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Initial insights into the development and implementation of a citizen-science drone-based coastal change monitoring program in the Great Lakes region

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ABSTRACT

High-resolution spatio-temporal data are needed to improve coastal management programs, particularly along the Great Lakes where lake level fluctuations pose challenges to coastal decision-making and planning. Unfortunately, there is a paucity of coastal change monitoring datasets, particularly those that document event-scale changes over a large spatial scale. This paucity of data is compounded by the large size and range of shore types throughout the region.

Unoccupied aerial vehicle (UAV) or drone data collected by citizen scientists are a potential solution to this challenge. However, no citizen science coastal change monitoring program exists in the Great Lakes region, nor does a comprehensive drone-based coastal change monitoring programs exist anywhere in the United States. To inform the development of drone-based citizen science programs, the goal of this paper is to describe the development and implementation of a citizen science coastal change monitoring program along the Great Lakes shores of Michigan. The citizens participating in this project generate imagery in two ways: (1) the submission of photos of coastal changes or hazards via a web app developed for the project called PicShores and (2) drone collection of survey-quality aerial imagery for use in the generation of orthomosaic images and digital elevation models (DEMs). This paper presents the methods utilized to develop the citizen science monitoring program, some initial findings from the citizen science monitoring, and explores some challenges and next steps for the program.
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Introduction

Coastal resilience, defined as the ability for a coastal area to cope through adaptation to disturbances such as storms and extreme water level fluctuations, has become the overarching goal of most coastal management efforts (Masselink and Lazarus, 2019; Molino et al., 2020; Rumson et al., 2020). In order to build resilience, management decisions must be data-driven and based on a process-focused understanding of the coastal system (Huang et al., 2021; Nichols et al., 2019; Rumson et al., 2020), which requires high-resolution spatiotemporal coastal monitoring documentation of coastal changes such as erosion, vegetation loss, and infrastructure damage over both long (years to decades) and short-time scales (events). For these data to be effectively utilized for management decisions, a community's management goals and capacity for using data must be considered when developing any coastal monitoring and research program (Molino et al., 2020; Wall et al., 2017).

Along the coasts of the Great Lakes of North America there is a paucity of coastal change monitoring datasets, particularly datasets that document event-scale changes across a regional spatial scale. At the present time, the only regional datasets that can be used to evaluate coastal change are topobathy LIDAR and aerial photographs. High-resolution remotely sensed satellite imagery became available in late 1990s, through multiple sources including GeoEye, WorldView, and Ikonos. Such data goes beyond other high-resolution datasets, specifically NAIP imagery, which, while having a broader time series, is more constrained in spectral and spatial resolution. Beginning in the mid-2000 s, aerial photographs from the USDA National Agriculture Imagery Program (NAIP) were collected on a near annual basis. While NAIP images help document and visualize shoreline and vegetation changes (Mack et al., 2020; Wernette et al., 2017; White et al., 2019), they do not

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provide quantitative information on geomorphic processes, nor do they provide information on coastal response to storm events. Topobathy LIDAR datasets can provide quantitative information on coastal erosion and accretion, however, they are relatively new (regional coverage beginning in the mid-2000 s for the Great Lakes) and are typically collected once every 5 years (Reif et al., 2013). Coastal monitoring of storm events at annual time scales remain locally focused and project-based throughout the Great Lakes region (e.g. Braun and Theuerkauf, 2021; Theuerkauf and Braun, 2021; Volpano et al., 2020). Given the large size and range of shore types throughout the region this type of monitoring is difficult for individual research teams and agencies to conduct regionally in any sort of coordinated fashion.

A potential solution to these challenges is to engage and train citizen scientists to utilize new unoccupied aerial vehicles (UAVs) or drones and smartphone technology to document and monitor coastal changes (e.g., Garcia-Soto et al., 2021, p.; Harley et al., 2019; Pucino et al., 2021). The use of a network of citizen scientists not only facilitates broader data coverage, but also enhances monitoring programs via local knowledge and community support (Conrad and Hilchey, 2011; Dickinson et al., 2010; Garcia-Soto et al., 2021). Currently, citizen scientists are being used for coastal erosion monitoring along ocean coasts via smartphone applications such as CoastSnap (Harley et al., 2019) and drone-based programs in Australia (Pucino et al., 2021). At the present time, no citizen science coastal change monitoring program exists in the Great Lakes region, nor does a comprehensive drone-based coastal change monitoring programs exist anywhere in the United States.

