Assessing the vulnerability of Coastal Aquifers in Arrowsic, ME

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1 Abstract

More than 40 percent of Maine's citizens depend on groundwater for their main source of water, with Arrowsic Island largely dependent on bedrock aquifers for freshwater. This project evaluates the vulnerability of coastal aquifers to saltwater intrusion in Arrowsic and the town's capability to meet the water demands of the future. We examine three components of projected water quality and quantity for the island: changes in precipitation patterns, sea level rise, and increases in population. Data for the project includes measured, historical and projected precipitation and temperature, historical and projected population scenarios based on potential affordable housing unit development on the island, and three sea level rise scenarios: no change, 3 ft rise, and 6 ft rise. By validating historical data and generating plausible future projections, we will develop a portfolio of analyses to help Arrowsic's residents make the best management decisions for the island's aquifer water resources.

2 Introduction

Aquifers exist as bedrock or sand and gravel structures all across the state of Maine. Aquifers specifically in Arrowsic are predominantly bedrock with little topsoil indicating very little storage capacity. "All the coastal islands are mostly rock, with a bit of soil, so there's not a lot of storage capacity. They have to be judicious in how much water they pump. And they're surrounded by salt water. If they contaminate their aquifer by pumping too hard, it will take years to flush it out." said Roger Crouse, head of the Maine Center for Disease Control and Prevention's Drinking Water Program (Island Institute, 2016). According to the Intergovernmental Panel on Climate Change, sea levels are rising at an increasing pace, and 95 percent of the world's ocean areas will be considerably affected by a sea level rise by 2100, hence increasing the risk of inundation and the intrusion of saltwater in coastal aquifers. While there has been ample research assessing the vulnerability of coastal aquifers through factors like precipitation and sea level rise, many papers have not considered the effects of incoming developments and the increasing population as a consequence of those developments. With this project, we examined how increasing population can contribute to increasing stress levels on water resources in Arrowsic along with precipitation and sea level rise.

3 Methodology

3.1 Precipitation

Precipitation data which was used to calculate the aquifer recharge rate was collected from the Regional Climate Center project at the National Centers for Environmental Information (NCEI) and the National Weather Service (NWS). We chose the measurement data for Bath, ME as it was the closest available measurement station to Arrowsic. For historically modeled and projected data we used Oak Ridge National Laboratory's (ORNL) 9505 dataset, which is based on a six-member General Circulation Model (GCM) ensemble from the Coupled Models Intercomparison Project phase 6 (CMIP6). The CMIP6 GCMs are downscaled using two different downscaling approaches (statistical-based DBCCA and dynamical-based RegCM) based on two meteorological reference observations (Daymet and Livneh), and then fed to two calibrated hydrologic models (VIC and PRMS) to simulate projected future hydrologic responses [7]. We identified the two models (CNRM-DBCCA-Daymet and BCC-DBCCA-Daymet) whose outputs most closely matched the NCEI measurements. We also performed Linear Regression among the three datasets with the CNRM and BCC models as independent variables and the NCEI data set as the dependent variable. Figure 2 shows that the modeled temperature is much more highly correlated to measurements than precipitation. [9, 12]. We then used the projections of these two models to characterize future precipitation for the island. Precipitation and temperature were both measured in inches per day and Fahrenheit per day respectively which was later converted to millimeters per day and Celsius per day to match the units used in the CNRM and BCC models. Recharge rate (mm/yr) was calculated by using the following formula [8, 1]:

