity, it probably doesn't matter whether there is a high or low groundwater vulnerability according to the DRASTICL model. It is likely that areas with high risk of contamination according to the Potential PFAS Source heatmap will have some PFAS contamination regardless of other factors (at least according to the Maine State Test Results data). Similarly, if the heatmap is blue, indicating low risk, or even if there is no color, indicating no facility nearby, one: there is a global background PFAS contamination[13], and two: it only takes one facility to contaminate a local groundwater system.

Future Work and Limitations

Project Limitations

This model should be viewed as a first step in mapping Maine's groundwater vulnerability. It is intended as a regional model to showcase regional patterns in vulnerability, but for local planning purposes, a larger scale local map (most likely with more data collection) should be created. In the same manner, "zooming in" on a certain portion of the map to look for a specific neighborhood or street is inadvisable, as the most accurate data in the model only goes to a 10 meter resolution, whereas many datasets within the model are 250 or 500 meter resolution.

Assumptions of the DRASTIC model itself that were stated by its creators are[18]:

1. “The contaminant is introduced at the ground surface”
2. “The contaminant is flushed into the ground water by precipitation”
3. “The contaminant has the mobility of water”
4. “The area evaluated using DRASTIC is 100 acres or larger”

Maps published by state natural resource departments (the Minnesota Department of Natural Resource’s Water Table Elevation and Depth to Water Table report[40], the corresponding GW-04 Methods for Estimating Water-Table Elevation and Depth to Water Table report[36], and the Guide to the Groundwater Vulnerability Map of Ohio[41]) served as a model for this DRASTICL model. These were constructed by teams of people in state agencies with much knowledge of more hydrogeology and local geology.

Future Work and Recommendations

To improve the accuracy of this model, as discussed above, the primary focus should be set on improving the Depth to Water/Water Table Elevation, Overburden Thickness/Bedrock Elevation, and Hydraulic Conductivity maps. Further analysis can be done to fine tune the Topo to Raster model and compare it to other interpolation methods to determine which is most accurate when mapping groundwater elevation. Additional data points can be collected for local maps to improve accuracy in areas with suspect depth to groundwater values. For the bedrock topography map, additional time can be spent interpolating available data points such as bedrock outcrops, surficial materials logs, well logs, and seismic refraction data. Adding synthetic data points to areas with known surficial geology can be done to shape subsequent interpolations until they appear to be more realistic. In terms of making the Hydraulic Conductivity map more accurate, a more extensive review can be done of the literature for Maine specific hydraulic conductivity values, or local geologists can give their input on associating specific surficial sediments and bedrock types with ranges of values. Additional transmissivity or pump test data would also improve the map, by locating fractures in the bedrock and obtaining local hydraulic conductivity values.

Several studies have been conducted on the interaction between PFAS and soils with differing cation exchange capacities and pH values[55][56][57]. By including these values into future models, the accuracy of the general groundwater vulnerability model can be optimized for PFAS specifically (with different chemicals in the PFAS family having different affinities).

Further limitations within this specific project include the data sources and their implementations. Although DRASTIC was designed to use widely accessible data for its parameters, most of the needed parameters were not available for Maine at a statewide level. Due to Maine's population center being along the southwestern coast, the highest resolution and largest coverage data were found along this region, with a lack of data in northwestern Maine. Perhaps the mapping of groundwater vulnerability is not as important in northwest Maine where few people live, but as the region is developed, or as a precursor to future development, more data should be collected in the region to develop mapping products such as this one.

The purpose of this project is to guide government agencies, private companies and nonprofit organizations towards the most likely PFAS contamination sites. The areas with the highest DRASTICL ratings and the hotspots on the Potential PFAS Sources heatmap should be prioritized for oncoming PFAS testing, as they are the most likely to yield results that are over state regulatory limits.

As Maine continues to be on the forefront of progressive PFAS regulation, it is equally important to identify current PFAS contamination in drinking water as it is to ban the production and consumption of new PFAS products. Increasingly, the chemical alternatives to PFOA and PFOS are being found to have similar long-term health concerns[42], so the list of PFAS products and related manufacturing facilities will continue to grow. To utilize financial resources efficiently until PFAS testing benefits from economies of scale, it is important to take advantage of maps such as those contained in this project, and their more accurate successors, to prioritize PFAS testing where groundwater contamination is most likely to occur. An even more cost effective method of PFAS prevention is to use these vulnerability maps to enact new zoning regulations to keep vulnerable aquifers undeveloped or under low risk land use practices.

Appendix

Detailed Methods for Map Creation in ArcGIS Pro 3.1.0

Depth to Water

Data were downloaded from the “Maine Well Database,” “USGS Groundwater Data,” the “National Hydrography Dataset Best Resolution (NHD),” “Maine Surficial Materials Seismic Line Point Features,” the gSSURGO dataset for Maine, the “Maine State Boundary Polygon,” the “Maine County Boundary Polygons Dissolved,” and a series of ⅓ Arc Second DEMs covering Maine (see Table 1 for sources). All the data were loaded into a blank map in ArcGIS Pro. The map was projected to NAD 1983 UTM Zone 19N so that all following calculations are in a consistent projection format, and distortion is minimized (the state fits perfectly in one UTM zone). Since no statewide depth-to-groundwater maps exist for Maine (unlike several midwestern states), one was interpolated using known static water level points.

The Minnesota Department of Natural Resources published methods in 2016[36] for their updated statewide water table elevation map, and unlike reports for other states with similar maps, this document is unique in its thorough explanation of techniques. Thus, the approaches used in the MN DNR “Methods for Estimating Water-Table Elevation and Depth to Water Table” methodology are adapted for the Maine groundwater elevation map and subsidiary depth-to-water table map.

Surface elevation data in DEM form is available in 1 by 1 degree quadrangles across the state from the USGS, which needs to be converted to a single statewide DEM. For consistency, ⅓ Arc Second resolution data were used as the highest available elevation data that covers the whole state. However, 1/9 Arc Second and 1 meter resolution DEMs are available for the coastal and Canadian border portions of the state. The ⅓ Arc Second quadrangles can be mosaiced to one raster using the Mosaic to New Raster (Data Management Tools) tool in ArcGIS Pro. The individual DEMs should be selected as input rasters, the output location and file type should be specified (with no file extension to store as an ESRI Grid), the spatial reference should be NAD_1983_UTM_Zone_19N to conform to the map projection, the pixel type should be 32 bit float, the number of bands should be set to 1, and the Mosaic Operator should be set to blend (although there should be no overlap between quadrangles, so this setting does not matter as much). The cell size will be set to the largest cell size of the input rasters by default, which in this case is 8.83 m. A clipped version was created using the Extract by Mask tool and the Maine State Boundary Polygon.

Well data with validated static water levels are the best source of water-table data, as they can be found across the state, drillers usually have access to accurate measuring devices, and they can show averaged data if logs are kept for longer periods. However, these ideal circumstances are not usually met, with few wells having static water level measurements, few data points in unpopulated areas, while wells drilled into fractured bedrock are not representative of the local water table. Therefore, the well data are supplemented with gSSURGO soil water table data, surface water data, and seismic refraction profile data.