This manuscript details the development and implementation of a citizen science coastal change monitoring program along the Great Lakes shores of Michigan over the past year (Fig. 1). The program is entitled "Interdisciplinary Citizen-based Coastal Remote Sensing for Adaptive Management (IC-CREAM)" and is funded by a grant (Award #: 1939979) from the National Science Foundation's Coastlines and People program (CoPe). The overarching goal of IC-CREAM is to empower coastal communities to conduct data-driven coastal management by developing and supporting a network of citizen scientists focused on documenting coastal change using imagery. The citizens participating in this project generate imagery in two ways: (1) the submission of photos of coastal changes or hazards via a web app developed for the project called PicShores and (2) drone collection of survey-quality aerial imagery for use in the generation of orthomosaic images and digital elevation models (DEMs). This paper presents the methods utilized to develop the citizen science monitoring program, some initial findings from the citizen science monitoring, and explores some challenges and next steps for the program.

Overview of the IC-CREAM program

The goal of the IC-CREAM program is to build community capacity for resilient coastal management by generating high-resolution datasets of use for decision-making. To achieve this goal, it is necessary to build a network that is focused on community needs, interests and coastal management capacity. This community centered approach aims to move beyond one-sided scientific guidance to communities based on their perceptions of need (see Tribbia and Moser, 2008 for a discussion of this) and towards a co-production of knowledge. This collaborative relationship started with coastal communities by holding an initial workshop that provided an overview of the program to decision makers and community personnel (e.g., town managers, supervisors, public works departments, etc.) and discussed coastal management issues and capacities. The latter is achieved during the workshops through three activities: a coastal hazards knowledge evaluation, a coastal risk mapping activity, and focus groups. Additional information on concerns, needs, and capacity related to coastal management and coastal issues are solicited through surveys provided to both the workshop registrants as well as community members at large.

Knowledge and perceptions about coastal hazards are evaluated through an activity where participants are shown pictures of coastal changes and hazards and asked to identify what they see in the image and whether it is a concern for their community. Next, a coastal hazards mapping activity is conducted to identify priority monitoring locations within the community based on perceived risks by workshop participants. Another component of the workshops are focus groups that are designed to collect information about five items: 1) coastline hazards, 2) community resources, 3) the coastal management process, 4) perceptions of drones and drone applications and 5) community expectations about participation in the project.

Another important component of these initial workshops was to provide attendees with an understanding of the drone and smartphone monitoring programs and what data products can be generated. This discussion represents the start of an ongoing conversation between the research team, the citizen scientists, and the community decision makers about what data products should be generated from the drone data. Additionally, this portion of the workshop aids in recruiting a citizen scientist drone pilot from the community. If pilot volunteers were not identified during the workshop, local pilots were found through ads placed in the local media and workshop community connections.

Once a citizen scientist drone pilot is selected, they are enrolled in an Michigan State University developed Part 107 exam preparation course which provides an overview of the aeronautical and legal aspects of drone operations in preparation for the FAA Part 107 exam. While passing this exam is an FAA requirement to operate a drone for research purposes, one does not actually have to demonstrate proficiency in operating a drone to pass the exam. Therefore, additional, in-the-field training was conducted to teach citizen scientists how to fly a drone to conduct mapping operations.

Potential monitoring sites were derived from the workshop's mapping activity in each community. During this initial phase of the IC-CREAM program, only publicly owned (e.g., county, township, state) sites are being monitored, however, the aim is to expand the program to private sites if there is sufficient interest by community members. Once sites are identified and permission received for site access, the research team conducts an initial baseline drone survey using the exact same drones, flight control software, and mapping parameters that the citizen scientists will use. Only quadcopter drones (DJI Phantom 4 Pro, DJI Mavic Pro II, and an Autel Evo Pro II) and their associated flight control software (DJI Ground Station Pro and Autel Explorer) are used for this program. The mapping parameters are standardized to ensure consistency in the imagery collected and include: 80% front and side overlap, only downward-looking imagery, and a flight altitude that yields either a 1.5 cm/pixel or 2.0 cm/pixel image resolution, depending on the elevation of trees and other obstacles (typical altitudes range from 100 to 300 feet above ground level). The flight control software creates a mission based on these parameters, then the mission is flown to gather the imagery. Prior to conducting missions at each site, ground control points (GCPs) are surveyed with a Trimble R10-2 RTK-GPS system. Existing infrastructure such as sidewalks, parking lot markings, sewer manhole covers, or other fixed objects are preferentially used as GCPs. However, if there are not sufficient items at the site to use as GCPs then semi-permanent GCPs are installed by the research team, with permission from the community. These are utilized instead of other options for establishing ground control points, such as GPS-enabled ground targets

Fig. 1. Pilot citizen science communities across the Michigan Great Lakes shoreline. Six communities are monitoring and imaging their coastline in partnership with this project: Marquette, Manistique, Manistee, South Haven, Chikaming, and Iosco County.

(e.g., Propeller AeroPoints) because they are much more cost-effective and accessible.

