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Supporting coastal flood forecasting and community-led adaptation with tide gauges, community science and youth engagement

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As sea level rise shifts coastal flooding from future threat to present reality, communities must transition from planning to implementing operational solutions for managing increasingly frequent and damaging floods. Coastal flood management requires both technical and human capacity, including access to reliable water level forecasts, established relationships between water level and local impact, and an informed and engaged network of practitioners and community members. Here, we describe the transferable approach of a multidisciplinary team of research, civic, community, education, and industry partners working to expand the collection of coastal water level and flood impact data in coastal Maine, USA. The approach centers community leadership and youth engagement to achieve project sustainability and translation of data toward community resilience. We installed a network of ultrasonic and radar tide gauges and developed local capacity for running and sustaining a coastal-flooding community science program that collects geo- and time-referenced flood impact data. We also involved youth through a newly developed curriculum in which students

contribute flood observation data and engage with decision-makers in their communities around flood adaptation strategies. National Weather Service forecasters are using paired water level and flood impact observations to establish new total water level forecast points, local flood thresholds, and detailed impact statements. Municipalities are applying the data to near-term event response and long-term climate planning and adaptation projects. Embedding flood awareness in communities through this suite of data, tools, activities, and events is fostering a form of climate resilience and preparedness that is somewhat intangible and yet deeply valuable.

KEYWORDS

citizen science, coastal flooding, community science, sea level rise, tide gauge, youth engagement

1 Introduction

Routine high tide flooding and storm-driven coastal flooding events are increasingly producing significant impacts globally (e.g., Fox-Kemper et al., 2021; Thompson et al., 2021; Sweet et al., 2022; May et al., 2023). As communities contend with increasingly frequent and damaging flooding, there is an urgent need to develop operational flood preparedness and management solutions alongside forward-looking sea level rise planning efforts. These solutions require both technical and human capacity. Coastal water level records and reliable water level and wave forecasts define the hazard, and an established relationship between hazard and specific local impacts, hereafter called flood thresholds, enable action. For example, a total water level forecast of 3 meters above mean lower low water (MLLW) becomes actionable when paired with knowledge of which emergency access routes and infrastructure flood at 3 meters. Human capacity is equally important. A network of practitioners (e.g., emergency managers and municipal staff) prepared to respond to the forecast, as well as an informed and engaged community equipped to make and support high-quality social, economic, and environmental decisions, are needed for adaptation (NOAA Office of Education, 2015).

Here we present the work of a multidisciplinary team of research, civic, community, education, and industry partners aimed at expanding technical and human capacity for forecasting and building resilience to coastal flooding in Maine, United States (Figure 1). Similar community-based monitoring efforts are underway in other regions (e.g., Alaska Ocean Observing System, 2016; Hernandez et al., 2025; Hino et al., 2025; Martinez-Osuna et al., 2025). We adapt some of these approaches to develop a scalable, community-collaborative process for collecting and applying local water level and flood impact data that provides transferable design principles for flood forecasting and broader climate engagement efforts in other regions. We demonstrate that water level data from low-cost ultrasonic and radar sensors can be combined with community science observations of flood impacts to improve forecasting, public awareness, and community resilience. We also show that providing tools and resources for community-led work that includes collaboration among youth, municipal decision-makers, and adult community members builds knowledge and sustained capacity for climate action. This is, to our knowledge, the first coastal water-level sensor network that is integrated with community-led science and a robust multigenerational engagement strategy. This approach that centers local

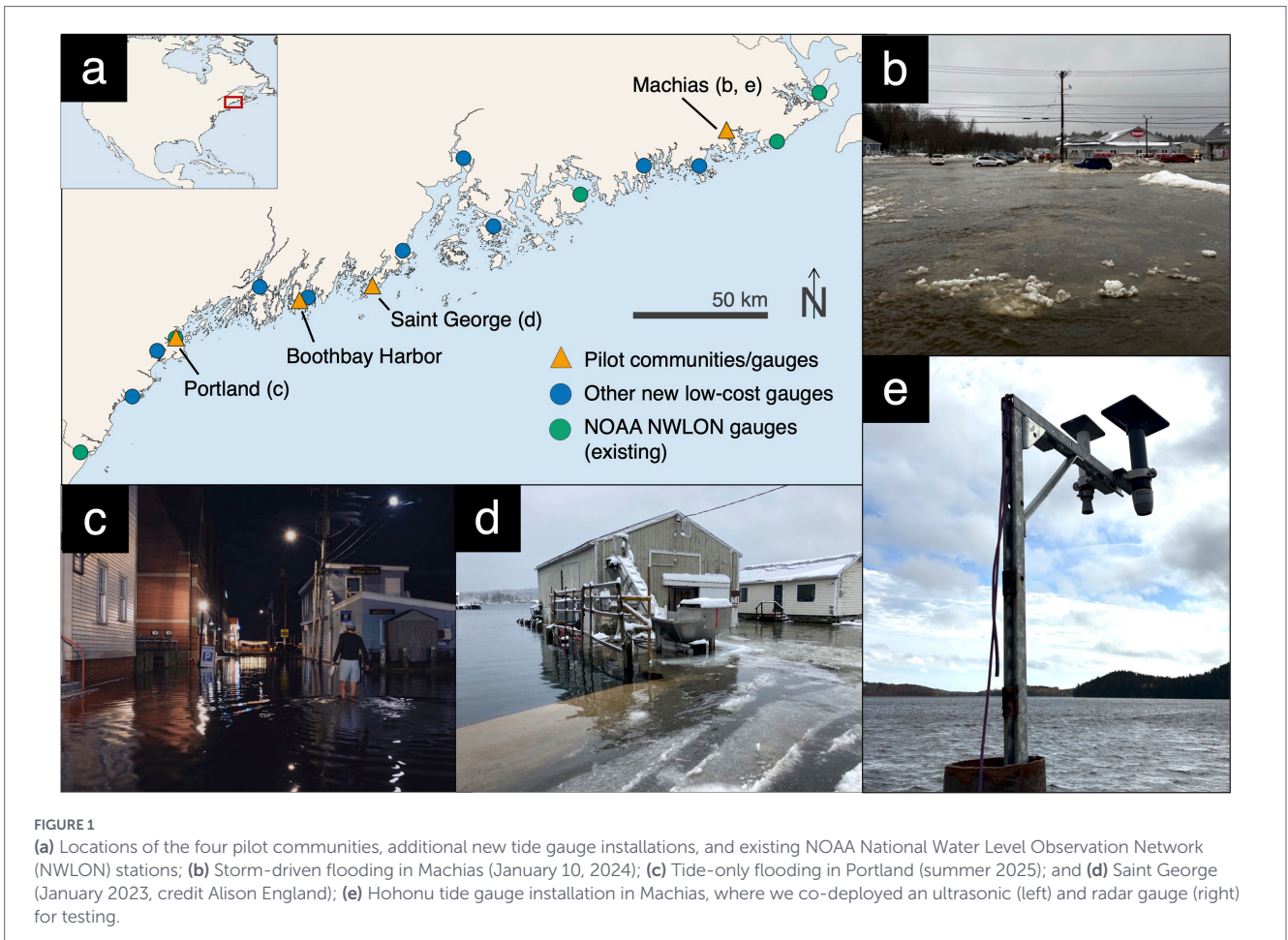
engagement and leadership has facilitated the ongoing application of data to expanding flood forecasting and supporting local planning.