$$R_e = 0.25(P - 400)$$

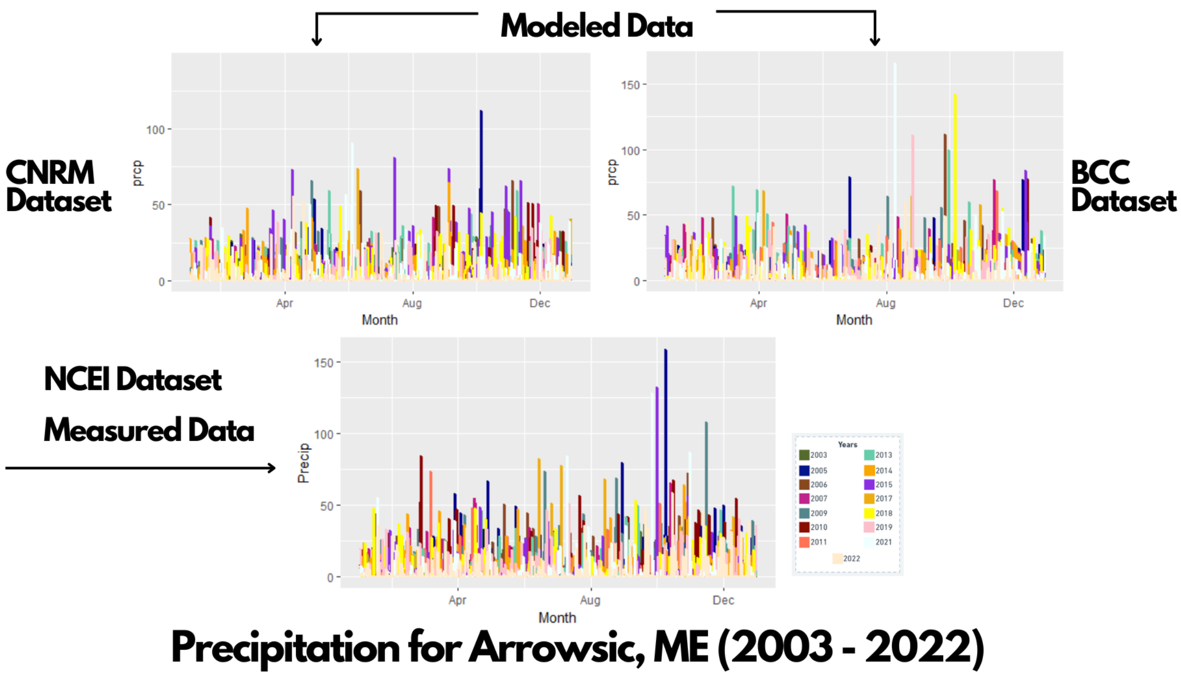


Figure 1: Precipitation(mm) as seen in two different types of data sets: Historically Modeled and Historically Measured. CNRM and BCC models validated using the NCEI dataset

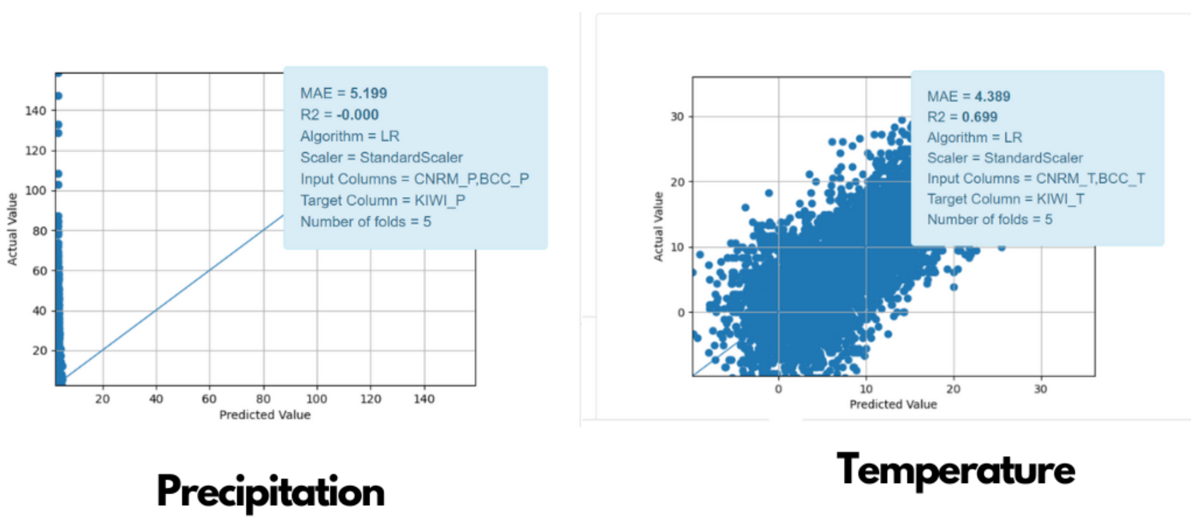
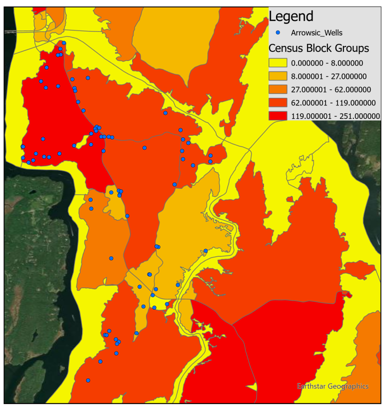