Either during baseline surveys, or shortly thereafter, the research team joins the citizen scientist in the field to conduct drone operation training. All aspects of drone operations are covered during these trainings including an overview of the mission settings (which are provided to the pilot during this training and are based on the initial baseline survey) as well as basic handling of the drone from takeoff to landing. Pilots are also instructed on weather conditions to avoid for flights due to safety or data quality reasons, such as high winds and rain. Other important protocols are covered including site access and installation and removal of semi-permanent GCPs. When the training mission is complete the citizen science pilot should be ready to complete mapping missions on their own and will begin regular monitoring of the sites, using a drone provided by the project team. The research team was available to provide further technical assistance to the citizen scientists, through a phone or video call, or additional site visits.

At a minimum, the citizen scientist will map each site in their community once every two months during the ice-free season (April through December). Flexibility of exact days and times is required due to site accessibility issues (some beaches are popular during the summer months and can only be accessed during the week or early in the morning) and weather conditions. The pilots will also be requested to map the sites before and after major storm events (defined by a Storm Warning issued by the National Weather Service), which typically occur in the spring and fall. Storm events in the Great Lakes are typically characterized by wave heights in excess of 2 m (Hubertz, 1992). When these storm events are approaching, the research team will contact the pilots and alert them of the need to map. Ideally pilots will fly a day or two before the storm and a day or two after. However, this is subject to safe site access and weather conditions. Once the pilots have completed a mission, the imagery is uploaded to a pilot portal created by the research team specifically for this project. From here, the research team takes over and processes the data.

Agisoft Metashape Professional software processed the initial drone imagery from the individual overlapping images into a 3-D point cloud. GCP data were entered into Metashape and used to generate orthomosaic images and DEMs. Some of the GCPs that were surveyed in the field were used during the processing as check points to evaluate the horizontal and vertical errors of the DEMs, which are typically around 5 cm. The orthomosaics and DEMs were exported out of Metashape in a standard projection (UTM) and vertical datum (NAVD88) and then imported into Golden Software's Surfer and ESRI's ArcGIS for additional processing. Surfer was used to generate topographic maps and DEMS of difference (DODs), which visualize the spatial distribution and magnitude of erosion and accretion zones (Fig. 2). The DODs can also be used to estimate volume change between surveys as well as in comparison to previous LIDAR or engineering surveys. Various metrics of coastal change can be digitized from the orthomosaics in ArcGIS, including the erosion hazard line (Norton et al., 2011, 2013) and the shoreline (Moore, 2000). These metrics can be compared to successive drone surveys or can be compared to historical data generated from aerial photographs. These standard data products and accompanying interpretation will be shared with the community and utilized to conduct coastal geomorphology research.

Initial coastal monitoring results

Citizen science derived drone data can provide information on coastal processes, such as beach and dune morphology response to storms, at time scales that may be difficult for a single research team to achieve given travel logistics. For example, a storm event with wave heights in excess of 5 m occurred along southern Lake Superior on October 31- November 1, 2020. In response to this storm, the IC-CREAM team alerted the citizen scientist for the Marquette, MI area to conduct a drone survey as soon as conditions improved. The citizen scientist mapped the monitoring sites on November 2, 2020. These data provided decision makers a snapshot of what the sites looked like immediately after the storm, information useful for making repairs or for guiding coastal management actions. Perhaps more importantly, when this dataset is compared to the previous survey conducted by the citizen scientist in June of 2020, it provides quantitative information on how the sites changed in response to the storm event (Fig. 2). This information can be used to identify why a given area changed and what could be done to prevent such change in the future. For example, the DEMs and DODs from Lake Superior Roadside Park reveal that the beach morphology had a strong control on bluff erosion during this storm (Fig. 2). A wider and higher elevation beach was present along the western edge of the site, which protected the bluff along