Reliable well data come from the Maine Geological Survey and the United States Geological Survey (USGS). The Maine Geological Survey (MGS) has a dataset of 81,103 located wells[Table 1], published from "an original survey of well drillers in the 1970s, a voluntary well driller reporting program in the mid-1980s, and the present mandatory reporting program which relies on the submission of well information by drillers." Of these records, 7,985 wells have data for static water level, but several have either negative values, or a value of 999, which are not included in the analysis. This leaves 7,971 wells with usable data. With the static water level in feet below ground level, the value was converted to meters and subtracted from the surface DEM elevation data (using the Extract Values to Points (Spatial Analyst) tool). This resulted in each point having a groundwater elevation value. The selected wells were further screened to only use non-bedrock wells (where well type was equal to: “DUG”, “GRAVEL”, “GRAVEL PACKED”, “OBSERVATION”, “OTHER”, “OVERBURDEN”, and “SPRING”), narrowing down the selection to 677 wells. The Copy Features (Data Management Tools) tool was used to make a new feature class containing only the selected features.

Bedrock wells were excluded from the selection, as they are unrepresentative of the local water table. Firstly, the fractures in bedrock which these wells take advantage of are not necessarily connected to the surficial groundwater system, so water levels within the wells may not be similar to the regional water table[36]. Also, wells consist of a steel casing from the surface to the bedrock, and screening along a select portion of the fractured bedrock portion[28]. Due to this, the well water level is isolated from the local water table (separated by steel casing in the overburden), and the screening may be over a limited interval of the bedrock formation, which is not representative of the overall water-bearing zone.

Data from the USGS were taken from the National Water Information System, USGS Groundwater Data for Maine webpage[Table 1]. Field measurement data exist for 1,171 sites in Maine, 18 of which are actively providing automated measurements at regular intervals. All measurements were saved as a tab-separated file and processed in Excel to provide averaged static water levels for each site. The Extract Values to Points tool was used to extract surface DEM values to the point data. A new column was added to convert depth to water table in feet to meters, and then water table elevation values were calculated using surface DEM elevation data.

Additional direct measurements of water table elevation were obtained from surface water bodies. Surface water represents points in the topography where the water table elevation is higher than the land surface. Thus, using the National Hydrography Dataset, waterbody and flowline shapefiles were added, where streams, rivers, artificial drainage paths, coastlines, ponds, lakes, reservoirs, wetlands, and estuaries were selected as meaningful data points. In line with the MN DNR methodology, to process the data for interpolation, the Points Along Line tool was used to space points every 100 meters along line features (including endpoints) and the perimeters of polygon features that were 1 US acre (4046.86 square meters) or larger. For polygons less than 4046.86 square meters, a centroid point was created for each, using the Feature to Point (Data Management Tools) tool. All of these surface water points were assigned elevation values extracted from the surface DEM elevation using the Extract Values to Points tool.

The Maine Geological Survey makes available 12- and 1-channel seismic refraction profile data from 3,169 points across the state. The profiles vary from 60 to 2150 feet (18.29-655.32 m) in length, but only one datum is offered per profile (at one end of the profile line feature), with minimum and maximum depth values. Ideally, multiple data points would be generated from each line, corresponding to the depth at each point in the profile, but the only full profile data are stored in a low-resolution pdf, so instead an average depth was computed and used for each seismic point. Using a statewide map scale, this resolution is acceptable, but for local scale maps looking to accomplish similar goals, more precise data should be used. The data in the attribute table were contained in “BDRK_A”, “BRK_B”, “BDRKAVG”, “WTR_A”, and “WTR_B” fields, representing depth to bedrock and water (in feet) via text-string data. Some non-numeric characters were used, such as “>”, “<”, “≤”, and “≥”, so a new field was created of data type “double” and a python script was used to strip all non-numeric characters and convert each value to an integer. “<1” was set equal to 0 and all other values were simply stripped of their non-numeric characters (no water values had non-numeric characters, and all of the Bedrock_Avg values were already created and used exclusively “≤” or “≥”, so the numeric values were used as they were). All depth values were converted to meters, and subtracted from the surface DEM elevation data (using Extract Values to Points to assign surface elevation values).

Surficial material point data are provided by MGS, which contains logs of all field observations from geologists across the state, describing bedrock outcrops, test pit findings, core sample findings, and observations from quarries or other exposed geological profiles. The fields of interest for this project are “BDRK”, “WATER”, “STRIKE”, and “SYMBOLOGY.” Using points which have depth to water data, a new feature class was created using Copy Features. Elevation data were extracted from the DEM elevation data, and a water table elevation in meters was calculated.

gSSURGO is the National Resource Conservation Service’s (NRCS) Gridded Soil Survey Geographic (gSSURGO) Database, which is an agglomerate of all publicly accessible soil data, and generally regarded as the most detailed soil data available[Table 1]. Soil data from the gSSURGO dataset comes in the form of a raster with values equal to map unit keys (MUKEYs) unique to each combination of soil components. A singular map unit can be associated with multiple soil components, each with multiple soil horizons. An array of tables with many soil properties is also included in the gSSURGO dataset, where the raster MUKEY values must be joined to MUKEY values in the tables, with corresponding joins to other tables that have more specific properties, resulting in a series of parent-child table relationships that can be several joining keys separated from the initial raster join. One property in the MUAGGATT table is “Water Table Depth - Annual - Minimum” which was used in this project to obtain more water table depth data points. By joining the MUKEY raster with MUAGGATT via common MUKEY values, annual minimum depth to water values are available for most map units. These values are in centimeters, so Calculate Field must be used to make a new field with the values in meters. Then using the Lookup (Spatial Analyst) tool, a new raster can be created with the value field equal to annual minimum depth to water values in meters. This raster cannot be readily combined with the other data points in its current form, so using the same method as the Minnesota Department of Natural Resources[36], a grid of points was created and the raster values were extracted to the points, which can then be merged with the other discrete water table elevation data and interpolated. The grid of points was created using the Create Fishnet (Data Management Tools) tool, with the Maine State Boundary Polygon as a template, the cell size width and height set to 100 meters, the “Create Label Points” box checked, and the “Geometry Type” set to Polyline.

With the fishnet grid created, the polylines can be removed, leaving just the point feature. The Extract Multi Values to Points tool can then be used to extract the annual minimum depth to water values to the points. The same tool should be used to extract surface DEM data to the points, so the water table elevation can then be calculated by subtracting the depth value from the surface DEM value. A particular note of importance in the Minnesota DNR methodology is to exclude perched water table data from the soil data, so the perched water table property must be extracted to the points as well.

Excluding perched water table water depth values is important because it would affect the interpolation process by representing the local water table elevation as higher than the actual average depth, as only a small portion of a geographic area is most likely perched. Additionally, in the context of this model, a perched water table is not representative of the actual groundwater vulnerability. Having a perched water table implies a confining layer of impermeable material relatively close to the surface, which would not be the aquifer that a local well would be accessing. Due to the low water storage capacity of a perched water table, a well would be drilled through the impermeable layer to deeper water resources. Those deeper water resources would in fact be sheltered from surface PFAS contamination by the impermeable layer rather than extremely vulnerable as a low water table depth value from a perched water table would suggest. All of those reasons are likely why the Minnesota DNR chose to exclude perched water table values, and this map will as well.