2 Context

2.1 Geographic setting

Maine has 144 coastal communities and 5,000 miles of tidally influenced coastline, the most of any state in the continental United States. Maine's population is 61.4% rural (U.S. Census Bureau, 2020) with under-resourced municipalities that cite lack of capacity, expertise, and funding as barriers to addressing climate risk (Maine Climate Council, 2020). Rural communities, however, are also poised to respond. They have relatively high social cohesion (Henning-Smith et al., 2019) and place-based knowledge (e.g., Brondizio et al., 2021; Wolf et al., 2025), and the small communities involved in this project are highly collaborative and creative.

Coastal Maine communities already experience impacts from both minor high tide flooding and severe storm-driven flooding. Consecutive extratropical cyclones drove widespread damage along Maine's coast on January 10 and 13, 2024. Both storms broke total water level records at three of Maine's long-term tide gauges, caused at least \$90 million US Dollars in damage to public infrastructure, and damaged or destroyed an estimated 70% of Maine's working waterfront (Maine Climate Council Scientific and Technical Subcommittee, 2020; Maine Infrastructure Rebuilding and Resilience Commission, 2025). Parts of Portland, the most populous city in Maine, now flood routinely. For example, the National Weather Service minor flood threshold of 12 ft. (3.7 m) above MLLW, where low-lying streets and wharfs flood, was exceeded 15 times in 2024. While both tropical and extratropical cyclones impact Maine, extratropical cyclones are the primary driver of flooding. They are significantly more common, follow tracks more favorable to surge generation, and produce longer-duration surges that are more likely to intersect with high tide (e.g., Catalano and Broccoli, 2018; Baranes et al., 2020). Maine's coastal greater diurnal tidal range is between 2.7 and 5.9 meters, and the most severe recorded storm surges are less than 1.5 meters; thus, the timing and magnitude of the astronomical tide relative to storm surge is a primary determiner of flood severity (e.g., Maine Climate Council Scientific and Technical Subcommittee, 2020).



2.2 Coastal flood forecasting in Maine

The Gray and Caribou National Weather Service (NWS) offices provide coastal flood forecasts for Maine. NWS has limited tools and resources for forecasting coastal flooding from extratropical cyclones, so regional forecasters have developed a process that combines model guidance, instrumental observations, and forecaster expertise. Methods for developing the Official Total Water Level Forecast are described in [Thompson \(2011\)](#) and briefly summarized here. Note that “total water level” includes the combined influences of storm surge, astronomical tide, and wave setup, but excludes wave runup, swash, and overtopping. NWS forecasts nearshore wave conditions and includes wave impact messaging in Coastal Flood Warnings, but operational wave forecasting is beyond the scope of this project.

Modeled gridded storm surge predictions from the operational Extratropical Storm Surge,¹ Probabilistic Extratropical Storm Surge², and Surge and Tide Operational Forecast System models³ are linearly combined with gridded astronomical tide predictions. Forecasters then manually adjust the total water level forecast based on experience with the specific synoptic pattern and known systematic biases in model surge or tide predictions. At locations where real-time coastal water level observations are available from tide gauges, an additional

default bias correction is applied using the offset between modeled and observed water levels. Specifically, the average of observed-minus-modeled total water level (the “anomaly”) over a selected tidal phase and time period (the default is 3 days at high tide) is added to the model forecast for the next high water. During storm events, forecasters often apply a manual bias correction based on expert knowledge of persistent meteorological conditions and/or synoptic characteristics of a specific event. This practice of assessing forecast error via comparison of observed and modeled water level is now standard at all Eastern Region Weather Forecast Offices. Although the gridded total water level forecast is available along the entire Maine coast, the NWS Gray and Caribou offices only release forecasts at select locations where tide gauge or human observations can provide validation of model performance. Consequently, when this project began in late-2022, there were only total water level forecasts available at 16 coastal locations in Maine.