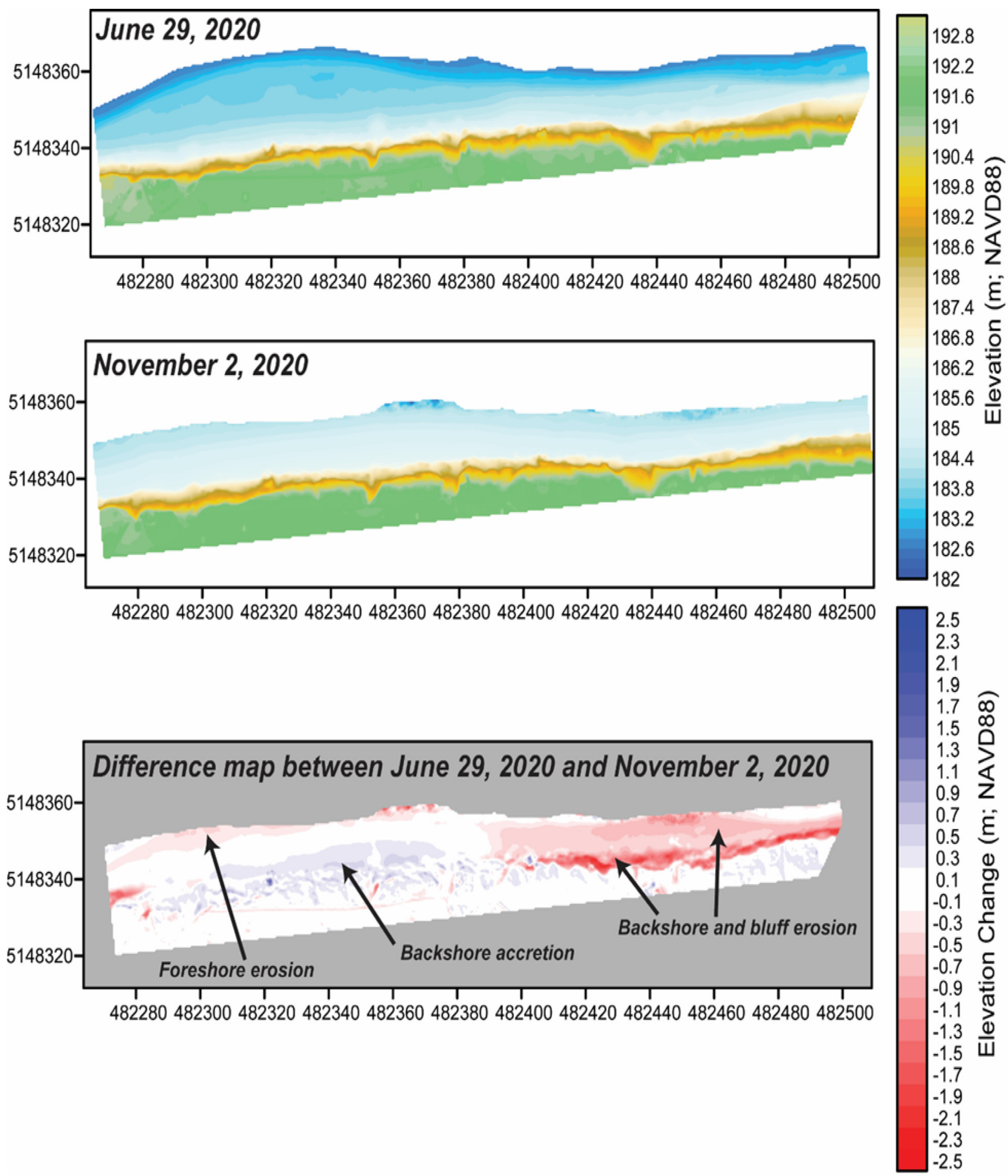

Fig. 2. (Top 2 panels) DEMs of Lake Superior Roadside Park near Marquette, MI generated from citizen science drone data. (Bottom panel) DEM of Difference depicting areas of erosion and accretion throughout the site in response to a storm event in the fall of 2020. Note the wide beach present in June 29, 2020 along the western end of the site that protected the bluff from the extensive erosion that was observed along the eastern end of the site.

this stretch from erosion during the storm. In fact, substantial backshore accretion was documented in response to the event. Along the eastern end, the narrow beach led to significant erosion of the beach and bluff during the storm. If prevention of bluff erosion is a management priority at this site, then maintaining a wide beach is critical.

That same storm system also caused strong winds along the northern end of Lake Michigan where another IC-CREAM community, Manistique, is located. This site was mostly sheltered from the northwesterly winds that generated large waves at Marquette. The citizen scientist for Manistique, MI mapped that community's sites on November 3, 2020, to document the impacts. While this event was not as powerful along Lake Michigan as it was on Lake Superior, some minor coastal erosion was documented at one of the sites (Township Park; Fig. 3). This comparison of impacts from the same event between Marquette and Manistique demonstrates the utility of the citizen science approach to monitoring coastal change on a regional scale.

In addition to changes in beach and dune morphology, the citizen science monitoring can also reveal changes to the built environment in response to storms. An example of this comes from a site along Lakeshore Boulevard in Marquette, MI. This site is a mix between a shoreline that is armored with a rock revetment along its northern half and a more natural sandy beach and low elevation foredune along its southern half. In response to the Lake Superior storm event, substantial erosion was documented along the more natural southern end (Fig. 4). Minimal change was observed along the armored stretch of the coast, however, some rocks along the revetement were displaced (Fig. 4). It is possible that the erosion along the southern end of the site was enhanced by the northern revetment, as these types of structures tend to promote scour of downdrift sites (Terpstra and Chrzastowski, 1992; Theuerkauf et al., 2019).