The perched condition attribute is not currently available in the gSSURGO dataset, but was obtained from Kyle Stephens of the Soil Survey Database Team at the NRCS as a joinable table with MUKEY values[43]. After the table was joined to the MUKEY raster, a new raster was created with the Lookup tool, and perched values were extracted to the annual minimum depth to water data points. All points which have no water depth values or indicate a perched water table were removed. This leaves 5,784,073 points, comprising a large majority of the water elevation data points (similar to in the Minnesota DNR process which estimated 80-90% of points to come from soil data[36]).

All derived data point feature layers (Soil data, MGS well data, USGS well data, surface water data, and seismic profile data) were merged into a single point layer using the Merge (Data Management) tool. With 6,807,798 points, the data has to be divided to be processed, so data were split up by county.

To obtain individual county polygons, the Maine County Boundary Polygons Dissolved feature was used, where a county was selected in the attribute table and the Copy Features tool was used to make a new feature. The process was repeated for each county, resulting in 16 new shapefile features. To prevent edge effects in the interpolation process, data from outside the county border should be included, to create a smooth elevation model through the county boundary. The Buffer (Analysis Tools) tool was used to create a 1,000 meter buffer for each county, with the Dissolve Type set to “Dissolve all output features into a single feature” to result in a single polygon with buffered boundaries. The main water elevation data point feature was clipped to each buffered county using the Clip (Analysis Tools) tool.

Then, the Topo to Raster (Spatial Analyst) tool was run for each county using the corresponding clipped point layer as the sole input (set as data type “TopoPointElevation”) and the enforce parameter set to “NO_ENFORCE.” The Topo to Raster tool creates a hydrologically correct (ensuring a connected drainage structure and flow paths) digital elevation model (DEM) using a modified spline interpolation technique (interpolation being the process of filling in data between known points using one of several mathematical formulas, each with their own benefits and limitations). The Clip tool was used to shape each raster to its county’s borders (unbuffered). Mosaic to New Raster was applied to form the county rasters into a statewide water table elevation raster.

With the water table DEM created, the Raster Calculator (Spatial Analyst) tool can be used to subtract the new raster from the surface DEM to obtain a Depth to Water Table raster. Ideally, all cell values in the Water Table Elevation raster should be below the Surface Elevation Raster cells, but due to spatial resolution (raster cell size) and the Topo to Raster tool’s interpolation method, this is not always the case. In future iterations of this map, additional data and better interpolation techniques should aim to minimize the number of cells with negative values in the Depth to Water Table raster, but for this version, all cells with negative depth values were set to 0, using the Reclassify (Spatial Analyst) tool.

In the symbology tab, the raster was classified into seven categories, and the upper values were manually defined according to the corresponding DRASTIC Depth to Water Table values[Table 2]. The DRASTIC values are in feet, whereas the raster's values are in meters, so a conversion from meters to feet was used, where 1 foot is equal to 0.3048 meters. A color scheme was applied, using a similar color scheme as the Minnesota Depth to Water Table[40]. The Reclassify tool was used to create a new raster, assigning each class a DRASTIC rating according to the original methodology values[Table 2].

Net Recharge

Data were downloaded from Nielsen and Westenbroek (2019), where 25-year Maine net annual recharge data were loaded into a blank map in ArcGIS Pro as a raster[Table 1]. The data were simulated by Nielson and Westenbroek using data collected between 1981 and 2015, with a final USGS dataset released in 2019, containing average precipitation, along with maximum, mean, median, minimum, and standard deviation net annual recharge data. Median net annual recharge was chosen for this project to provide a representative product, with less weight from outlier years. A significant portion of Maine along the northwest border was categorized as not having enough data to produce median values. Other datasets were also lacking data in the same region, possibly due to low population density and thus lower sampling rates. With the population center along the coast, the Maine Geological Survey's particular coverage of those regions in terms of higher resolution mapping is a logical allocation of resources.

The map was projected to NAD 1983 UTM Zone 19N, with raster data classified in the symbology tab to match the DRASTIC ratings, set to classes of 0-5.08, 5.08-10.16, 10.16-17.78, 17.78-25.4, and 25.4+ centimeters of net annual recharge. An appropriate color ramp was chosen from ESRI defaults, with purple tones representing lower recharge rates, and turquoise representing higher rates. Using the Reclassify tool, each recharge class was assigned a DRASTIC rating according to the original DRASTIC methodology[Table 3].

Aquifer Media

Data were downloaded from “Surficial Geology 250K Units,” “Maine geologic map data,” “Maine Aquifers,” “Quaternary sediment thickness and bedrock topography of the glaciated United States east of the Rocky Mountains,” and “Karst in the United States: A Digital Map Compilation and Database” [Table 1]. All data were added to a blank ArcGIS Pro map. Additionally, the Depth to Water and statewide DEM rasters were added to the map. The map was projected to NAD 1983 UTM Zone 19N.

No aquifer media geology maps exist for Maine at regional scales beyond the Surficial Sand and Gravel Aquifer mapping project. The project delineates sand and gravel aquifers with potential well yields of 10 or more gallons per minute in order to provide information about natural drinking water resources. This can be a useful source of hydraulic conductivity and aquifer media data, but the significant aquifer area only covers 3,513.74 square kilometers, or 4.39% of Maine’s land[Table 1], leaving a majority of the state with no data for the DRASTICL model. However, as there is bedrock geology and surficial geology data for the whole state, aquifer media can be determined based on the depth to water map, created as the first step of this project. Discussed in the background section, *Understanding Maine’s Surficial Geology,* aquifers are water bearing geologic materials that can store or transmit groundwater. Aquifers are found below the vadose zone, and their upper boundary is defined by the local water table. Therefore, the Maine bedrock and surficial geology maps describe the local aquifer media, but it must be determined which material is water bearing at that location.

In order to use bedrock and surficial geology data to determine aquifer media, the geology units must be categorized similarly to the original DRASTIC ratings table[Table 4]. In the Maine geologic map data from USGS, bedrock geologic units were separated into three rock types, with the first being the most dominant. When no second or third rock type was listed, the geologic unit was assigned one of the original DRASTIC bedrock classifications: Massive Shale; Metamorphic/Igneous; Weathered Metamorphic/Igneous; Massive Sandstone; Massive Limestone; Basalt; or Karst Limestone. There were four notable exceptions where the categories "Confining Layer," "Conglomerate," "Mudstone/Graywacke," and "Volcanic" were created to describe rock types that did not fit within the original classifications. These rock types could not be well-described by the DRASTIC general categories and/or had differing permeabilities from the general DRASTIC rating given to their parent category. The new classifications were assigned DRASTIC ratings of 2, 7, 4, and 9[Table 5] based on literature permeabilities[44] compared to geologies with predefined DRASTIC ratings. When second and third rock types exist, if the sequence contained more than one sedimentary rock, the geologic unit was assigned Bedded Sandstone, Limestone and Shale Sequences from the original DRASTIC classification, and otherwise assigned according to the dominant first rock type.