When conditions warrant, NWS also issues Coastal Flood Advisories for expected “Minor” flooding and Coastal Flood Watches and Warnings for expected “Moderate” or “Major” flooding. NWS relies on human observations from forecasters, local emergency management partners, and the public to develop the Minor, Moderate, and Major flood thresholds, which represent standardized inundation depths and levels of threat to life and infrastructure ([Thompson, 2011](#)). Remotely sensed, LiDAR-derived elevation measurements complement human observations, but LiDAR alone does not account for effects of human-built flood control structures or post-measurement shoreline change. In Maine, these Advisories, Watches, and

1 <https://slosh.nws.noaa.gov/etsurge/>

2 <https://slosh.nws.noaa.gov/pets>

3 <https://polar.ncep.noaa.gov/estofs/>

Warnings cover an entire coastal county and therefore provide limited specific, actionable information on anticipated impacts.

Sparse tide gauge and human observation coverage limit NWS's ability to issue localized flood forecasts, and this limitation is reflected by geographic discrepancies in the number of warnings issued across Maine. Between January 2006 and November 2025, NWS issued an average of 78 Coastal Flood Warnings per coastal county in the southern Maine region (York and Cumberland counties), but only 45 per county in the more rural Midcoast region (Sagadahoc, Lincoln, Knox, and Waldo counties), and 19 per county in the most rural Downeast region (Hancock and Washington counties; [Iowa Environmental Mesonet, 2025](#)). Thus, expansion of the region's tide gauge network and further development of systems to share local observations of flood impacts with NWS offices represent clear pathways for improving the reliability and geographic coverage of coastal flood forecasts in Maine.

2.3 Recent development of new tide gauge networks

The National Oceanographic and Atmospheric Administration (NOAA) Center for Operational Oceanic Products and Services (CO-OPS) currently maintains a National Water Level Observation Network (NWLON) that includes over 200 tide gauges providing real-time coastal water levels in the United States ([McLaughlin et al., 2024](#)). They are expensive to install and maintain, in part because they require millimeter-scale accuracy for measurement of long-term sea level trends and sensor redundancy for time-series reliability. The initial installation cost can range from \$75,000 to over \$1,000,000 USD depending on the location's complexity and remoteness, and the annual cost of maintaining a station and the associated data products and services at NWLON standards is typically \$25,000 to \$50,000 USD (NOAA CO-OPS, personal communication, December 17, 2025). Five NWLON gauges are in Maine ([Figure 1](#)). Five gauges is sufficient for determining tidal datums and relative sea level trends (NOAA CO-OPS, 2014), but it constitutes sparse coverage for characterizing meteorologically-influenced high waters (such as storm tides) because the geomorphic and oceanographic complexity of the coastal environment limits the extent over which point-specific water level measurements can be reliably applied (e.g., [Cannon, 2007](#)).

Lower-cost ultrasonic and radar tide gauges have enabled communities to monitor water levels where NWLON data do not sufficiently capture variability due to wave exposure and other factors that affect local water levels. The gauges are being developed by groups ranging from scientific instrumentation companies and academic laboratories to high school classrooms. As the technology has improved, collaborative groups have begun to establish local and regional water level observation networks that provide real-time flood alerts, high water marks, and tidal datums to support flood management and planning at locations where NWLON stations do not characterize local water level. Examples include the Alaska Water Level Watch ([Alaska Ocean Observing System, 2016](#)); the Southeast Water Level Network ([Hernandez et al., 2025](#)); FloodNet NYC ([Silverman et al., 2022](#); [Mydlarz et al., 2024](#)); Virginia StormSense ([Loftis et al., 2018](#)); and a North Carolina network ([Hino et al., 2025](#)), as well as developing projects in Woods Hole and Boston, Massachusetts.

These new networks are contributing to a developing understanding of uses and limitations of data from these sensors (e.g., [Hernandez](#)

[et al., 2025](#); [Martinez-Osuna et al., 2025](#)). Work is underway to consolidate these findings and provide more comprehensive guidance around hardware, siting, data quality, elevation control, and data access standards at the national level through the U.S. Integrated Ocean Observing System (IOOS) and in the Northeast region through the Northeast Regional Association for Coastal Ocean Observing Systems (NERACOOS).

2.4 Community science and youth engagement in support of flood threshold development and human capacity building

Community science is a proven approach for simultaneously filling data gaps, building understanding of and connection to local climate impacts, and facilitating student engagement in scientific research (e.g., [Danielsen et al., 2010](#); [Dickinson and Bonney, 2012](#); [McGreavy et al., 2016](#); [Pecl et al., 2019](#)). We note that we use the term "community science" rather than "citizen science" because it is preferred among our partners, and the project maintains focus on community priorities and leadership (e.g., [Cooper et al., 2021](#)). Community science builds participant knowledge of scientific concepts and processes, and it contributes to greater social wellbeing by giving participants voice in local decision making when projects are designed to attend to participant outcomes ([Bonney et al., 2016](#)). Participant learning and scientific outcomes can also be both complementary and mutually reinforcing ([NASEM, 2018](#)).