Program next Steps: Dissemination of data to communities and Great Lakes-Wide expansion

Once imagery is collected by the citizen scientists, processed, and analyzed by the research team, results are shared with the community to inform decision-making and educate the public on coastal processes. This is the current stage of the IC-CREAM program, as the initial steps of establishing sites and getting citizen

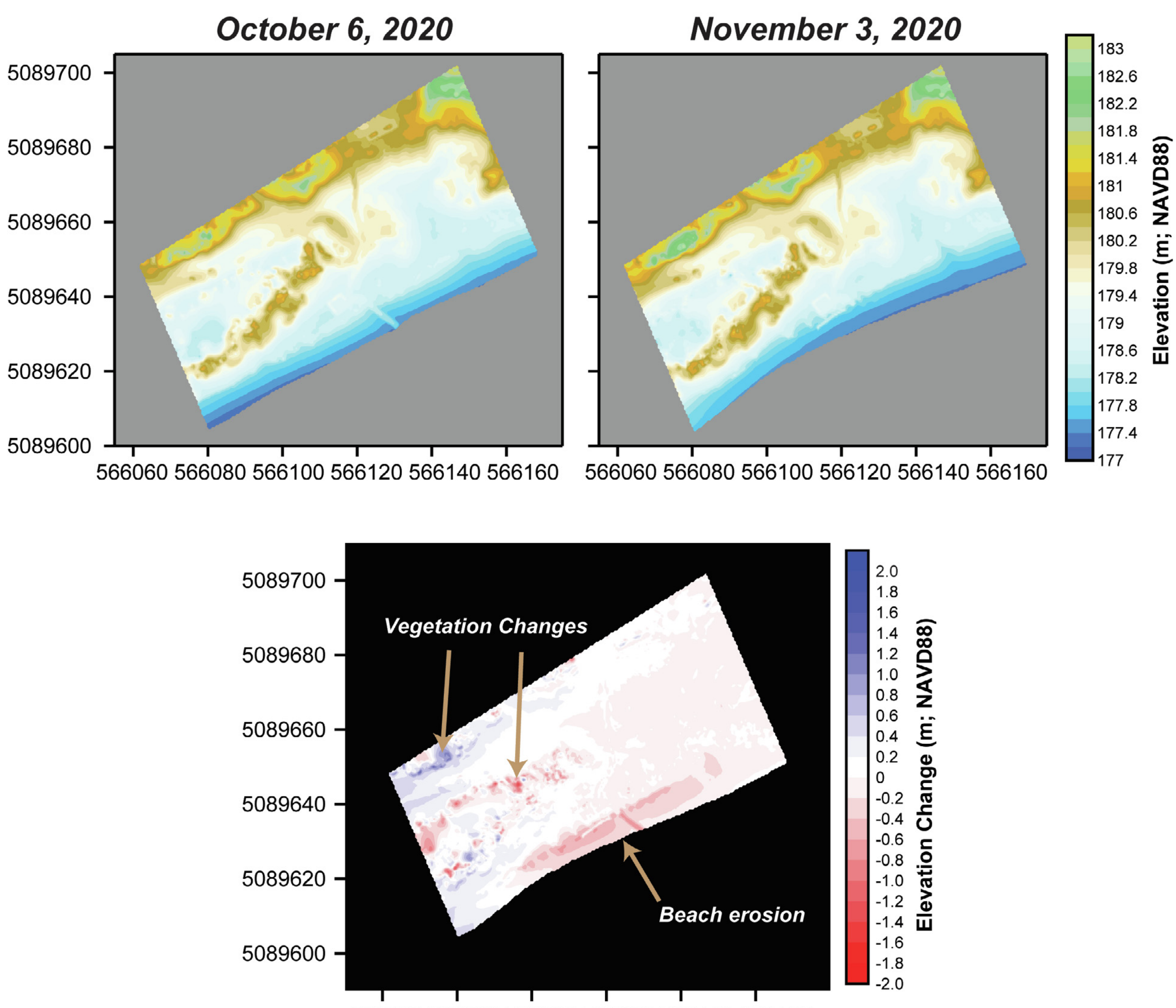

Fig. 3. (Top) DEMs of Township Park in Manistique, MI generated from citizen science drone data. (Bottom panel) DEM of Difference depicting areas of erosion and accretion throughout the site in response to a storm event in the fall of 2020. Note that some areas along the northwestern edge of the site experienced changes in vegetation cover between the two surveys resulting in apparent erosion or accretion. If volume change estimates were to be generated from these maps these areas must be excluded.

