SALTWATER INTRUSION IN A FRACTURED GRANITE AQUIFER

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INTRODUCTION

Vinalhaven is an island located in Penobscot Bay off the coast of Maine and is home to 1300 year round residents. The summertime population peaks at 4000, placing a strain on the island's limited water resources, which consist of 28.8 acres of freshwater ponds and a fractured granite aquifer. Water consumption on Vinalhaven is projected to increase by 100% by 2025 (Vinalhaven Comprehensive Plan Committee, 2005), raising concern for the sustainability the island's water resources, especially with respect to decreasing well yields and saltwater intrusion.

The town of Vinalhaven, located on the southern shore of the island, draws its water from Round Pond, and during dry years, from Folly Pond. Residences not connected to the public water supply receive water from private wells. Vinalhaven is underlain mainly by granite, and due to thin soil cover, groundwater is stored almost exclusively within fractures in the bedrock. The Vinalhaven aquifer forms a freshwater lens surrounded on all sides by seawater, and excessive pumping of drinking water wells may draw seawater landwards, resulting in contamination of the freshwater aquifer.

My research focused on two areas located in the northern section of Vinalhaven, Mill River and Calderwood Neck. These two study areas were chosen for their similar population densities, similar bedrock lithology (coarse-grained granite), similar proximity of drinking water wells to the ocean, and yet their differing rates of saltwater intrusion (Fig. 1). Calderwood Neck has had no reported incidents of saltwater intrusion, while Mill River has four reported incidents. Therefore, my study sought to determine the relative influence of several factors – fracture density and geometry, fracture network connectivity to the ocean, and localized topography– on the occurrence of saltwater intrusion in this particular area of Vinalhaven.

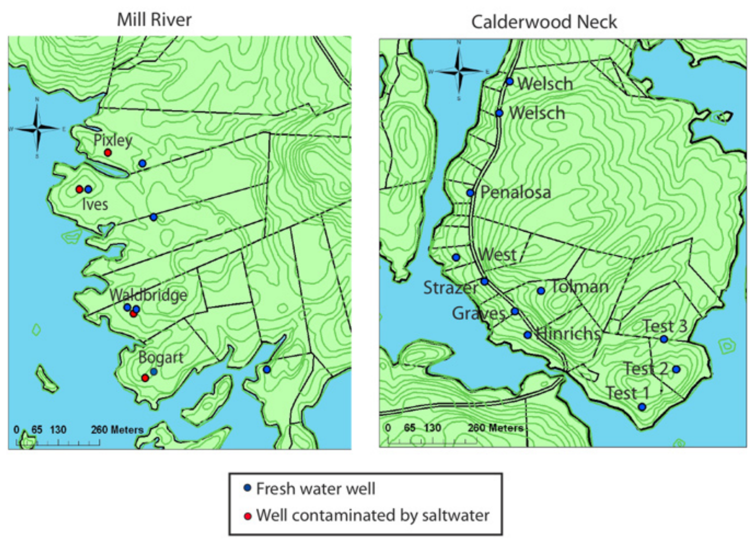

Figure 1: Study areas with well locations, property boundaries and contours. Note the greater occurrence of salt water intrusion at Mill River.

METHODS

Field Methods

Fracture orientations were measured at 22 outcrops spread between Mill River and Calderwood Neck (Fig. 2).