A Depth to Bedrock raster has to be created to determine whether surficial overburden in a given cell extends below the water table, or whether bedrock should be used as aquifer media. A Quaternary sediment thickness map is available at a national scale (1:5,000,000) from Soller and Garrity (2018)[Table 1], which was used in conjunction with depth to bedrock data from the gSSURGO dataset to create a larger scale map. The gSSURGO raster data were already joined with the MUAGGATT table from earlier, which contains a parameter, “Minimum Depth to Bedrock.” The Lookup tool was used to create a new raster with minimum depth to bedrock values as the raster value. Using the Mosaic to New Raster tool, the Quaternary sediment thickness raster and gSSURGO data were combined, with the Mosaic Operator setting set to Minimum in order to use the lower of each two cell values being compared, when combining the rasters.

The bedrock and surficial geology shapefiles were rasterized using the Feature to Raster (Conversion Tools) tool, with the Unit field selected as the new value field (the associations between units and raster values can be found in Table 5). Using the Raster Calculator tool, the expression, *Con(“OverburdenDepth” > “DepthToWater”, “SurficialGeology”, “BedrockGeology”)*, can be used where “OverburdenDepth” is the name of the raster with depth to bedrock values, “DepthToWater” is the name of the raster with Depth to Water values, “SurficialGeology” is the name of the raster with surficial geology media types, and “BedrockGeology” is the name of the raster with bedrock geology media types. The Con (Spatial Analyst Tools) tool must then be used so that the values 16, 17, 18, and 20[Table 5] (representing bedrock or low overburden depth in the surficial geology) are replaced with the bedrock geology values in the same spatial location.

The resulting raster has Aquifer media values corresponding to bedrock or surficial geology units. However, there are two more modifications to make to the raster. Karst features occur in bedrock which has partially dissolved due to having weaker and/or more soluble materials mixed in with the main low-permeability matrix (which in Maine occurs in limestone and marble)[45]. Due to the nature of bedrock aquifers storing all of their water in fractures (since the consolidated geology is low-permeability or impermeable), karst features dramatically increase water storage, but also increase groundwater vulnerability. Connections to the surface have no filtration before entering the aquifer – all surface fractures are directly linked to the aquifer. Using USGS data from Weary and Doctor (2014)[Table 1], a shapefile of Karst features exists for the continental US. Rasterizing that shapefile, the Raster Calculator tool can be used with the expression, *Con(IsNull("Karst"), "AquiferMedia", Con(("AquiferMedia"==27) | ("AquiferMedia"==28), 31, "AquiferMedia")),* where "Karst" is the Karst raster and "AquiferMedia" is the raster of aquifer media from bedrock and surficial geology. 31 is the unit code assigned to Karst Limestone in Table 5, where 27 is the unit code for bedded sandstone, limestone, and shale, and 28 is the unit code for limestone. A similar process was used for the Maine Aquifer data, where the Raster Calculator tool was used with the expression, *Con(IsNull("SGAquifer"), "AquiferMedia", 8),* where "SGAquifer" is the rasterized significant sand and gravel aquifer shapefile data, "AquiferMedia" is the newly updated Aquifer Media raster, and 8 is the unit code for coarse grained glaciomarine deposits in Table 5, which has the same assigned DRASTIC rating for Aquifer Media as the sand and gravel DRASTIC category (also 8). The Aquifer Media unit values can then be replaced using the Reclassify tool with the corresponding Aquifer Media DRASTIC ratings[Table 5]. A blue to pink color scheme was chosen where blue is the least vulnerable, and pink is the most vulnerable.

Soil Media

Theoretically, data can be downloaded from the gSSURGO dataset[Table 1] and the MUKEY raster can be joined with the COMPONENT table, which can be joined with the CHORIZON table, which can be joined with the CHTEXTUREGRP table, which can be joined with CHTEXTURE and finally CHTEXTUREMOD. However, the horizon number identifier parameter is currently not available, and the NRCS has designed the Soil Data Development

Toolbox for ArcGIS to make mapping such characteristics as soil texture straightforward, but it is made for ArcMap and is currently not compatible with ArcGIS Pro. Therefore, Kyle Stephens of the Soil Survey Database Team at the NRCS provided a raster of surface soil texture with texture modifiers[43]. Loaded into a blank map with the coordinate system NAD 1983 UTM Zone 19N, the raster was reclassified according to adapted DRASTIC ratings (shown in Table 7) from the original DRASTIC ratings in Table 6 and symbolized with a color scheme from brown to yellow, with yellow being the highest vulnerability.

Topography

The statewide DEM was loaded into a blank map with the coordinate system NAD 1983 UTM Zone 19N. The Slope (Spatial Analyst Tools) tool was used to create a new raster with cell values of percent slope. Using the percent slope DRASTIC classes from Table 8, the raster was symbolized using a white to dark brown color scheme, with dark brown being the lowest vulnerability. Table 8 was also used to reclassify the percent slope classes to their assigned DRASTIC ratings.

Impact of the Vadose Zone Media

Creating the map of the Vadose Zone Media was a similar process to creating the map of the Aquifer Media. Data were downloaded from “Surficial Geology 250K Units,” “Maine geologic map data,” and “Karst in the United States: A Digital Map Compilation and Database”[Table 1]. The vadose zone is the layer below the soil and above the water table. It is assumed that the surficial geology is the vadose zone except in places where bedrock is at the surface, which are coded as 16, 17, 18, and 20, as discussed in the creation of the Aquifer Media map. The Con tool was used with the surficial geology raster as an input, and the values 16, 17, 18, and 20 as a selection, where if True, the cell value is replaced with the bedrock geology raster value and if False, kept as the surficial geology raster value. The new Vadose Media raster was subjected to the same Karst modification, where the Raster Calculator tool can be used with the expression, *Con(IsNull(“Karst”), ”VadoseMedia”, Con((“VadoseMedia”==27) | (”VadoseMedia”==28), 31, ”VadoseMedia”))*. The only parameter changed is “VadoseMedia” as the Vadose Media raster in place of “AquiferMedia” as the raster for Aquifer Media. The raster was reclassified with the Vadose Zone Media values from Table 5 and symbolized with the same blue to pink color scheme as the Aquifer Media map.

Hydraulic Conductivity

Hydraulic Conductivity is a direct parameter of Aquifer Media, where it refers to the degree at which water (and contaminants in the case of the DRASTIC model) can move through a material. A higher hydraulic conductivity for an Aquifer Medium such as sand and gravel represents a higher flowthrough rate, where water can easily pass through the medium, and low would represent the opposite in the case of unfractured bedrock or an impermeable layer such as clay. The Aquifer Media DRASTIC component is different from Hydraulic Conductivity in that it refers to the filtering capacity of the material instead of the rate of flow through.