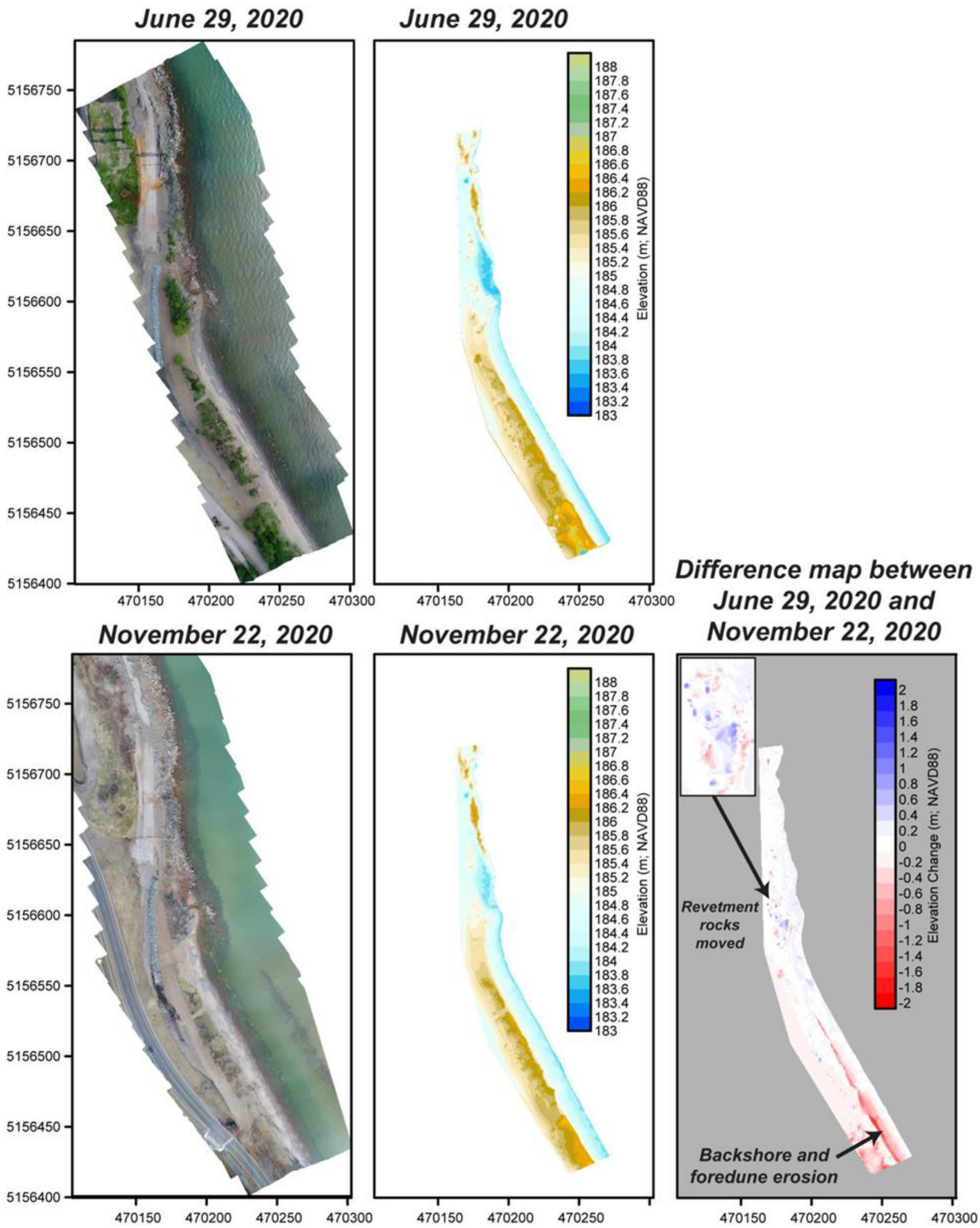

Fig. 4. (Top left and bottom left) Orthomosaic images generated from the citizen science collected imagery for a site near Lakeshore Boulevard in Marquette, MI. (Top middle and bottom middle) DEMs generated from citizen science collected imagery. (Bottom right) DOD documenting erosion in response to the fall 2020 storm as well as movement of rocks on the revetment (inset).

scientists trained and flying have been completed. While some preliminary data sharing related to the fall 2020 Lake Superior storm has occurred with stakeholders in Marquette, additional collaboration with all of the communities to develop effective data and information sharing products and strategies will be a key focus of the next year. Initially, basic products such as DODs and erosion hazard line movement, along with commentary by the research team will be shared with community stakeholders for feedback.

The research team will then work with the communities to incorporate their feedback and ensure delivered data products and results are useful for community management objectives.