Community science, therefore, represents an ideal tool for addressing the dual challenge of collecting local observations that tie measured water levels to flood impacts, while simultaneously building community engagement with and understanding of local climate impacts. In fact, numerous coastal flooding community science projects exist in the United States and are managed across federal, regional, state, and the community levels. A key gap in these programs is intentional design for youth engagement. There is broad recognition that community science provides rich context for youth learning and empowerment (e.g., [NASEM, 2018](#)). Furthermore, youth voice is critical to the climate planning and resilience building process (e.g., [Bey et al., 2020](#)) and there is need for work that develops best practices for including youth in meaningful climate action ([Donger et al., 2025](#)).

3 Key programmatic elements

We developed a scalable and transferable approach for building both the technological and sustainable social infrastructure necessary to expand local data collection and improve flood preparedness and management. A 6-month planning grant (Oct 2022–Mar 2023) supported relationship-building and pilot tide gauge installations paired with community-contributed observations. This was followed by a 1-year grant (Oct 2023–Sept 2024) to co-design and pilot the approach in four coastal Maine communities that already experience regular flooding and represent a range of demographics and municipal capacities: Portland, Boothbay Harbor, Saint George, and Machias ([Figure 1](#)). While working deeply in these four communities, NERACOOS, the regional ocean data integration entity, simultaneously worked toward geographic scaling by installing additional sensors throughout the northeast and contributing to a broader community of practice and set of standards.

3.1 Expanding the northeast tide gauge network

3.1.1 Tide gauge technology and installation

During the six-month planning grant, we identified Hohonu as an ideal partner for providing technology suited to Maine's environment while meeting the project's civic and community engagement goals within the timeframe of a fast paced, 12-month pilot. Hohonu is a public-private partnership launched from a University of Hawaii at Manoa laboratory. At the onset of the project, they were building solar powered ultrasonic sensors using 3G telemetry to transmit data in real-time. They had validated their hardware and data quality assurance protocol through multiple installations adjacent to NOAA NWLON stations, including one in Portland, Maine. Data are public and open via a user-friendly web-based viewer and unlimited API access with no licensing fees. This was critical for integrating data into the NWS forecasting workflow and engaging classrooms and the public. Their subscription-based model includes a commitment to replacing or upgrading sensors to maintain reliable data delivery. This enabled NWS to rely on the sensors for forecasting in an environment with harsh winters, a large tidal range, and patchy cellular network coverage. They also made several improvements based on project needs, including switching to LTE telemetry, adding on-board data storage to handle cellular network outages, and testing co-deployments of radar and ultrasonic gauges.

During the planning and pilot period, we installed ultrasonic gauges in Portland, Boothbay Harbor, and Saint George, and both an ultrasonic and a radar gauge in Machias. As part of the broader expansion effort, we supported or led additional Hohonu ultrasonic gauge installations in Kennebunkport, Scarborough, Bath, East Boothbay, Stonington, and Milbridge; a Hohonu radar gauge in Jonesport; and Greenstream radar gauges in Bucksport and Rockland (Figure 1). Sensors provide measurements of "distance to water," and conversion to water surface elevations that can be compared to points on land requires measuring the elevation of the sensor. We followed SECOORA's protocol (SECOORA, 2023) and used Emlid RS2 + GNSS receivers to tie the sensor elevation to the NAVD88 vertical datum. This protocol is designed to achieve a total vertical position uncertainty less than 5 centimeters and involves measuring the sensor elevation relative to an established National Spatial Reference System (NSRS) benchmark or a newly established benchmark (via a post-processed static point measurement), along with three surrounding control points on stable land.

The model forecast guidance used by NWS provides water levels relative to MLLW (this is the datum of the gridded astronomical tide predictions); thus, an offset between MLLW and NAVD88 is required to use the sensors for forecast bias correction. We calculated tidal datums using the CO-OPS Tidal Datums Analysis Calculator⁴, following guidance on time series length in Licate et al. (2017). For Machias, where there was no infrastructure for siting the sensor over a location that does not drain at low tide, so we used the offset drive from NOAA VDatum.⁵

⁴ <https://access.co-ops.nos.noaa.gov/datumcalc/>

⁵ <https://vdatum.noaa.gov/vdatumweb/>

3.1.2 Data management approach

Data management was led by NERACOOS, an IOOS-certified Regional Coastal Observing System (RCOS) that aims to aggregate and disseminate coastal and ocean observation data in the region. The robust data management system adheres to IOOS Data Management and Cyberinfrastructure data standards and requirements for data access services, data formats, quality control, and metadata. Requirements include publishing data to an ERDDAP server, adoption of IOOS Metadata standards, and implementation of real-time data quality control guidance. Guidance for quality assurance and control comes from the IOOS-led Quality Assurance/Quality Control of Real-Time Oceanographic Data (QARTOD) program which develops and maintains protocols for evaluating quality of real-time data (IOOS, 2021). QARTOD tests were incorporated into real-time data workflows and are used to flag observations that do not meet defined conditions based on gross range, spike, rate of change, flat line and climatology tests. We leveraged the expertise of NWS and NOAA partners to set baseline configuration values due to the relatively short installation period for these gauges. Water level data are distributed via the ERDDAP server managed by NERACOOS⁶. NWS and the National Data Buoy Center have established protocols to access data from ERDDAP servers, so they can readily access the new water level data for forecasts and models. NERACOOS also developed a Water Level Dashboard that is modeled after the NOAA CO-OPS interface and provides a centralized location to host and distribute data from multiple sensor types, tide predictions, and water level forecasts.⁷

3.1.3 Developing a water level monitoring community of practice

As part of the water level network expansion, NERACOOS, in partnership with the Northeast Regional Ocean Council (NROC) and NOAA's Office for Coastal Management (OCM), hosted workshops to form a community of practice that bridges technical and scientific expertise with local knowledge. This group is adapting and expanding on the work done in other regions to develop guidance for data management, site selection, elevation control, and operations and maintenance of gauges in the Northeast. We hosted two workshops in 2024 and 2025 that brought together partners from across the five coastal New England states who have experience with gauge deployment and decision-making based on the data.