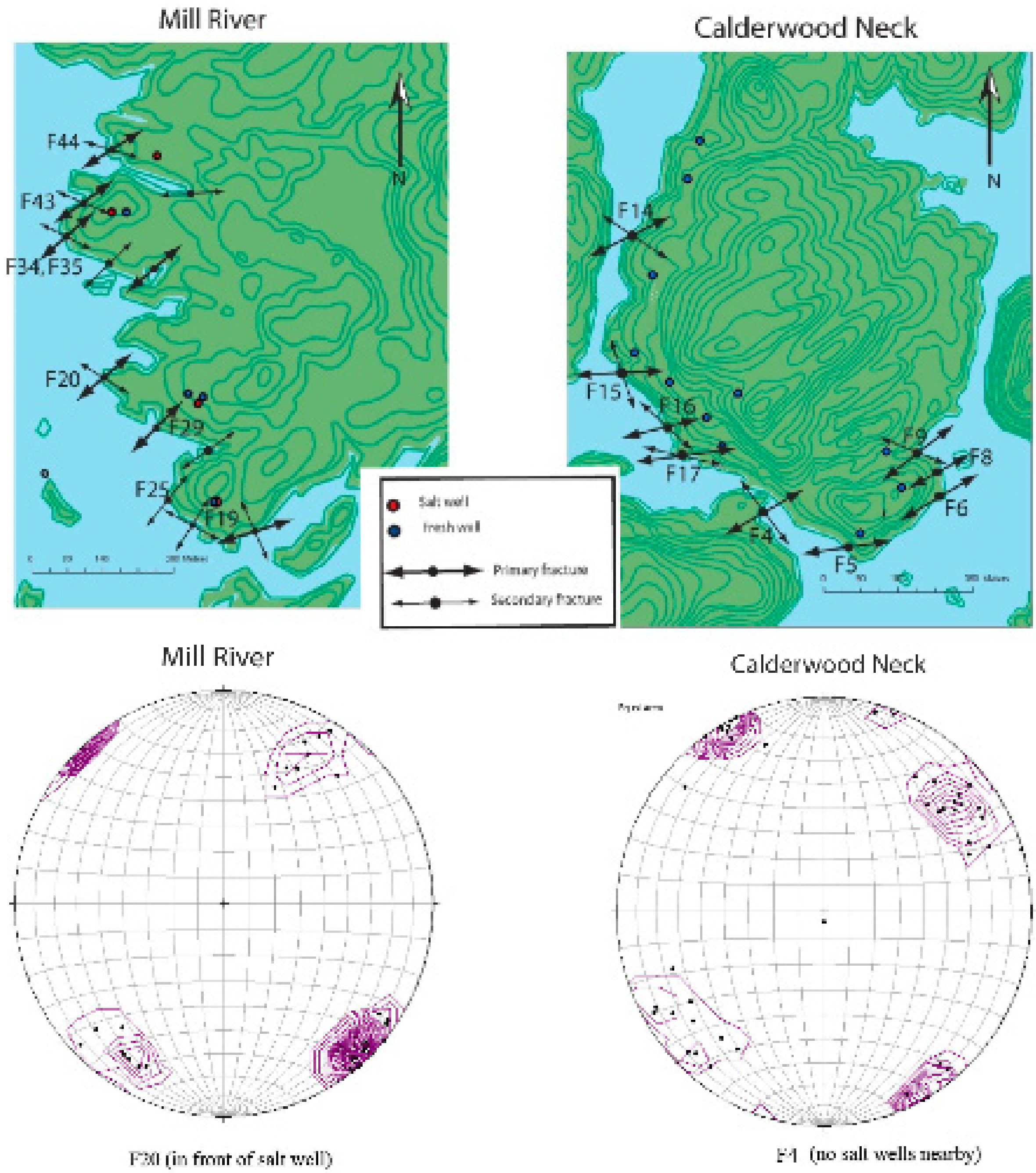

Figure 2: Maps with fracture orientations for Mill River and the southern part of Calderwood Neck. Equal angle contoured stereonets showing the similar fracture geometry at the Mill River and Calderwood Neck locations.

The width, lateral extent, and density distribution of these fractures were also noted where possible. Water chemistry data collection comprised a large part of my field work. Surface water samples were collected at 22 locations both in my study area and the interior of the island. I also selected 13 wells to sample in the study area. Some of the wells were currently being used but many were abandoned. Depth sampling was performed on five wells (three at Mill River and two at Calderwood Neck) at intervals of 5-10 meters. All water samples were analyzed on site for pH, total dissolved solids (as a measure of saltwater intrusion), and temperature using a YSI 63 instrument.

Well water levels were also measured where possible to gain a better understanding of water table elevation. Well monitoring devices were placed on one well at Mill River and three test wells at Calderwood Neck to measure tidal fluctuation and seasonal variations in the water table. Data collection began March 2, 2006 and is ongoing. Water levels were recorded by an In-Situ Inc. Mini Troll device and then transferred to a computer using Win-Situ version 4.523.