Outreach to the broader public will also be a focus in the next year and will be accomplished through both the PicShores mobile app and community-education facilitated by citizen scientists. The PicShores mobile app can be used by anyone in the Great Lakes region to document coastal hazards and explore how disparate communities might be affected by the same storm event or lake level changes. An important aspect of this program is to help educate citizens on coastal processes. One way to do this is to encourage the citizen scientists to share their work with the community. Studies have shown that one of the benefits of citizen science is to increase public support for science (Bonney et al., 2016). Focus group data support this benefit and suggest citizen generated data will enhance community support for the project. Focus group data also indicate that this program will provide much needed data to communities who have a need to understand and benchmarks changes in the coastline over time. Participating communities also see a need for collaborative approaches to coastline management and are looking forward to information sharing about strategies to protect one of Michigan's biggest natural resources. Thus, the team will explore whether information sharing across communities enhances the knowledge base of parties involved in protecting the Great Lakes shoreline.

The first phase of the IC-CREAM program, develop and implement a citizen science coastal change monitoring program in the Great Lakes was successful. Imagery are being collected and processed at a number of sites for a number of events. Next year, this initial success will be expanded through the release of the PicShores app as well as the remaining image processing and dissemination of the results to the local communities. PicShores has been developed and is operational, the research team is currently working to release it through the AppStore and Google Play. Currently, the web application, which can be used on a mobile device, is available to the public. Over the next year, the research team will continue to support the citizen science network in data collection, promote broad participation in citizen science through the PicShores app. The team will also disseminate images, results, and knowledge gleaned from the citizen science data back to the communities. Beyond these data collection and data sharing efforts, the research team ultimately aims to expand the program to all Great Lakes states to help empower decision makers to conduct data-driven coastal management and educate the public on the dynamic nature of the Great Lakes shores. To do this a two-phased approach will be employed. First, we look to strengthen the community engagement component of the project through outreach activities directed at understanding data needs and understanding. Second, we look to expand the program, to do this the team will apply for additional funds to purchase drones and other equipment so that the team can recruit more communities and begin to train more citizen scientists to fly drones and map the dynamics of the Great Lakes shoreline in multiple states. However, it should be noted that even now, though the use of our PicShores app, any community can begin the process of taking part in the IC-CREAM program.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Bonney, R., Phillips, T.B., Ballard, H.L., Enck, J.W., 2016. Can citizen science enhance public understanding of science? Public Underst. Sci. 25 (1), 2–16. https://doi.org/10.1177/0963662515607406.

Braun, K.N., Theuerkauf, E.J., 2021. The role of short-term and long-term water level and wave variability in coastal carbon budgets. iScience 24, 102382. https://doi.org/10.1016/j.isci.2021.102382

Conrad, C.C., Hilchey, K.G., 2011. A review of citizen science and community-based environmental monitoring: issues and opportunities. Environ. Monit. Assess. 176 (1-4), 273–291. https://doi.org/10.1007/s10661-010-1582-5.

Dickinson, J.L., Zuckerberg, B., Bonter, D.N., 2010. Citizen Science as an ecological research tool: challenges and benefits. Annu. Rev. Ecol. Evol. Systemat. 41 (1), 149–172. https://doi.org/10.1146/annurev-ecolsys-102209-144636.

Garcia-Soto, C., Seys, J.J.C., Zielinski, O., Busch, J.A., Luna, S.I., Baez, J.C., Domegan, C., Dubsky, K., Kotynska-Zielinska, I., Loubat, P., Malfatti, F., Mannaerts, G., McHugh, P., Monestiez, P., van der Meeren, G.I., Gorsky, G., 2021. Marine citizen science: current state in europe and new technological developments. Front. Mar. Sci. 8. https://doi.org/10.3389/fmars.2021.621472.

Harley, M.D., Kinsela, M.A., Sánchez-García, E., Vos, K., 2019. Shoreline change mapping using crowd-sourced smartphone images. Coastal Eng. 150, 175–189. https://doi.org/10.1016/j.coastaleng.2019.04.003.

Huang, X., Song, Y., Hu, X., 2021. Deploying spatial data for coastal community resilience: a review from the managerial perspective. Int. J. Environ. Res. Public Health 18 (2), 830. https://doi.org/10.3390/ijerph18020830.

Hubertz, J.M., 1992. *User's guide to the Wave Information Studies (WIS) wave mode, version 2.0*. Available at: https://apps.dtic.mil/sti/ citations/ADA254313 (Accessed: 10 August 2020).

Mack, E.A., Theuerkauf, E., Bunting, E., 2020. Coastal typology: an analysis of the spatiotemporal relationship between socioeconomic development and shoreline change. Land 9, 218. https://doi.org/10.3390/land9070218.