3.2 Community science and multigenerational, cross-sector engagement

3.2.1 Community science program and data platform

We designed a coastal flooding community science program that combines tide gauge data with volunteers' flood impact observations to inform flood threshold development, post-event analysis, and planning. It is intentionally designed to enable youth participation and local leadership, supporting project sustainability. When a community

⁶ <https://data.neracoos.org/erddap/tabledap>

⁷ <https://mariners.neracoos.org/water-level>

joins the project, we work with their leaders, who have extensive place-based knowledge, to identify high-priority, publicly accessible locations for monitoring flood impacts. Participants (or community scientists) submit geo- and time-referenced photographs and respond to multiple-choice questions describing inundation depth, wave impacts, wind, and precipitation. They can also assign tags to their observations (e.g., “working waterfront,” “causeway or bridge”), include flood narratives, and answer optional questions about their community role, level of concern, and preferred adaptation actions. The data collection protocol was developed with input from a variety of end users, including NWS forecasters, town planners, emergency managers, and educators. Data are submitted and viewed through the Gulf of Maine Research Institute’s Ecosystem Investigation Network (Table 1), a community science platform that has engaged thousands of participants in local ecological investigations. Data submissions are manually reviewed to remove photos with identifiable faces of individuals under age 13 and to check that the date, time, and location are accurate. Submissions that have been reviewed are marked with a validation symbol.

We developed a new visualization tool that co-displays community observations and photos with measured water levels from the nearest tide gauges. It is designed to further knowledge of the water level and weather conditions that lead to specific levels of flooding. Observations appear on an interactive map filterable by date, flood severity, community, and descriptive tag. When an observation is selected, community photographs and responses are displayed alongside water level time series, with the observation time plotted as a vertical line (Figure 2). Users can hover over the time series to view the measured water level at the observation time.

3.2.2 Building local capacity for program sustainability

We developed local capacity for sustaining community science programming through funded collaborations with six partner organizations in the pilot communities: Downeast Coastal Conservancy, Maine Coast Heritage Trust, Sunrise County Economic Council, Herring Gut Coastal Science Center, the Education Division of the Maine Department of Marine Resources, and Portland Trails. Each of these organizations has strong local relationships, capacity to support participation, and organizational goals aligned with the project. The Gulf of Maine Research Institute provided training, resources, and funding that enabled partner organizations to conduct outreach and education, including group data collection events called “coastal meet-ups” that are designed to reduce participation barriers. Resources include a freely available community engagement package with a facilitation guide, multi-media outreach materials and educational content, evaluation tools, and instructional recordings (Table 1). We also hosted a virtual High Tide Discussion Series, where adult and student participants from across all communities met throughout the storm season to share personal experiences and learn how researchers and civic partners were using their data.

3.2.3 Youth-centered curriculum and engagement

We developed a freely available, action-oriented curriculum that equips students to take meaningful climate action, while addressing science content standards through project participation (Figure 3;

TABLE 1 Community science and education resources.

Resource name	Description
Ecosystem Investigation Network ^a	Community science platform for submitting and viewing data; landing page for information and resources associated with the project
Community engagement package ^b	Resources that support partner organizations in leading the coastal flooding community science program locally, including a facilitation guide, multimedia outreach materials, educational content, evaluation tools, and instructional recordings
Coastal Flooding Curriculum: Building Background ^c	Students explore the evidence for, impacts, and drivers of coastal flooding. They apply all information learned directly to their lived experience by building three dimensional models of their community and repeatedly testing ideas with these models.
Coastal Flooding Curriculum: Community Science ^d	Students learn about sea level rise and make their own observations of coastlines at or around predicted flooding events through the Coastal Flooding: Storms and Sea Level Rise community science project.
Coastal Flooding Curriculum: Decision-Making and Action ^e	These lessons are designed to provide a space and structure for young people to participate in conversations about sea level rise and engage with civic action on behalf of their communities. They utilize a modified version of “Planning Forward,” a municipal action planning tool being used by teams of stakeholders in coastal communities around Maine.

^ahttps://investigate.gmri.org/project/coastal_flooding.

^b<https://drive.google.com/drive/folders/1k1q1lLW11NxrUt9z17mfQwvhOj5K0JdQ>.