Figure 2: Linear Regression using CNRM and BCC as independent variables and the NCEI (measured) data as the dependent variable.

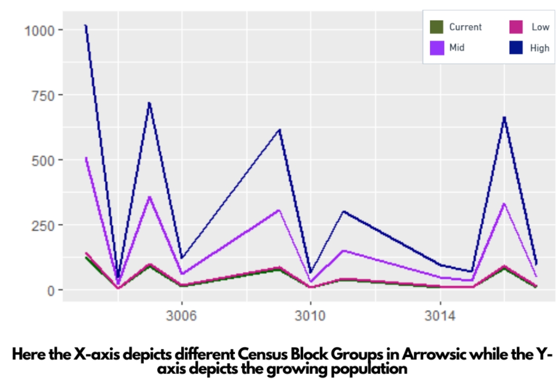
3.2 Population and Developments

Census block-level population data for 2022 were obtained from US Census Tiger/Line shapefiles [6]. To generate population projection scenarios for the island, we used population growth information from the City of Arrowsic and documentation on proposed affordable housing units for the state of Maine [10]. Tiger/Line data are spatial extracts from the Census Bureau's Master Address File/Topologically Integrated Geographic Encoding and Referencing (MAF/TIGER) System for use with geographic information systems (GIS) software, which is a geodatabase from the Census Bureau (Figure 3). Census blocks, the smallest geographic area for which the Bureau of the Census collects and tabulates decennial census data, are formed by streets, roads, railroads, streams and other bodies of water, other visible physical and cultural features, and the legal boundaries shown on Census Bureau maps.

- Low - 12 percent increase per decade based on data collected by the City of Arrowsic
- Mid - Added 2 houses per block based on the Town Council's recommendation and the Meeting Minutes taken from www. Arrowsic.org
- High - Added 4 houses per block based on the Affordable Housing Units document released by the government of Maine, which mentions building a maximum of 4 houses per lot if there are sufficient water resources [10].



(a) Census Block Data(2020) as mapped on ArcGIS Pro showcasing 11 blocks and all the wells in Arrowsic, ME



(b) Projections of the three population scenarios(2030) and the current population(Census Bureau, 2020)

Figure 3: Population in Arrowsic, ME

Well yield was calculated as the sum of all the well yield reported by the Maine Geological Society [5] in the subset of wells for Arrowsic Island. Current and future water consumption was estimated using the United States Geological Survey (USGS) report [13] that a 2-person household uses up to 80-100 gallons of water per day. All population scenarios were divided by 2 and multiplied by 100 to get an aggregated value for water consumption. All of these values were then compared with the recorded well yield of all the wells in Arrowsic. The recorded well yield of all the wells in Arrowsic is sufficient for even the highest population scenario. However, a decreasing recharge rate can cause the overall well yield to decrease and increasing sea levels in addition to low recharge can turn the water brackish. If recharge continues to decrease and saltwater intrusion into the aquifers continues to increase, waters pumped out of the wells might not be potable or useful for the citizens. However, more data (e.g., annual records of the well yield and well salinity for a representative sample of Arrowsic wells) will be required for a complete analysis.