However, due to the direct affiliation between Hydraulic Conductivity and Aquifer Media, where the DRASTIC model uses the Hydraulic Conductivity of the Aquifer[18], the same Aquifer Media raster was used for Hydraulic Conductivity. The original Hydraulic Conductivity DRASTIC ratings[Table 10] are based on classes of Hydraulic Conductivity values measured in gallons per day per square foot, rather than Aquifer Media type, so values are derived from literature Hydraulic Conductivity studies. These values are summarized in Table 11, with the primary sources being Freeze and Cherry’s 1979 textbook, *Groundwater*[47]*;* several values differentiating sand particle sizes from West's 1995 textbook, *Geology applied to engineering*[48]; and as many Maine specific values as could be found to describe the general categorizations, with Lyford, Garabedian, and Hansen's 1999 study, "Estimated hydraulic properties for the surficial- and bedrock-aquifer system, Meddybemps, Maine"[46]. The Aquifer Media raster was reclassified using the adapted DRASTIC ratings[Table 5], and symbolized with a purple, orange, red and tan color scheme, where blue and purple are low vulnerability and tan is the highest, with orange and red in the middle.

Land Use

This DRASTIC model is modified to be a DRASTICL model which takes land use into account as well as the seven original DRASTIC parameters, as many previous studies have found that land use is an important predictor of groundwater contamination[19][49]. Using the parameter weight and Land Use ratings from Maqsoom et al. (2020)[20], the map was given a weight of 5, with land use classes generally being described as water, wetland, forest, wasteland, agriculture, light development, medium development, and heavy development, in order of least to most vulnerability[Table 12]. data were downloaded from NOAA's 2016 C-CAP Regional Land Cover dataset[Table 1], and loaded into a blank map with the coordinate system NAD 1983 UTM Zone 19N. The raster was reclassified with DRASTICL ratings as described[Table 12], and symbolized with a light green to dark blue color palette.

DRASTICL

The DRASTICL raster was created using the Raster Calculator tool, implementing Eq. 2 by adding the 8 parameters multiplied by their respective assigned weights[Table 13]. The eight considered parameters are Depth to Water (D), Net Recharge (R), Aquifer Media (A), Soil Media

(S), Topography (T), the Impact of the Vadose Zone Media (I), Hydraulic Conductivity (C), and Land Use (L). The DRASTICL Index (DI) is calculated using the following equation:

$$DI = D_rD_w + R_rR_w + A_rA_w + S_rS_w + T_rT_w + I_rI_w + C_rC_w + L_rL_w \qquad (2)$$

where, r = ratings allocated to each parameter; and w = weights allocated to each parameter. The raster is classified into 10 categories, No Data, (surface) Water, <100, 100 - 120, 120 - 140, 140 - 160, 160 - 180, 180 - 200, 200 - 220, and 220+. Following the original DRASTIC specifications, with modifications for No Data, Water, and adjusting the shades slightly to be suitable for a colorblind viewer, the categories are symbolized in the same order as follows: gray, light blue, violet, indigo, dark blue, dark green, neon green, yellow, orange, red[18].

Potential PFAS Sources

Data were downloaded from the EPA Facility Registry Service through the Geospatial Data Download Service as a State Combined CSV file[Table 1]. Using a combination of NAICS[50] and SIC[51] industry codes, the facilities were assigned risk scores based on their industry, as was done in Ojha's (2022) geospatial model of PFAS contamination of Kentucky public water systems[12]]. Additionally, Potential PFAS Source data were downloaded from the MGS "Maine DEP PFAS Investigation," Maine DEP's "Closed Municipal Landfills," Maine DOT's "Airports," the Maine DEP's "Maine E911 Addresses Feature Fire Stations," the USGS' "Fire Stations," and the US DOT's "Military Bases" [Table 1]. All data were loaded into a blank map with the coordinate system NAD 1983 UTM Zone 19N. The table with EPA facilities and assigned risk scores was converted to spatial data using the XY Table to Point (Data Management Tools) tool, specifying NAD 1983 UTM Zone 19N as the coordinate system, with Longitude as the X

Field and Latitude as the Y Field. The sewage and sludge sites were downloaded from the Maine DEP PFAS Investigation ArcGIS Online web app as CSVs, and converted to spatial data using the XY Table to Point tool, with NAD 1983 UTM Zone 19N as the coordinate system. The military sites data were in shapefile format, so the Feature to Point tool was used to convert each polygon to a point at its center. The data points were all combined using the Merge tool, assigning industry type to each based on its source data. A new column was then added to associate a risk score with each facility.

Most industries' risk scores were assigned according to the work done by Ojha et al.[12], but land-applied sewage and biosolids facilities were added as an additional contamination source, and assigned a risk score of 25[Table 16]. Based on a review of soil samples taken at land-application sites[14], the PFOS concentration can range from 6.6 to 5,500 ppb, with PFOA ranging from 4.4 to 2,531 ppb. The site with soil concentrations in the single digits reported mean groundwater concentrations between 0.015 and 0.024 μg/l total PFAS[52], with soil:groundwater ratios of between 4 and 58. The higher magnitude soil concentration studies did not measure groundwater concentration, but another study simulated groundwater contamination at two Illinois field sites to be over 0.070 μg/l directly below biosolid land application sites[53]. Lastly, another study reported groundwater concentrations up to 0.029 μg/l for PFOA below a land-applied field site[54]. These studies however are mainly measuring PFOS and PFOA, biasing the results to underestimate total PFAS concentrations, as long-chain PFAS have been shown to attenuate in soil at much higher rates than short-chain PFAS[52][53][54]. This can be demonstrated with the EGAD PFAS Statewide Test Results[Table 1], where Pearson Field has a groundwater concentration of 21.1 μg/l, a similar upper magnitude to the other low tier facilities from Ojha et al.[12], earning these sites a risk score of 25.

With the facility point data in one file, and risk scores assigned, the data can be symbolized as a heatmap, similarly to in Ojha et al.[12]. The radius parameter was set to 10, to produce a visually similar density as the map in Ojha et al.,[12] and the weight field was set to the Risk Score attribute field. The default blue to yellow color scheme was accepted to represent sparse, low risk score areas as blue, and dense, high risk areas as yellow.

PFAS Test Results Overlay

The DRASTICL raster and Potential PFAS Source heatmap were loaded into a blank map with the coordinate system NAD 1983 UTM Zone 19N. The EGAD PFAS Statewide Test Results[Table 1] were then downloaded as an Excel file separated into spatial data and test results across two sheets. The Sample Point Numbers column was used to join the two sheets, using Get Data->Combine Queries->Merge tool path on the Data ribbon.

Two new columns were added to the merged sheet: Detect/Non-Detect and a converted concentration column. The Detect/Non-Detect attribute categorizes all rows (each row representing a single PFAS chemical being tested for in an individual sample) into Detect or Non-Detect, based on whether the PFAS concentration was above or below the Method Detection Limit (MDL), defined as “the minimum measured concentration of a substance that can be reported with 99% confidence that the measured concentration is distinguishable from method blank results”[58].