Masselink, G., Lazarus, E.D., 2019. Defining coastal resilience. Water 11, 2587. https://doi.org/10.3390/w11122587.

Molino, G.D., Kenney, M.A., Sutton-Grier, A.E., 2020. Stakeholder-defined scientific needs for coastal resilience decisions in the Northeast U.S. Mar. Policy 118, 103987. https://doi.org/10.1016/j.marpol.2020.103987.

Moore, L.J., 2000. Shoreline mapping techniques. Journal of coastal research, 111–124.

Nichols, C.R., Wright, L.D., Bainbridge, S.J., Cosby, A., Hénaff, A., Loftis, J.D., Cocquempot, L., Katragadda, S., Mendez, G.R., Letortu, P., Le Dantec, N., Resio, D., Zarillo, G., 2019. Collaborative science to enhance coastal resilience and adaptation. Front. Mar. Sci. 6. https://doi.org/10.3389/fmars.2019.00404.

Norton, R.K., Meadows, L.A., Meadows, G.A., 2011. Drawing Lines in Law Books and on Sandy Beaches: Marking Ordinary High Water on Michigan's Great Lakes Shorelines under the Public Trust Doctrine. Coastal Management 39 (2), 133–157.

Norton, R.K., Meadows, G.A., Meadows, L.A., 2013. The deceptively complicated "elevation ordinary high water mark" and the problem with using it on a Laurentian Great Lakes shore. Journal of Great Lakes Research 39 (4), 527–535.

Pucino, N., Kennedy, D.M., Carvalho, R.C., Allan, B., Ierodiaconou, D., 2021. Citizen science for monitoring seasonal-scale beach erosion and behaviour with aerial drones. Sci. Rep. 11, 3935. https://doi.org/10.1038/s41598-021-83477-6.

Reif, M.K., Wozencraft, J.M., Dunkin, L.M., Sylvester, C.S., Macon, C.L., 2013. A review of U.S. army corps of engineers airborne coastal mapping in the Great Lakes. J. Great Lakes Res. Remote Sens. Great Lakes Other Inland Waters 39, 194–204. https://doi.org/10.1016/j.jglr.2012.11.002.

Rumson, A.G., Garcia, A.P., Hallett, S.H., 2020. The role of data within coastal resilience assessments: an East Anglia, UK, case study. Ocean & Coastal Manage. 185, 105004. https://doi.org/10.1016/j.ocecoaman.2019.105004.

Terpstra, P.D., Chrzastowski, M.J., 1992. Geometric trends in the evolution of a small log-spiral embayment on the illinois shore of Lake michigan. J. Coastal Res. 8, 603–617.

Theuerkauf, E.J., Braun, K.N., 2021. Rapid water level rise drives unprecedented coastal habitat loss along the Great Lakes of North America. J. Great Lakes Res. 47 (4), 945–954. https://doi.org/10.1016/j.jglr.2021.05.004.

Theuerkauf, E.J., Braun, K.N., Nelson, D.M., Kaplan, M., Vivirito, S., Williams, J.D., 2019. Coastal geomorphic response to seasonal water-level rise in the Laurentian Great Lakes: an example from Illinois Beach State Park, USA. J. Great Lakes Res. 45 (6), 1055–1068. https://doi.org/10.1016/j.jglr.2019.09.012.

Tribbia, J., Moser, S.C., 2008. More than information: what coastal managers need to plan for climate change. Environ. Sci. Policy 11 (4), 315–328. https://doi.org/10.1016/j.envsci.2008.01.003.

Volpano, C.A., Zoet, L.K., Rawling, J.E., Theuerkauf, E.J., Krueger, R., 2020. Three-dimensional bluff evolution in response to seasonal fluctuations in Great Lakes

water levels. J. Great Lakes Res. 46 (6), 1533–1543. https://doi.org/10.1016/j.jglr.2020.08.017.
Wall, T.U., McNie, E., Garfin, G.M., 2017. Use-inspired science: making science usable by and useful to decision makers. Front. Ecol. Environ. 15 (10), 551–559. https://doi.org/10.1002/fee.2017.15.issue-1010.1002/fee.1735.
Wernette, P., Shortridge, A., Lusch, D.P., Arbogast, A.F., 2017. Accounting for positional uncertainty in historical shoreline change analysis without ground reference information. Int. J. Remote Sens. 38 (13), 3906–3922. https://doi.org/10.1080/01431161.2017.1303218.
White, R.A., Piraino, K., Shortridge, A., Arbogast, A.F., 2019. Measurement of vegetation change in critical dune sites along the eastern shores of Lake michigan from 1938 to 2014 with object-based image analysis. J. Coast. Res. 35, 842–851. https://doi.org/10.2112/JCOASTRES-D-17-00141.1.