Bedrock fractures control groundwater flow and wetland initiation in metamorphic terrane at Great Marsh, southeastern Pennsylvania

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Introduction

Valley bottom wetland ecosystems have existed across Southeastern Pennsylvanian since the beginning of the Holocene but were largely covered up with legacy sediment due to colonial mill damming (Walter and Merritts 2008). Great Marsh in Elverson, PA is an extensive (3 km²) marsh ecosystem and one of Pennsylvania's few remaining examples of an undammed pre-historic valley bottom wetland. The ecosystem consists of obligate and facultative wetland plants across the entire valley bottom, indicating that there must be a constant, pervasive source of freshwater flowing across the marsh. The most likely answer is spring water, which is freshwater sourced from groundwater reserves rather than from rivers or quick flow.

The bedrock is Precambrian gneiss, which generally has very low primary porosity (Bricker and Moss 1958). However, the bedrock has been extremely shattered and fractured repeatedly due to long-term tectonic processes and, more recently, frost cracking during Quaternary cold-climate conditions (Merritts and Rahnis, 2022). Our hypothesis is that this secondary porosity of highly fractured bedrock underlying and surrounding the marsh yields groundwater flow from springs (Fig. 1a).

Figure 1. (A) A groundwater spring feeding the marsh (photo February 21, 2025). (B) A HOBO sensor placed in a possible spring location in the middle of the marsh (photo February 21, 2025).

Methods

Twelve HOBO sensors were installed between July and November 2024 to collect temperature data continuously at 15-minute intervals at possible springs and small streams throughout the marsh (Fig. 1b). Additionally, we used Mayfly data loggers installed by the Great Marsh Institute for long-term temperature data. We compared these data with air temperature collected from a HOBO placed at the center of the Great Marsh Institute property (40° 7'40.03"N, 75°46'4.19"W) to determine the thermal sensitivity of water temperature to air temperature fluctuations.

Bedrock composition was determined from field mapping and analysis of thin sections with a petrographic microscope. Bedrock samples were collected from an outcrop on Fairview Road in East Nantmeal, PA (40° 7'19.812"N, 75° 42' 50.868"W) and made into thin sections by Spectrum Petrographics Inc. Fracture orientations (strike and dip) were determined in the field with a Brunton compass at outcrops within a three-mile radius of Great Marsh.

Thermal UAV (drone) data augmented from two different flight paths during a prolonged cold period in January 2025 revealed a series of warm spots relative to the frozen landscape. The "hotspots" were visited and the sites determined to be springs (Fig. 1a) in the field were surveyed and mapped with ArcGIS (Fig. 5).