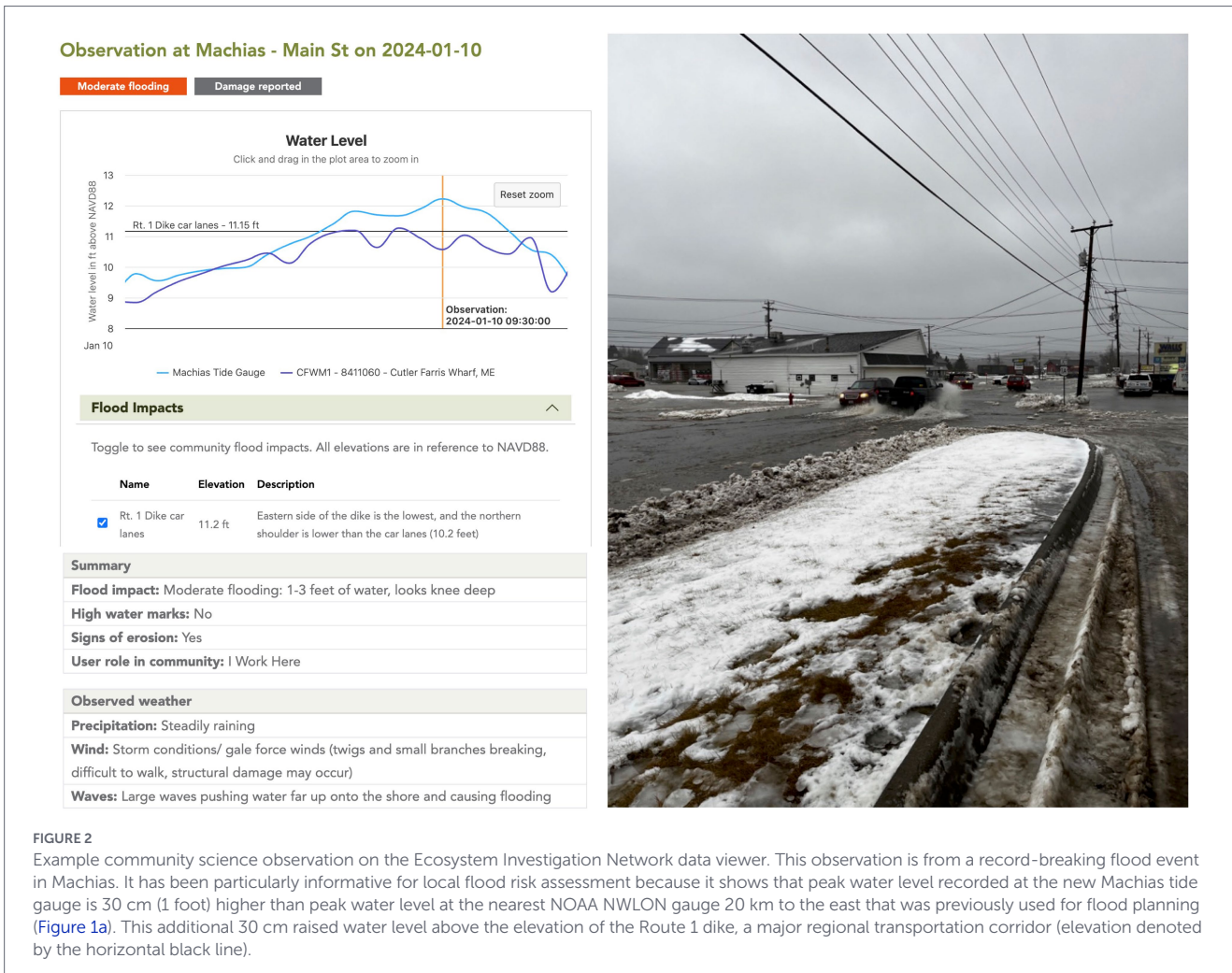
^c<https://teach.gmri.org/resources/coastal-flooding-building-background/>.

^d<https://teach.gmri.org/resources/coastal-flooding-community-science/>.

^e<https://teach.gmri.org/resources/coastal-flooding-decision-making-and-action/>.

Table 1). Students develop understanding of coastal flood drivers and build data collection and analysis skills through contributing to the community science project and working with tide gauge data. They learn strategies for taking climate action, including the importance of involving youth stakeholders in the process, participate in conversations about sea level rise with adult community members, and engage in civic action. For example, students in two partner communities shared their findings and recommendations at events attended by municipal leaders, partner organizations, and their families.

We piloted the curriculum across a range of student ages and school districts: King Middle School (~160 7th grade students, with 47% multilingual students), Boothbay Regional High School (~75 high school students), Saint George School (~20 7th grade students, very rural), and Washington Academy in Machias (~40 high school students, public/private partnership, very rural). Across all classrooms, it was important that



educators received resources and support to adapt the curriculum to their learning context. We provided funding for materials and field research for students, plus stipends for 2 days of professional development workshops that enabled teachers to collaborate with curriculum designers on developing a curriculum aligned to the Next Generation Science Standards that supports understanding of key scientific practices through locally relevant climate learning. We also adapted the community science protocol to reduce language barriers for Multilingual Learners and developing readers by creating a “visually supported” version that substitutes visual supports for written content.

4 Discussion

4.1 Project outcomes and impact

The project resulted in the installation of four new tide gauges in the pilot communities, plus an additional nine in the state and five more planned over the next several months. NWS used these new gauges to expand coastal water level forecasting to five new communities. There previously had been no forecasting available in much of Maine’s rural Midcoast region, and these gauges enabled the first forecasting in Knox, Lincoln, and Sagadahoc counties. At three of the new forecasting locations, NWS also used community-contributed photographs to establish

minor, moderate, and major flood thresholds, along with descriptions of localized impacts at various water levels. For example, they used photographs of the January 13, 2024 event of record to write that at 14.5 ft. MLLW in Saint George, “waterfront becomes flooded with greater than 1 to 2 feet of inundation impacting some local businesses. Numerous roads approaching Port Clyde become flooded, including Factory Road, Route 131, Horse Point Road, and Drift Inn Road. Water levels are similar to the January 13, 2024 storm tide.” Integration of other gauges into NWS forecasting is ongoing.

Over 700 observations have been submitted to the community science data platform, and community partners have hosted 16 coastal meetups. The Gulf of Maine Research Institute has hosted 7 educator workshops and conducted classroom and field visits with students, supporting approximately 1,500 students across 28 classrooms and non-school groups implementing the coastal flooding curriculum. Embedding flood awareness in communities through this suite of data, tools, activities, and events enables a form of climate resilience and preparedness that is somewhat intangible and yet deeply valuable.

