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Development and application of a real-time water environment cyberinfrastructure for kayaker safety in the Apostle Islands, Lake Superior

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ABSTRACT

Assessing all pertinent environmental variables to categorize a skill level to safely navigate the water environment can be difficult for inexperienced kayakers, especially at a remote site where internet access is limited. A real-time kayaker safety assessment of water environmental conditions at the Mainland Sea Caves of the Apostle Islands National Lakeshore, Lake Superior is achieved. We present a new cyberinfrastructure that provides kayakers with real-time data access and a Safety Index (SI) with consideration of multiple environmental factors to characterize the degree of navigational difficulty for classifying kayaker skill levels. Specifically, radar reflectivity is added to improve forecasts of dangerous conditions caused by convective storms using state-of-the-art weather and wave modeling. Spectral characteristics of surface waves are employed to correlate the occurrences of extreme and freak waves. In addition, unexpectedly dangerous conditions like coastal upwelling and freak wave occurrence due to changing wind directions are considered. A contingency plan is implemented to handle the issue of possibly missing required environmental data. Display of the SI and visualization of other real-time environmental data are communicated by a power-efficient kiosk. Web analytics demonstrates a public interest in real-time water conditions and the need for the on-site kiosk to provide the latest information before kayakers enter the water. The new real-time water environment cyberinfrastructure for kayaker safety in the Apostle Islands, Lake Superior has been successfully operated since 2014.

Introduction

Kayaking along the sculpted sea caves amidst a pristine wilderness is a popular activity at the Apostle Islands National Lakeshore (APIS), Lake Superior. The Mawikwe (or Mainland) Sea Caves are among the most visited destinations in the APIS for their natural beauty and accessibility (Kraft et al., 2007). Water conditions around the APIS can vary dramatically due to rapidly changing winds or fast moving storms (Scott and Huff, 1996; Anderson et al., 2015). For instance, sudden cold temperatures can appear at the coasts of the APIS when water at depth is upwelled when warm surface water that is moved offshore by interactions among wind, current, and the Coriolis force (Csanady, 1984; Chen et al., 2004; Rao and Schwab, 2007). Coastal processes like refraction, diffraction, or reflection around the islands can transform nearshore waves to form extreme waves (Anderson et al., 2015) or freak waves (Dean, 1990; Wu and Nepf, 2002; Liu et al., 2010) that are hazardous to recreational kayakers and have resulted in tragic drowning incidents near the Sea Caves [Duluth News Tribune, 8/24/2004; 6/26/2007; 09/12/2010; 06/09/2011]. Accidents often occur when kayakers have limited knowledge of the water environmental conditions or underestimate the skill level required to navigate safely (Bailey, 2010; Aadland et al., 2016). In view of the concerns for kayaker safety, there is a need to provide and assess water environmental conditions to reveal any hidden or unexpected dangers to kayakers of the APIS.

Several indices related to water environmental conditions have been used to assess safety of small crafts or kayaks. For example, different levels of indices like wind speed and/or wave height have been applied in Small Craft Advisory, Small Craft Advisory for Hazardous Seas, Small Craft Advisory for Rough Bar, etc., for marine warnings (Tew et al., 2008). For extreme kayaking, the Sea Conditions Rating System (SCRS), developed by oceanic kayaking experts Eric Soares and Michael Powers, is a self-assessment scaling measure for scouting sea conditions and relating them to skill levels (Soares and Powers, 1999). Variables considered in the SCRS include site geography, wind speed, wave height, water temperature, weather condition, time of day, etc. While the assessed levels obtained from the SCRS are comprehensive, there are a few caveats. First, a kayaker may underestimate the appropriate class of skill level due to personal assessment bias in rating multiple environmental conditions. A kayaker is therefore strongly encouraged to compare an individual assessment with others. Second, a kayaker may not be able to obtain water environmental conditions at the destination