Results

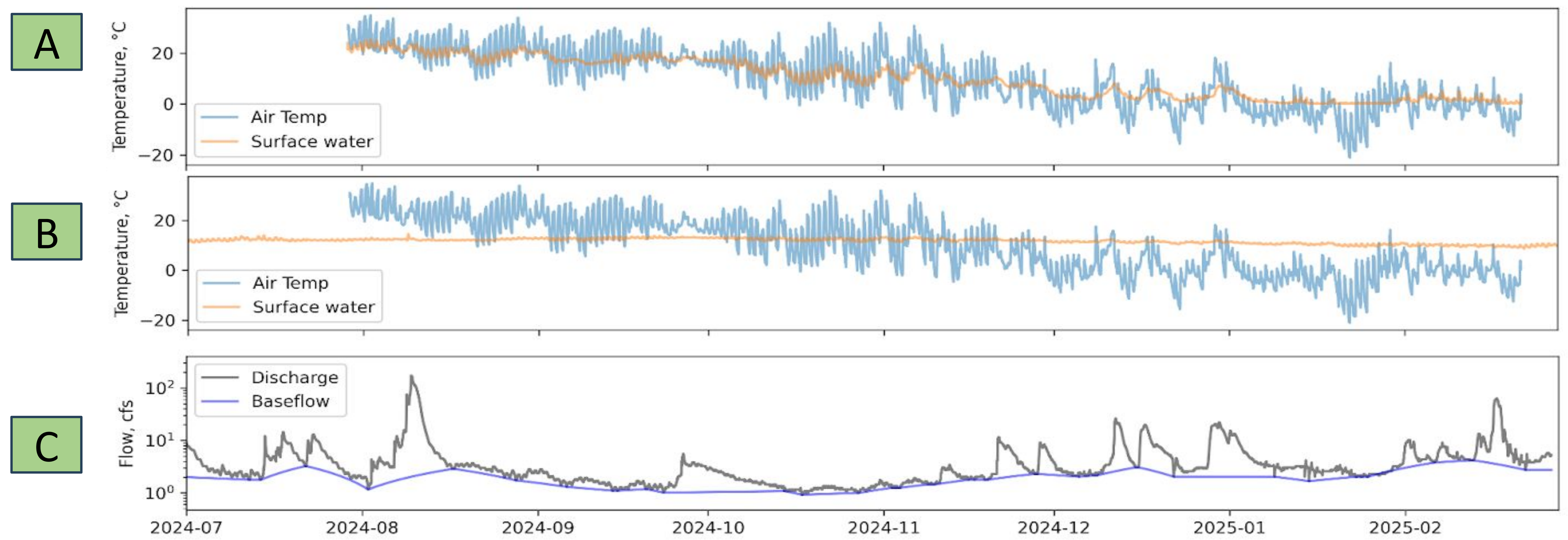

Figure 2. Temperature data (~7 months) represented in three graphs: (Fig. 2a, 2b) air and water temperature over time and (Fig. 2c) the quick flow and groundwater flow at the gage station at nearby Marsh Creek near Glenmoore, PA (#01480675) over time. (A) Data from HOBO21852518 located at 40° 7'51.52"N, 75°46'17.56"W. (B) Data from Mayfly CTD6 located at 40° 7'30.18"N, 75° 45'56.0268"W.