Laboratory Methods

In the laboratory, water samples were analyzed for nitrates and chlorides using a Milton Roy Company Spectronic 20D spectrophotometer. To test for nitrates, samples were combined with 1 Nitraver 5 Nitrate reagent packet and run in the spectrometer calibrated to 500 nm. For chlorides, samples were combined with 2 ml Mercuric Thiocyanate solution and 1 ml ferric iron solution, then run in the spectrometer calibrated to 455 nm. Water samples were also analyzed for the following trace metals using inductively coupled plasma-optical emission spectrometry on a Spectro Ciros CCD ICP machine: Na^{+}, Mg^{2+}, $Mn^{2/3+,}$ Ca^{2+}, Al^{3+}, Fe^{3+}, Zn^{2+}, As, Cu^{2+}, and Ba^{2+}.

RESULTS

Fractures

Fracture analysis revealed three consistent orientations at both Mill River and Calderwood Neck:

- A high-angle set striking ENE and dipping NNW
- A second high angle set striking SE and dipping NE or SW, and
- A sub-horizontal set with highly variable strike and dip.

The ENE striking set was dominant at most outcrop locations, with generally greater length and aperture than the SE striking set. Fracture length varied from less than one meter to greater than 10 meters, but only about 10% of fractures persisted greater than 10 meters at both sites. Exposure to sub-horizontal fractures was limited to outcrops with significant vertical relief.

Fracture density has been linked with hydraulic conductivity in crystalline aquifers (Johnson, 1998; Khallouf, 2003), and therefore is important to assess in this study. There is a large spatial variation in fracture density at both locations. Exposed rock along the coastline revealed alternating regions of high fracture density and almost no fractures at all.

Water Chemistry Analysis

At both study sites, most wells showed no evidence for saltwater intrusion. All Calderwood Neck samples contain sodium concentrations below 100 mg/L, chloride levels below the U.S. EPA Maximum Contaminant Level (MCL) standard of 250 mg/L, and total dissolved solids below the recommended 500 mg/L. Interval sampling of two Calderwood Neck test wells revealed no increase in concentrations of total dissolved solids with depth (Fig. 3). The majority of Mill River well samples also contain sodium, chloride, and total dissolved solids below US EPA standards. However, two samples exceeded these levels: the Ives well at depth 250 feet and the Pixley well. Both wells had been previously identified by the town of Vinalhaven to be saltwater contaminated. The bottom of the Ives well contains levels of sodium, chloride, and TDS that classify it as brackish (Fig. 3). The Pixley well contains high chloride concentrations, but sodium and TDS within the normal range. Two other wells at Mill River that were reported to have been previously saltwater contaminated (at the Bogart and Waldbridge residences) showed no evidence for contamination.