To compare standardized concentrations across sites, all water based concentration units (mg/l, µg/l, and ng/L) were converted to ng/L (ppt). Solid based units (g/kg and similar) were excluded from the conversion, as only PFAS test results from water sources are desirable for validating the DRASTICL model. As seen earlier looking at test results across soil and groundwater samples at land-applied biosolid fields, the concentration of PFAS can vary by several magnitudes across mediums, with sometimes no detection in groundwater below contaminated soil, so only the groundwater samples are desired for comparison with the groundwater vulnerability models.

Maine regulates six PFAS chemicals: perfluorooctanoic acid (PFOA), perfluorooctane sulfonic acid (PFOS), perfluorohexane sulfonic acid (PFHxS), perfluorononanoic acid (PFNA), perfluoroheptanoic acid (PFHpA) and perfluorodecanoic acid (PFDA), with a drinking water standard of 20 parts-per-trillion ppt (ng/L)[59]. Thus, although the statewide testing data has many different sites and sample types (groundwater, leachate, surface water, drinking water, fish filet, etc) almost all include at least tests for PFOA and PFOS, with many testing for all six regulated chemicals. Although many test for more than just the six regulated PFAS, the majority have a row with the sum of the six regulated PFAS concentrations. To standardize a sum concentration that can be compared across all water samples, only the sum of six PFAS test results is used, and within that subset, only those samples taken from drinking water or groundwater sources were used.

The DRASTICL raster, Potential PFAS Source heatmap, and PFAS Test Results point data are arranged in that order, from back to front, in order to best compare the data. The Potential PFAS Source heatmap has a varying transparency from 50% in the blue spectrum, transitioning to 20% in the red spectrum, and staying at 20% through the yellow spectrum. This color scheme was designed to show more of the DRASTICL color scheme in lower PFAS risk areas, while exaggerating the higher PFAS risk in dense industry sectors, while still remaining transparent enough to view the DRASTICL colors underneath. The PFAS test data are 0% transparency, with a point size of 4 pt. The data were classified into seven classes, showing logarithmic increases in PFAS concentration for each increase in class, ranging from 0 to

100,000+. The colors for the PFAS test data points were chosen to be a yellow to red spectrum, with red being the highest magnitude concentration, and points with a concentration of below the MDL set to gray and “Non-Detect”

Tables

Table 1: Data Sources

Data Type	Source	Spatial Reference
Maine Well Database Christian H Halstead Maine Geological Survey Downloaded 2/28/2023	https://mgs-maine.opendata.arcgis.com/datasets/maine::maine-well-database-well-depth/about	WGS 1984
USGS Groundwater Data for Maine - Field Measurements US Geological Survey Downloaded 3/20/2023 Newest Data from 3/9/2023	Maine Page: https://waterdata.usgs.gov/me/nwis/gw Sites in Web Browser: https://nwis.waterdata.usgs.gov/me/nwis/gwlevels?county_cd=23001&county_cd=23003&county_cd=23005&county_cd=23007&county_cd=23009&county_cd=23011&county_cd=23013&county_cd=23015&county_cd=23017&county_cd=23019&county_cd=23021&county_cd=23023&county_cd=23025&county_cd=23027&county_cd=23029&county_cd=23031&group_key=NONE&sitefile_output_format=html_table&column_name=agency_cd&column_name=site_no&column_name=station_nm&format=rdb&date_format=YYYY-MM-DD&rdb_compression=value&list_of_search_criteria=county_cd	NAD 1983
USGS National Hydrography Dataset Best Resolution (NHD) - Maine (published 2022/12/05) FileGDB 1:24,000/1:12,000 scale	https://prd-tnm.s3.amazonaws.com/index.html?prefix=StagedProducts/Hydrography/NHD/State/GDB/ https://www.sciencebase.gov/catalog/item/61f8b8dad34e622189c32914	NAD 1983 UTM Zone 19N
Maine Surficial Materials Seismic Line Point Features Christian H Halstead	https://mgs-maine.opendata.arcgis.com/datasets/maine::maine-surficial-materials-seismic-line-point-features/about	WGS 1984

Maine Geological Survey Downloaded 4/5/2023		
gSSURGO soil textures for Maine Natural Resources Conservation Service U.S. DEPARTMENT OF AGRICULTURE 10 m cells	https://www.nrcs.usda.gov/resources/data-and-reports/soil-survey-geographic-database-ssurgo Downloaded October 2022 gSSURGO by state data from: https://nrcs.app.box.com/v/soils/file/1055258990645	NAD 1983 Contiguous USA Albers
1/3 Arc Second DEM U.S. Geological Survey Elevation Products (3DEP) TNM (the National Map) Download 8.83 m cells	https://apps.nationalmap.gov/downloader/#/ https://www.usgs.gov/ngp-standards-and-specifications/3dep-product-metadata	NAD 1983 UTM Zone 19N Transverse Mercator Meters NAD 1983
Maine State Boundary Polygon State of Maine 1:24,000	https://services1.arcgis.com/RbMX0mRVOFNTdLzd/arcgis/rest/services/Maine_State_Boundary_Polygon/FeatureServer ArcGIS Online: "Maine State Boundary Polygon Feature" by Emily.Pettit@maine.gov (an authoritative layer)	NAD 1983 UTM Zone 19N
Maine County Boundary Polygons Dissolved State of Maine 1:24,000	https://services1.arcgis.com/RbMX0mRVOFNTdLzd/arcgis/rest/services/Maine_County_Boundary_Polygons_Dissolved/FeatureServer ArcGIS Online: "Maine County Boundary Polygons Dissolved" by Emily.Pettit@maine.gov (an authoritative layer)	NAD 1983 UTM Zone 19N
Simulated 25-year potential annual recharge 1991-2015 Using Median dataset (in/year)	https://www.sciencebase.gov/catalog/item/5d10d0c9e4b0941bde550113 Nielsen, M.G., and Westenbroek, S.M., 2019, Simulated 25-year potential	NAD 1983 UTM Zone 19N Transverse Mercator Meters

250 m cells	recharge datasets for Maine, 1991-2015: U.S. Geological Survey data release, https://doi.org/10.5066/P9052ULY.	NAD 1983
Surficial Geology 250K Units Christian H Halstead Maine Geological Survey 1:250,000 scale 250 m cells	https://www.maine.gov/dacf/mgs/pubs/digital/surf250.htm https://www.maine.gov/dacf/mgs/pubs/mapuse/series/surf-250/surf-exp.htm https://mgs-maine.opendata.arcgis.com/datasets/maine::maine-surficial-geology-250k-units/about	WGS 1984
Maine geologic map data US Geological Survey 1:500,000 scale	https://mrdata.usgs.gov/geology/state/state.php?state=ME U.S. Geological Survey. (2006). Preliminary integrated geologic map databases for the United States: Connecticut, Maine, Massachusetts, New Hampshire, New Jersey, Rhode Island and Vermont [Open-File Report 2006-1272]. Retrieved March 9, 2023, from https://pubs.usgs.gov/of/2006/1272/	WGS 1984
Maine Aquifers Christian H Halstead Maine Geological Survey 1:24,000	https://mgs-maine.opendata.arcgis.com/datasets/maine::maine-aquifers/about	WGS 1984
Quaternary sediment thickness and bedrock topography of the glaciated United States east of the Rocky Mountains US Geological Survey 1:5,000,000 500 m cells	https://pubs.er.usgs.gov/publication/sim3392 Soller, D.R., and Garrity, C.P., 2018, Quaternary sediment thickness and bedrock topography of the glaciated United States east of the Rocky Mountains: U.S. Geological Survey Scientific Investigations Map 3392, 2 sheets, scale 1:5,000,000. https://doi.org/10.3133/sim3392.	Clarke 1866 Albers
Karst in the United States: A Digital Map Compilation and	https://pubs.usgs.gov/of/2014/1156/	