Water level and community science data have begun to inform planning and adaptation efforts in coastal Maine. We note that this project was primarily focused on expanding data collection and building capacity and relationships. Translation to supporting planning and adaptation is therefore ongoing, and we describe initial results here. Two events of record occurred during the project period (January 10 and 13, 2024), providing municipalities with documented baselines for extreme events (e.g.,



FIGURE 3

Youth engagement programmatic elements. (a) King Middle School students contributing data to the coastal flooding community science project at a high tide in Portland; (b) Teacher professional development workshop; (c,d) Middle school students presenting their observations and solutions to families, municipal decision-makers, and teachers.

Figure 2). Municipalities and partner organizations around Machias are using paired water level and community science observations to develop the Upper Machias Bay Master Plan, a multistakeholder community-engaged effort to plan a resilient and prosperous future for the region, which will include recommendations for flood protection and infrastructure upgrades. FEMA base flood elevation (the water surface elevation associated with FEMA's estimated 1% annual chance flood event) was exceeded nine times between 2018 and 2024 in Machias. Thus, water levels measured by the new tide gauge, along with the associated community-contributed photographs, have provided a water surface elevation and impact documentation that are characteristic of a modern-day extreme event to inform regional planning efforts.

Municipalities that participate in the coastal flooding community science program but do not have tide gauges have used photographs from the January storms in a similar way for municipal climate vulnerability assessments. These municipalities (to date: Tremont, Southwest Harbor, Phippsburg, and Woolwich) have used the Ecosystem Investigation Network data viewer to find photographs with high water marks (e.g., a rack line) or clear water lines documented around the time of peak water level from the January storms, then used lidar to estimate the elevations of the high water marks and water lines. This process has been especially valuable because, like Machias, these towns are located in Maine counties with FEMA Flood Insurance Rate Maps that estimate the 1% annual chance event for sea level conditions over the 1983–2001 time period. Other examples of project data informing planning and adaptation include South Portland using community documentation of erosion to plan and apply for funding to implement nature-based solutions; engineering firms using water levels and photographs to validate a statewide hydrodynamic flood risk model and determine the design height for a sea wall around a wastewater

treatment plant; and the City of Portland evaluating the efficacy of one-way storm drain valves in preventing backflow through storm drains during high tides.

Youth involvement in climate action is also ongoing. There are now student representatives from two area high schools and the University of Maine at Machias serving on the leadership committee for the Upper Machias Bay Master Plan. The students' interest and the knowledge they are bringing to the master planning effort stemmed directly from their engagement in this project. In Portland and Saint George, students led public information sessions for the community, making recommendations for resilience actions directly to municipal leaders. Students in Saint George also partnered with a local engineering firm to develop a 3D model of the community showing future high water levels to be used for public education and decision-making.

Finally, the Gulf of Maine Research Institute also reserved funds to provide each community with a non-competitive grant supporting continued project outcomes. This was a key mechanism for enabling translation of data to relevant, local community impact to continue beyond 1 year. Project partners in Machias created kiosks displaying past, present, and possible future uses of their shoreline. They built upon the intergenerational project approach by combining tide gauge and community science data with narratives and art developed by students.

4.2 Transferable design principles

4.2.1 Match the gauge installation plan to the application

The intended use of water level data should guide decisions around sensor type, installation location, elevation survey protocols,

and data recovery (real-time versus post-collection) and integration methods. The lower-cost installations described here with lower-precision sensors and survey techniques offer advantages for applications such as flood monitoring, forecasting, and threshold development; however, there are important limitations to consider. For example, sensors cannot be used to measure long-term sea level change and may not be sufficiently reliable for operational use in high-consequence applications. Higher quality sensors generally provide a structured API that makes data simpler to integrate into a standardized data platform, while less expensive or maker-type sensors without an API require custom technology solutions that can be expensive to build, difficult to maintain, and harder to scale.

As described by [Hernandez et al. \(2025\)](#), we also note that although the cost of a sensor itself may be low (hundreds of USD), there are additional significant expenses that can be prohibitive. Installation planning, data integration, maintenance, and surveying require significant personnel time, expertise, and community engagement effort. Furthermore, these sensors only have impact if there are robust partnerships in place that enable forecasters, emergency managers, regional and municipal leaders, and the broader public to use the data. The effort required to cultivate and maintain these partnerships is critical to achieving project impact goals.

4.2.2 Work through cross-sector local partnerships

Working through mission-aligned partnerships with municipalities, educators, and local organizations emerged as a key factor contributing to project impact and sustainability. Local knowledge and relationships proved essential for tide gauge siting, installation, and maintenance (everything from finding a ladder to managing challenges with boat traffic) and selection of coastal flood monitoring sites. In small, under-resourced communities, it was especially important to work with partners who have deep, longstanding relationships and are trusted as valuable providers of information to foster buy-in and acceptance.

Direct municipal connections supported integration of this work with ongoing operational and planning resilience projects. For example, our team participated in monthly meetings with the Machias town manager and leaders of all the climate-related projects in the area. Those connections led to application of gauge data in developing technical materials for the Upper Machias Bay Master Plan, mobilizing emergency response during the January 2024 storms, and producing post-storm rapid response maps. Among the pilot communities, Machias stands out as leveraging the tide gauge, community science program, and youth curriculum for progressing operational flood solutions and multi-generational, community-engaged planning. This progress is due to strong local leaders who have collaborated on the project since the conceptualization and proposal writing stage.