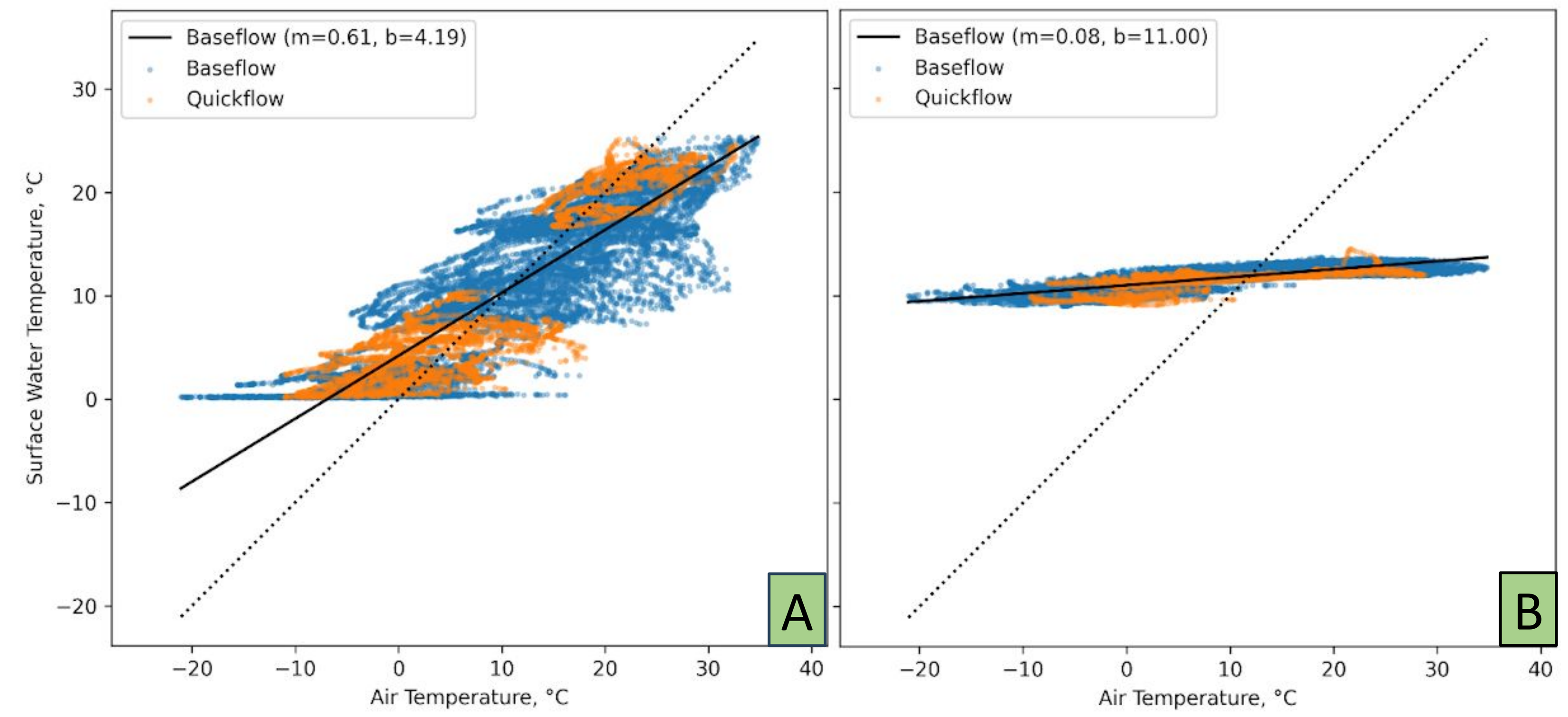

Figure 3. Thermal sensitivity of surface water temperature, with water temperature data categorized as quick flow or baseflow depending on gage height (represented in Fig. 2c). (A) Data from HOBO21852518 located at 40° 7'51.52"N, 75° 46'17.56"W. (B) Data from Mayfly CTD6 located at 40° 7'30.18"N, 75° 45'56.0268"W.