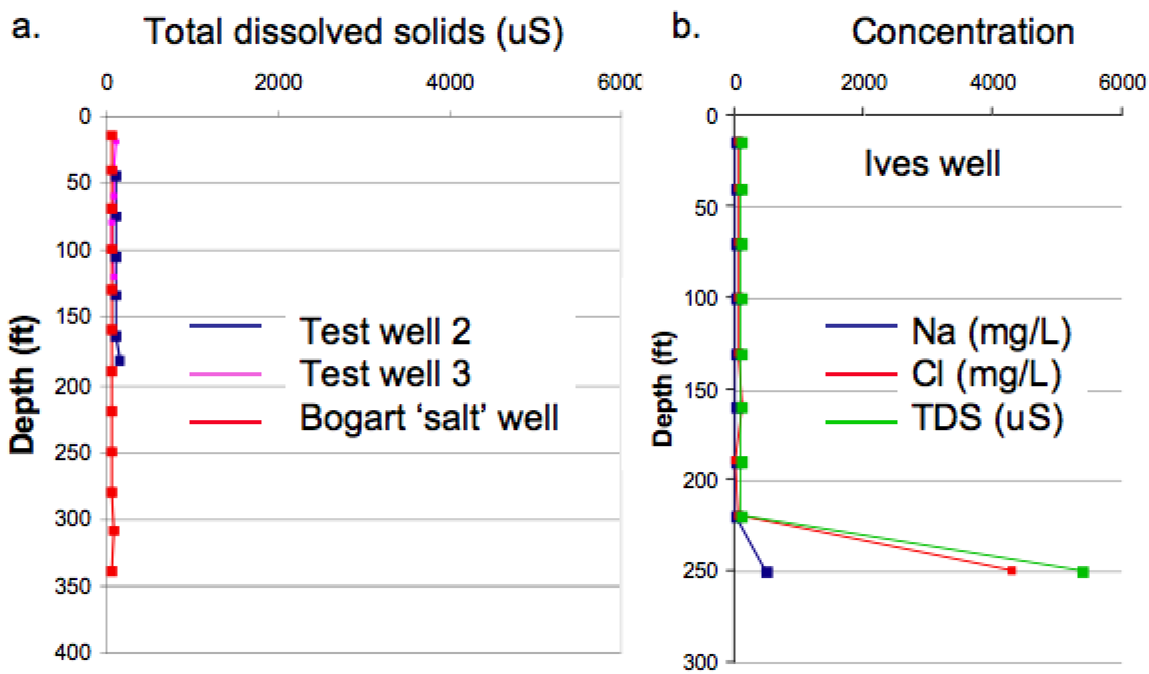

Figure 3: a) Absence of saltwater contamination in three wells indicated by low TDS throughout sampling profile. b) Evidence for saltwater intrusion of the Ives Well indicated by increase in Na, Cl, and TDS at the bottom of the well.

Tidal Variation

Three test wells at Calderwood Neck and one residential well at Mill River were monitored for water level fluctuations due to tidal activity. The amplitude of fluctuation varied from well to well, with up to two feet of fluctuation in Test Well 2 and no discernible fluctuation in the Bogart well on Mill River. Well logs reveal differing tidal efficiencies in three test wells at Calderwood Neck located equidistant from shore and in close proximity to each other (Fig. 4). Tidal fluctuation was significantly less in the freshwater test wells at Calderwood Neck than in saltwater contaminated wells on the south shore of Vinalhaven (Fig. 4).

DISCUSSION

Fractures

In his generalized study of Maine, Caswell (1979a) argues that saltwater intrusion is usually the result of a particular orientation of water-bearing fractures along the coastline. Fracture geometry at Calderwood Neck and Mill River are very similar, perhaps due to the similar geology, the close proximity (~1km) of the study areas and the fact that the fractures were likely caused by similar tectonic processes at similar times. Therefore, fracture orientation alone does not appear to be responsible for the much higher rate of saltwater intrusion at Mill River. Sufficient information does not exist to evaluate whether differences in fracture type are a controlling factor. No notable fracture displacements were observed at either location. Studies have shown that relatively small displacements can increase hydraulic conductivity of fractures by orders of magnitude (Berkowitz, 2002).

Assessing fracture connectivity plays an important part in determining hydraulic conductivity of fracture networks. Theoretically, higher connectivity leads to higher conductivity and therefore greater potential for saltwater intrusion. This study attempts to quantify fracture conductivity indirectly, through measurement of ocean tidal efficiency in well water levels. Nine wells were monitored in total on Vinalhaven and there appears to be no relationship between tidal efficiency and distance from shore or water table