Partners' autonomy in leading coastal meetups and developing project ideas for community grant funds fostered sustained connection. Partners have continued to run the community science program beyond the end of the one-year pilot, and even served as hubs for expanding it into neighboring communities. Partners also shared that coastal meetups served as spaces for storytelling and building of collective experience, and in one community, were an entry point for individuals to further engage in a municipal vulnerability assessment.

4.2.3 Design the project to facilitate youth engagement and leadership

Learning that began through the one-year pilot has extended into multiyear projects involving community organizations, municipal leaders, and students. This sustained engagement stems from three key design elements: intentional curriculum design that meets educator needs, multigenerational engagement with clear pathways for youth participation and leadership in community decision-making, and action- and solutions-oriented learning experiences. Learning through community sciences does not happen automatically. It requires integration of community science into the formal science curriculum, with standards-aligned resources designed for specific learning outcomes (e.g., [Bonney et al., 2016](#); [NASEM, 2018](#)).

Connection between schools and community partners made the work authentic for students, extending beyond classroom exercises to build project longevity. In Machias, for example, students documented flooding alongside adult community members mobilized by Maine Coast Heritage Trust, while local decision-makers visited classrooms to discuss ongoing adaptation work. One participating teacher explained, "I am able to facilitate data collection and learning experiences that are connected, relevant, and engaging... students have voice and agency. It gives them perspective and permission to have input and an opinion on community topics, concerns, and problems. With the Machias dike replacement issue, they are aware that they will be dealing with this within 10 years... they see what they are inheriting and they have ideas and potential solutions" (Colleen Maker, Washington Academy, Machias).

The action- and solutions-oriented focus of this work also addresses growing recognition of the psychological and societal benefits of moving youth from climate anxiety to action ([Dunlop and Rushton, 2022](#)). One teacher reflected, "[This project] helps me as an educator empower students to see themselves as scientists and community problem-solvers. My teaching now emphasizes the interconnectedness of environment, economy, and community – helping students understand that their curiosity and problem-solving skills can make a real difference" (Carol Coryea, Washington Academy, Machias). Students also articulated the complex emotions and transformative nature of this work. A seventh-grade student from Saint George shared work that included stories of their favorite place and projections showing flooding that would make it inaccessible in the future. They explained that although the flooding made them worried, they would rather have a place to talk about and plan for the future, rather than worrying on their own. Another student shared, "It was a very interesting and at times conflicting feeling seeing the effects of climate change so up close. It was really exciting on one hand, being able to do some real groundwork research and feel like a part of the solution, but at the same time a pit of fear sometimes would sit in my stomach when I realized what I was looking at. The marvel of nature is beautiful and dangerous in a way which kind of mirrors the astronomical extremes of the universe. A sobering realization of both the fragility of life and the interconnected chaos of the universe. I could not help but feel grateful in a way" (Student, Washington Academy, Machias).

4.3 Project challenges

Despite the project's successes, several challenges remain. It is difficult to assess the accuracy of the MLLW-NAVD88 offset (required for using tide gauge measurements for forecast bias correction) at locations along tidal rivers or that drain at low water. For example, the

observation-based offset at the Bath gauge (located on a tidal river) was 32 cm less than the modeled VDatum offset. It remains uncertain whether this discrepancy is due to river influence, insufficient model resolution, or some other cause. Future investigation with more and longer-duration gauge installations will support assessment of the VDatum offset at locations where there is no available installation location for measuring water level through the entire tidal range.

Flood thresholds also require continued refinement. Initial thresholds have been set by NWS in some locations using a combination of tide gauge data, community-contributed observations, LiDAR, and satellite imagery. More quantitative (water levels and surveys) and qualitative (e.g., damage to infrastructure) data are needed to ground-truth the thresholds; however, these efforts require time and resources. Additionally, erosion and infrastructure damage caused by severe events often necessitates further adjustment of flood thresholds.

Finally, sustained engagement takes time, creativity, and persistence. Although robust data platforms and collaborations among teachers and local organizations are contributing to project sustainability, continued participation of grant-funded researchers, community engagement specialists, and local project partners has been a challenge. In the absence of major storm events, community-driven interest can also wane. We found that fostering emotional connections to the issue through storytelling, personal place-based observations, and youth engagement sustains participation during periods of low flooding activity.

Data availability statement

Water level data are available via the NOAA ERDDAP data server (<https://data.neracoos.org/erddap/tabledap/>). The community science protocol, data, and other supporting resources are available on the Gulf of Maine Research Institute's Ecosystem Investigation Network (https://investigate.gmri.org/project/coastal_flooding/). The coastal flooding curriculum is available on the Gulf of Maine Research Institute's Learning Resource Hub in three parts: Building Background (<https://teach.gmri.org/resources/coastal-flooding-building-background/>), Community Science (<https://teach.gmri.org/resources/coastal-flooding-community-science/>), and Decision Making and Action (<https://teach.gmri.org/resources/coastal-flooding-decision-making-and-action/>).

Author contributions

HB: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. GB: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. DR: Conceptualization, Funding acquisition, Project administration, Supervision, Writing – original draft, Writing – review & editing. MH: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing. RM: Conceptualization, Data curation, Formal analysis, Funding

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Conflict of interest

Authors KM and BG were employed by Hohonu, who partnered with GMRI to develop the NSF proposal, and both served as a contractor on the NSF grant (they received funds for improving their hardware and data analysis methods), and received funds for the sensors in the four pilot communities.

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