Database	Weary, D.J., and Doctor, D.H., 2014, Karst in the United States: A digital map compilation and database: U.S. Geological Survey Open-File Report 2014–1156, 23 p., https://dx.doi.org/10.3133/ofr20141156. ISSN 2331-1258 (online)	
2016 C-CAP Regional Land Cover National Oceanic and Atmospheric Administration Office for Coastal Management: Digital Coast 30 m cells	https://coast.noaa.gov/digitalcoast/data/ccapregional.html National Oceanic and Atmospheric Administration, Office for Coastal Management. “Name of Data Set.” Coastal Change Analysis Program (C-CAP) Regional Land Cover. Charleston, SC: NOAA Office for Coastal Management. Accessed Month Year at www.coast.noaa.gov/htdata/raster1/landcover/bulkdownload/30m_lc/.	NAD 1983 UTM Zone 19N
EPA FRS Facilities State Single File CSV Download Geospatial Data Download Service	https://www.epa.gov/frs/epa-frs-facilities-state-single-file-csv-download	NAD 1983 UTM Zone 19N
Maine DEP PFAS Investigation (Formerly the “Septage and Sludge Map”) Maine Geological Survey Downloaded 4/9/2023	https://maine.maps.arcgis.com/apps/webappviewer/index.html?id=468a9f7ddcd54309bc1ae8ba173965c7	NAD 1983 UTM Zone 19N
Solid Waste - Closed Municipal Landfills Maine Department of Environmental Protection Last updated 10/14/2020 Downloaded 3/26/2023	https://www.maine.gov/dep/gis/datamaps/index.html	WGS 1984
MaineDOT Airports	https://maine.hub.arcgis.com/datasets/b1c2f8191e254ba5b322fbf31352e5ef_2/abou	WGS 1984

State of Maine Last updated 9/28/2021 Downloaded 3/25/2023	t	
Maine E911 Addresses Feature Fire Stations Maine GIS State of Maine Last updated: 9/21/2021 Downloaded: 3/26/2023	https://maine.hub.arcgis.com/datasets/maine::maine-e911-addresses-feature-fire-stations/about	WGS 1984
Fire Stations Homeland Infrastructure Foundation-Level Data (HIFLD) US Geological Survey 1:24,000 Last updated: 2/7/2020 Downloaded: 3/23/2023	https://hifld-geoplatform.opendata.arcgis.com/datasets/geoplatform::fire-stations/about	WGS 1984 Web Mercator (auxiliary sphere)
Military Bases US Department of Transportation: Bureau of Transportation Statistics Last Updated: 12/20/2022 Downloaded: 3/26/2023	https://data-usdot.opendata.arcgis.com/datasets/fb5aff99c6e74ed99cd8b36dfae1c469_0/about	WGS 1984
EGAD PFAS Statewide File November 2022 Maine Department of Environment Protection Last Updated: 11/22/2022 Downloaded: 3/5/2023	https://www.maine.gov/dep/spills/topics/pfas/ Maine Department of Environmental protection, EGAD (Environmental and Geographic Analysis Database), http://www.maine.gov/dep/maps-data/egad/ Note: an Excel version of the November 2022 data were obtained from Victoria	WGS 1984

	Eleftheriou P.E., Deputy Director at the Maine DEP: Bureau of Remediation and Waste Management with spatial data, that is not available on the public PFAS page	

Table 2: Depth to Water DRASTIC Ratings

Depth to Water				
Range (Feet)	Range (Meters)	Rating	Cell Count	% of Area
0 - 5	0 - 1.524	10	20275348	60.33
5 - 15	1.524 - 4.572	9	8280750	24.64
15 - 30	4.572 - 9.144	7	2965556	8.82
30 - 50	9.144 - 15.24	5	1118795	3.33
50 - 75	15.24 - 22.86	3	508205	1.51
75 - 100	22.86 - 30.48	2	219890	0.65
100+	30.48+	1	236526	0.70

Table 3: Net Recharge DRASTIC Ratings

Net Recharge		
Range (Inches)	Range (Centimeters)	Rating
0 - 2	0 - 5.08	1
2 - 4	5.08 - 10.16	3
4 - 7	10.16 - 17.78	6
7 - 10	17.78 - 25.4	8
10+	25.4+	9

Table 4: Aquifer Media DRASTIC Ratings

Aquifer Media

Range	Rating	Typical Rating
Massive Shale	1 - 3	2
Metamorphic/Igneous	2 - 5	3
Weathered Metamorphic/Igneous	3 - 5	4
Glacial Till	4 - 6	5
Bedded Sandstone, Limestone and Shale Sequences	5 - 9	6
Massive Sandstone	4 - 9	6
Massive Limestone	4 - 9	6
Sand and Gravel	4 - 9	8
Basalt	2 - 10	9
Karst Limestone	9 - 10	10

Table 5: Surficial/Bedrock Geology

Surficial and Bedrock Geology Values					
Symbol	Media Type	Raster Value	Aquifer Media DRASTIC rating	Impact of the Vadose Zone DRASTIC rating	Hydraulic Conductivity DRASTIC rating
a	Stream alluvium	1	7	7	2
s	Swamp, marsh, and bog deposits	2	3	3	1
b	Beach deposits	3	10	10	8
eb	Emerged beach deposits	4	10	10	8
e	Eolian deposits	5	8	8	6
L	Lake bottom deposits	6	4	4	1
m	Glaciomarine deposits (fine grained)	7	3	3	1
ms	Glaciomarine deposits	8	8	8	2

	(coarse grained)				
go	Glacial outwash deposits	9	8	8	6
g	Ice-contact glaciofluvial deposits (exclusive of eskers)	10	8	8	2
ge	Eskers	11	8	8	2
sm	Stagnation moraine	12	7	7	2
em	End moraines	13	6	6	1
rm	Ribbed moraine	14	6	6	1
t	Till	15	5	5	1
	Thin drift	16	bedrock	bedrock	bedrock
tdu	Thin drift, undifferentiated	17	bedrock	bedrock	bedrock
rk	Bedrock	18	bedrock	bedrock	bedrock
wa	Water	19	NODATA	NODATA	NODATA
unkn	Unknown	20	bedrock	bedrock	bedrock
	Metamorphic/Igneous	21	4	5	1
	Sandstone	22	6	6	1
	Basalt	23	9	9	2
	Mudstone/Graywacke	24	4	4	1
	Volcanic	25	9	9	2
	Conglomerate	26	7	7	1
	Bedded Sandstone, Limestone and Shale	27	6	6	2
	Limestone	28	6	6	1
	Shale	29	2	3	1
	Confining Layer	30	2	2	1
	Karst Limestone	31	10	10	10