3.3 Sea Level Rise

We used the Sea Level Rise Viewer developed by the National Oceanic and Atmospheric Administration(NOAA) [11]. With the three feet sea level rise, two low-lying areas were shown as inundated in Arrowsic, and with the six feet rise, a majority of the coastal land in Arrowsic became inundated. Even the freshwater Kennebec and Back Rivers show some seawater intrusion with sea level rise (Figure 4).

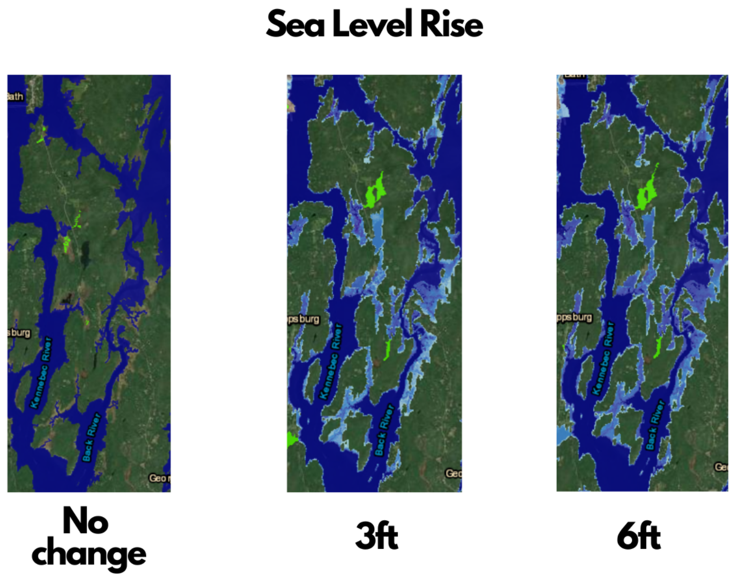


Figure 4: Sea Level Rise(ft) as seen at three different levels - No change, 3ft, 6ft. Simulated using the Sea Level Rise Viewer developed by NOAA

4 Results and Discussion

4.1 Precipitation

Climate data projections used for this study indicate increased temperature and annual precipitation, but precipitation predictions in the models are still uncertain [14]. Trends over recent decades suggest that the Northeastern US will see larger but fewer precipitation events. While regular and light rain can help replenish wells, extreme events of rain can lead to freshwater runoff leading to a decrease in recharge. Even without considering runoff from large events, recharge rates (mm/year) over the past twenty years have been decreasing (Figure 5). If this rate of decrease continues into the future, aquifer recharge will not be able to keep up with water demand.

4.2 Population and Developments

Based on the current population and number of housing units (Census, 2020) there is an average of two people in each house in Arrowsic.

$$477/258 = 1.84$$

For each of our three scenarios, we obtained the results shown in Table 1.

5 Conclusions

According to the Stewardship Guide for the Coastal Community, more than half of the precipitation in Maine turns into surface water runoff, which is why it is very important to protect groundwater. Our plots indicate the potential for increased precipitation but in the form of sudden large events in the future. These events often lead to freshwater runoff causing a decrease in recharge rate. When coupled with increasing sea level rise and increasing population, these issues can put a large amount of stress on the water levels. We also found multiple data gaps throughout the course of this project, which include:

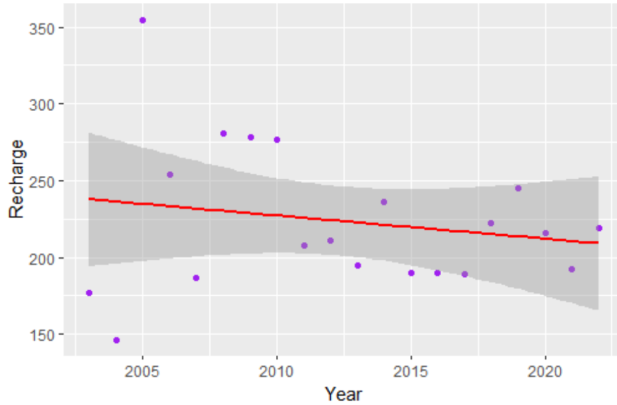


Figure 5: Recharge Rate(mm/year) as seen in the last twenty years(2003-2022) in Arrowsic, ME shows a decreasing trendline

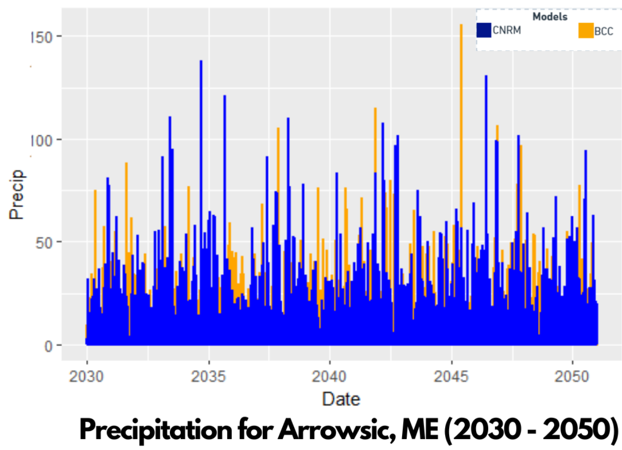


Figure 6: Precipitation Projections(mm/year) from 2030-2050

Table 1: Population scenarios

Block	Housing Units	Current Population	Wells	Low Scenario	Mid Scenario	High Scenario
3005	58	90	77	101	360	720
3016	33	83	12	93	332	664
3003	76	127	47	142	508	1016
3017	6	12	3	13	48	96
3011	14	38	5	43	152	304
3006	13	15	8	17	60	120
3015	5	9	4	10	36	72
3010	4	8	4	9	32	64
3014	5	12	6	13	48	96
3009	43	77	17	86	308	616
3004	1	6	0	7	24	48
Total	258	477	183	535	1908	3816

- Incomplete count and characterization of wells

- The precise number of people per residential lot is unknown
- Changes in annual the well yield unknown
- Annual measurement of well salinity not available

Due to time constraints, we weren't completely successful in looking at the impact of sea level rise and calculating a risk score for each well in Arrowsic. We have found some resources and techniques that can be used in future projects to find a risk factor. Different parameters that affect saltwater intrusion like elevation level (m), distance from the coast(s), and surficial geology can be given a risk (Ri) and a weight factor (Wi) to find the risk score (Di) of a particular well using the following formula:

$$D_i = \sum_{j=1}^{5} (W_i * R_i)$$

Parameter (*j*)	Subdivision Value	Risk Value (*R*)	Weight Factor (*W*)	Weighted Risk Value
Distance to coast (m)	<300	2	3	6
	300–500	1		3
	>500	0		0
Distance to lakes (m)	<300	0	2	0
	300–500	1		2
	>500	2		4
Soil type	Coarse sediments	2	2	4
	Fine sediments	1		2
	Bare bedrock	0		0
	No data	No data		No data
Prec. yearly average (mm)	<550	2	1	2
	550–600	1		1
	>600	0		0
Elevation meters above sea level (m.a.s.l.)	<5	2	3	6
	5–10	1		3
	>10	0		0

Figure 7: Risk analysis parameters and their respective risk factors and weight factors. More on this can be found here.[3] [4] [2]

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