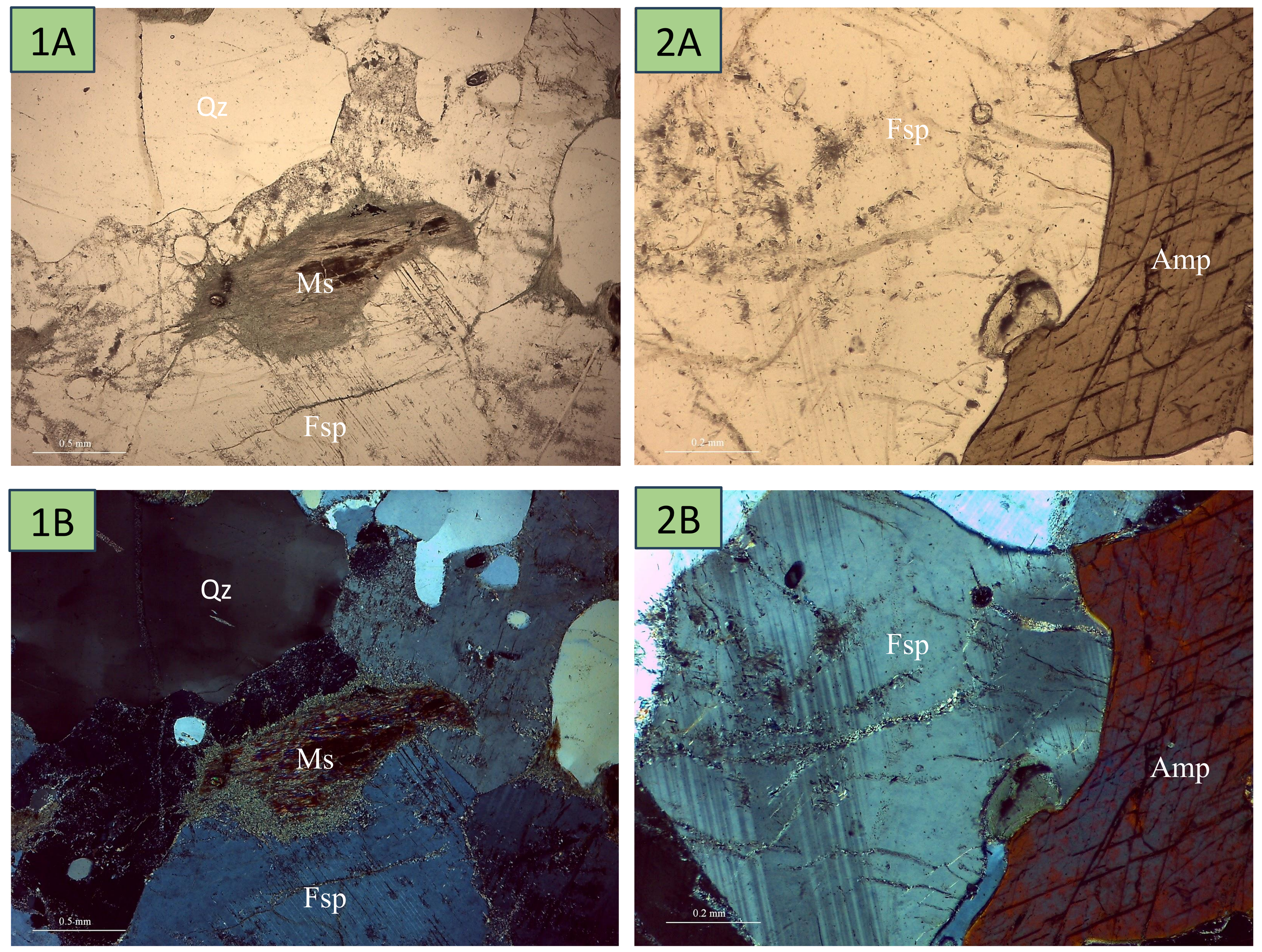

Figure 4. Two bedrock samples viewed under petrographic microscope under plane polarized light (PPL, Fig. 1a, 2a) and cross-polarized light (XPL, Fig. 1b, 2b). Sample 1 was photographed at 4x magnification; sample 2 photographed at 10x magnification. Samples were taken from a roadside outcrop on Fairview Road (40° 7'19.812"N, 75° 42' 50.868"W). Visible minerals include quartz (Qz), muscovite (Ms), feldspar (Fsp), and amphibole (Amp).

Discussion

The spring sites at Great Marsh remain around 11°C year-round and have a low thermal sensitivity (<0.2), meaning that they do not fluctuate with air temperature or quick flow (Kelleher 2012). The bedrock is a metamorphic gneiss that shows both micro and macro fracturing. In thin section, the bedrock fractures are filled in with secondary minerals, which limit the porosity and slow/stop water flow. However, at the outcrop scale, water visibly escapes along abundant fracture planes, demonstrating secondary porosity. The springs occur in a linear pattern across the marsh, which lie on one or more of these porous fracture planes (Fig. 5). As well as fracturing during metamorphism, frost cracking pervasive during Pleistocene cold-climate conditions might also have contributed to higher permeability at the weathered bedrock surface beneath the marsh.