Table 6: Soil Media DRASTIC Ratings

Soil Media	
Range	Rating
Thin or Absent	10
Gravel	10
Sand	9
Peat	8
Shrinking and/or Aggregated Clay	7
Sandy Loam	6
Loam	5
Silty Loam	4
Clay Loam	3
Muck	2
Nonshrinking and Nonaggregated Clay	1

Table 7: Soil Media Ratings Table

Soil Media Values	
Soil Type	DRASTIC rating
Bedrock	10
Cemented Material	1
Channery Loam	5
Channery Silt Loam	4
Coarse Sand	9
Cobbly Silt Loam	5
Extremely Gravelly Coarse Sand	10

Extremely Gravelly Sand	10
Fine Sandy Loam	6
Gravelly Coarse Sand	10
Gravelly Fine Sandy Loam	7
Gravelly Highly Decomposed Plant Material	9
Gravelly Loam	6
Gravelly Loamy Sand	9
Gravelly Sandy Loam	7
Gravelly Silt Loam	5
Highly Decomposed Plant Material	8
Loam	5
Loamy Fine Sand	7
Loamy Sand	8
Moderately Decomposed Plant Material	8
Muck	2
Mucky Loam	6
Mucky Peat	8
Mucky Silt Loam	5
Peat	8
Sand	9
Sandy Loam	6
Silt Loam	4
Slightly Decomposed Plant Material	8
Unweathered Bedrock	10
Variable	5

Very Fine Sandy Loam	6
Very Gravelly Sand	10
Very Gravelly Sandy Loam	10
Very Gravelly Silt Loam	6

Table 8: Topography DRASTIC Ratings

Topography	
Range (Percent Slope)	Rating
0 - 2	10
2 - 6	9
6 - 12	5
12 - 18	3
18+	1

Table 9: Impact of the Vadose Zone Media DRASTIC Ratings

Impact of the Vadose Zone Media		
Range	Rating	Typical Rating
Confining Layer	1	1
Silt/Clay	2 - 6	3
Shale	2 - 5	3
Limestone	2 - 7	6
Sandstone	4 - 8	6
Bedded Limestone, Sandstone, Shale	4 - 8	6
Sand and Gravel with Significant Silt and Clay	4 - 8	6
Metamorphic/Igneous	2 - 8	4

Sand and Gravel	6 - 9	8
Basalt	2 - 10	9
Karst Limestone	8 - 10	10

Table 10: Hydraulic Conductivity DRASTIC Ratings

Hydraulic Conductivity	
Range (gpd/ft^2)	Rating
1 - 100	1
100 - 300	2
300 - 700	4
700 - 1000	6
1000 - 2000	8
2000+	10

Table 11: Hydraulic Conductivity Literature Values

Hydraulic Conductivity				
Material	Range (gpd/ft^2)	Mean (gpd/ft^2)	Source	Hydraulic Conductivity DRASTIC rating
coarse-grained glaciomarine sediments	1.3E+02 - 5.8E+02	224	[46]	2
fine-grained glaciomarine sediments	7.5E-03 - 7.5E-02	0	[46]	1
till	7.5E-01 - 7.5E+00	4	[46]	1
Metamorphic/Igneous	2.2E-03 - 1.1E+01	6	[46]	1
Karst Limestone	1.0E+01 - 1.0E+05	50,005	[47]	10

Basalt	1.0E+00 - 1.0E+05	50,001	[47]	1
Fractured Igneous and Metamorphic Rocks	5.5E-02 - 1.0E+03	500	[47]	1
Limestone and Dolomite	5.5E-03 - 1.0E+01	5	[47]	1
Sandstone	1.0E-03 - 1.0E+01	5	[47]	1
Unfractured Metamorphic and Igneous Rocks	1.0E-07 - 1.0E-03	0	[47]	1
Shale	5.5E-07 - 5.5E-03	0	[47]	1
Unweathered marine clay	5.5E-06 - 1.0E-02	0	[47]	1
Glacial till	1.0E-05 - 1.0E+01	5	[47]	1
Silt, loess	1.0E-02 - 1.0E+02	50	[47]	1
Silty sand	1.0E+00 - 5.5E+03	2,751	[47]	2
Course Clean sand		782,443	[48]	10
Fine Clean Sand		178	[48]	2
Gravel	5.5E+03 - 1.0E+07	5,002,750	[47]	10

Table 12: Land Cover DRASTICL Ratings

Land Cover Values	
Land Cover Type	Rating
High Intensity Developed	9
Medium Intensity Developed	8
Low Intensity Developed	7
Developed Open Space	7
Cultivated	5
Pasture/Hay	5

Grassland	5
Deciduous Forest	2
Evergreen Forest	2
Mixed Forest	2
Scrub/Shrub	2
Palustrine Forested Wetland	1
Palustrine Scrub/Shrub Wetland	1
Palustrine Emergent Wetland	1
Estuarine Scrub/Shrub Wetland	1
Estuarine Emergent Wetland	1
Unconsolidated Shore	3
Bare Land	3
Water	0
Palustrine Aquatic Bed	0
Estuarine Aquatic Bed	0

Table 13: DRASTICL Weights

Assigned Weights for DRASTICL parameters	
Parameter	Weight
Depth to Water	5
Net Recharge	4
Aquifer Media	3
Soil Media	2
Topography	1
Impact of the Vadose Zone Media	5

Hydraulic Conductivity	3
Land Use	5

Table 14: DRASTICL Results

DRASTICL by Area		
Range (Rating)	Cell Count	% Area
No Data (0)	52926250	6.30
Water (1)	64790804	7.71
1 - 100	142708	0.02
100 - 120	11175660	1.33
120 - 140	75157695	8.94
140 - 160	420592464	50.04
160 - 180	165715759	19.72
180 - 200	42956868	5.11
200 - 220	6390793	0.76
220+	707090	0.08

Table 15: DRASTICL and PFAS Test Results Comparison

DRASTICL Class	Samples with PFAS Detected	Samples with No PFAS Detected	% Detected
No Data	0	0	---
Water	1115	422	72.54
<100	0	0	---
100 - 120	0	1	0.00
120 - 140	130	46	73.86

140 - 160	722	447	61.76
160 - 180	1604	1018	61.17
180 - 200	556	421	56.91
200 - 220	66	18	78.57
220+	13	3	81.25

Table 16: Potential PFAS Source Risk Scores

Source Type	Risk Score
Department of Defense	100
Landfill	100
Chemical manufacturing Industries	100
Airport	75
Fire training areas	75
Petroleum refineries	75
Textiles	50
Furniture	50
Paper	50
Rubber and plastics	25
Fire station	25
Fabricated metal	25
Land-applied sewage and biosolids	25

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