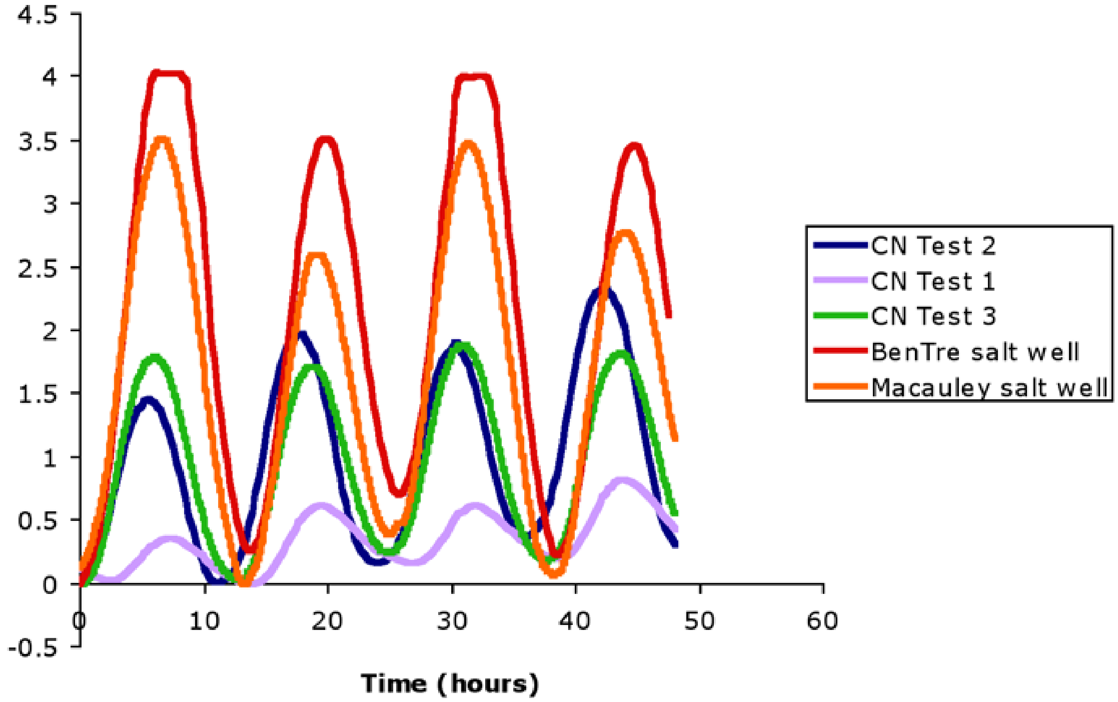

Figure 4. Comparison of tidally-induced water level fluctuations for three freshwater test wells at Calderwood Neck (CN) and two salt wells on the southern shore of Vinalhaven.

height, suggesting that differences in fracture network connectivity may be responsible. The larger tidal fluctuation in Calderwood Neck Test wells 2 and 3 compared to test well 1 suggest that a more hydraulically active fracture system connects them to the shoreline.

Water level monitoring data for Mill River is insufficient to make comparisons with Calderwood Neck at this time. The Bogart well showed no response to tidal influences despite the fact that it was previously known to be saltwater contaminated, which would seem to contradict the hypothesis linking fracture conductivity and potential for saltwater intrusion. Information on the speed of contamination of the Mill River wells was obtained from homeowners. The Ives salt well was drilled in 1977, and contaminated immediately at the first high tide (within one day). A second well was drilled 25 meters inland and has been functioning fine ever since (Steven Ives, Personal Communication). The Bogart well was drilled in 1990 but never used because saltwater was detected immediately by the drilling company (David Bogart, Personal Communication). The Waldbridge salt well, however, was drilled in 1977 but was not contaminated until 1983 (Mr. Waldbridge, Personal Communication). The more rapid contamination of the Bogart and Ives wells implies higher hydraulic connection to the sea.

Topography

It appears that local topography has an important effect on the degree of saltwater intrusion on Vinalhaven. Studies have shown that as beach slope decreases, the distance and velocity of intrusion increases (Mao, 2004). Saltwater infiltration into the aquifer occurs primarily at high tide, and a flatter beach slope intensifies this phenomena (Ataie-Ashtiani et al., 2001; Chen et al., 2003). The shoreline of Calderwood Neck has much higher relief than the shoreline of Mill River. This fact is verified by U.S.G.S. topographic maps, digital elevation model images, and visual observations of the area. In addition, the shoreline of Mill River is intersected by three small streams that discharge into the ocean, while Calderwood Neck has only one such stream, far from residential wells. Low-lying coastal areas dissected by streams are among the most susceptible areas to saltwater intrusion (Fetter, 2001) due to upstream migration of saltwater during high-tide and low flow conditions.

Another topographical factor that may contribute to the occurrence of saltwater intrusion is the sinuosity of the coastline. In theory, a longer coastline would provide more surface area for vertical and lateral infiltration into the aquifer. Examination of a map of the two study areas shows that the shoreline at Mill River is much more sinuous than at Calderwood Neck (Fig. 1). In an attempt to quantify sinuousity of the shoreline, two 1000 meter linear transects were drawn along the general NW shoreline trend at both locations. Along this linear distance, Calderwood Neck has 1.5 km of shoreline and Mill River has 3.3. km of shoreline.

Further study is needed to more precisely determine the relative importance of the aforementioned controls on saltwater intrusion. Borehole geophysical imaging could be used to assess subsurface fracture density and connectivity. Many tests wells need to be drilled and pumping tests performed to measure recharge rates, flow direction, and velocity of saltwater intrusion.

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