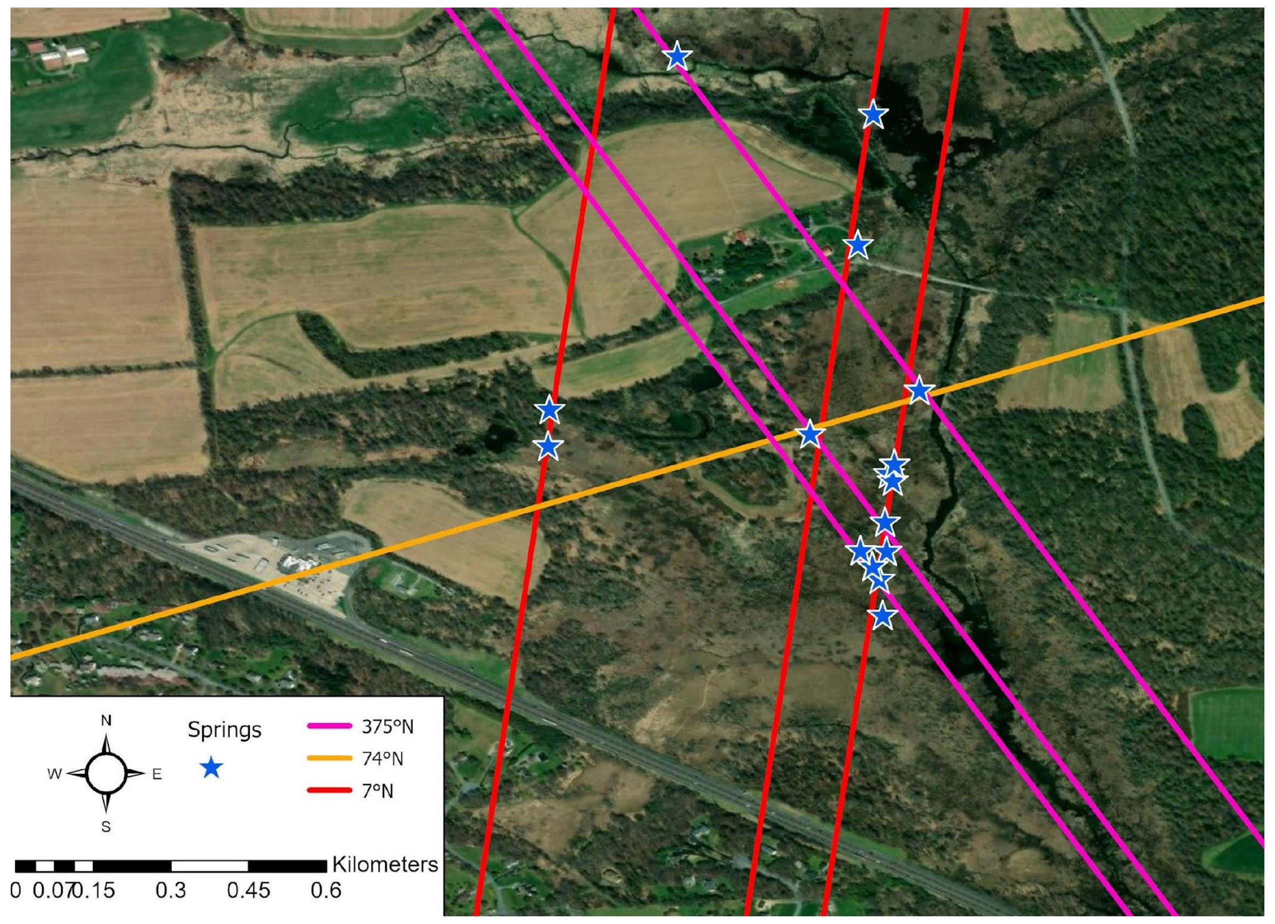

Figure 5. Satellite image of Great Marsh with field-mapped springs (blue stars). Lines represent extrapolated regional fracture trends based on structural mapping of outcrops adjacent to the marsh: Pink (375°NW), orange (74°NE), and red (7°NE).

Implications

Great Marsh demonstrates that pre-colonial marshes in Southeastern PA were self-sustaining due to groundwater flow from multiple springs. Therefore, when buried wetland sites are restored, the springs that are uncovered can feed, insulate, and sustain the marshes. The heavily fractured gneiss bedrock acts as pseudo-karst through its high level of secondary porosity.

Acknowledgements

We thank Emily Wilson for her laboratory assistance, and we recognize both Emily and Dr. James Jolles for their expertise of petrography. We thank Liam Connolly for his assistance in flying the thermal drone. We acknowledge the support and expert assistance of Bernard Brown in identifying possible spring locations across the marsh. Additionally, we thank María Fernanda Araoz Pozo, Charlotte King, Jake Hockwitt, Frankie Delgado, and Hannah Connuck for their help in the field. We thank Spectrum Petrographics Inc. for cutting and analyzing the rocks for thin section. Finally, we thank Lori Moore and the Great Marsh Institute for their hospitality and support during our research.

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