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due to unavailable data or spatially varying data caused by complex physical processes. For instance, a fast moving storm that is capable of generating meteotsunami like waves (Rabinovich, 2009; Bechle et al., 2016) may reach the kayaker's target location within an hour without any warning. Sheltering due to islands can cause spatial variability in wind and wave properties (Stopa et al., 2013; Anderson et al., 2015). Likewise, coastal upwelling can cool down water temperatures at certain localized areas while other areas in Lake Superior remain unaffected (Ragotzkie, 1974; Bogrien and Brooks, 1992). Third, a kayaker may not have access to timely information in the field due to the lack of tools to process data for implicit measures or analytics (e.g. wave steepness or spectral bandwidth of a wave field) that can be related to the likelihood of dangerous extreme waves or unexpected freak waves (Goda, 1970; Naess, 1985; Wu and Yao, 2004; Hultquist et al., 2006; Anderson et al., 2015). While the SCRS provides an excellent framework to relate the water environment to kayaking skill levels, logistical difficulties in accessing timely information and assessing reliable scaling for actual water conditions remains a challenging issue for kayakers.

In the last two to three decades, cyberinfrastructure technology has greatly advanced to serve as an automated tool for providing water environment conditions. For example, the Great Lakes Coastal Forecasting System (GLCFS), originally developed by the Great Lakes Environmental Research Laboratory (Liu et al., 1984; Schwab et al., 1984), was the first cyberinfrastructure to provide near real-time forecasting of currents, temperatures, winds, waves, and ice conditions using offshore buoys to collect and transmit observations in real-time at multiple locations around the Great Lakes. These predictions provide timely information to lake carriers, mariners, port and beach managers, emergency response teams, and recreational boaters, surfers, and anglers. However, the nearest buoy in Lake Superior to the APIS is approximately 65 km away, which could be too far to provide a reliable assessment of the nearshore conditions. In addition, the spatial resolutions of the models used in the GLCFS have yet been fine enough to resolve nearshore water conditions around the islands in the APIS. As a result, a new wave model, WAVEWATCH III, was embedded into the Coastal and Great Lakes Forecast, developed by National Centers for Environmental Prediction (Alves et al., 2014) and the National Weather Service (NWS) to provide nearshore zones around the Great Lakes. Currently, the new Great Lakes Marine Modeling & Analysis Branch (MMAB) operational wave models provide excellent wave forecasts for mariners in the APIS (http://www.nws.noaa.gov/om/marine/home.htm). Nevertheless, no available nearshore wave observations have been used to validate the nearshore wave forecast. Anderson et al. (2015) conducted nearshore wave measurements around the APIS to calibrate a Simulating WAves Nearshore (SWAN) model and characterized wave climatology based upon 35 years of data. To date, the nearshore water environmental factors have yet to be used in rating skill levels for kayakers in the Great Lakes. Furthermore, there has been no cyberinfrastructure that can provide timely assessment of the water environment in relation to skill levels for kayaker navigation safety at the mainland Sea Caves of the APIS.

The objective of this paper is to develop a cyberinfrastructure that provides real-time safety assessment of sea conditions for kayakers at the mainland Sea Caves of the APIS. A Safety Index (SI) with algorithms to assess the water environment is presented. We document the design of hardware and software components of a cyberinfrastructure including the Real-Time Wave Observation System (RTWOS) for data acquisition, an Integrated Nowcast and Forecast Operation System (INFOS) for data storage, management, integration, and computing, and the Real-Time Wave Kiosk System (RTWKS) for an energy-efficient display at the remote location. Results of the SI are examined to identify concerning safety conditions caused by moving storms, extreme waves, freak waves, upwelling, and changing wave directions. In addition, we show a display image of the RTWKS that gives an example of real-time water environmental information including a SI rating, past measured water and weather conditions, a latest webcam image, and a radar reflectivity animation related to moving storms. Finally we discuss the validity and adaptability of ratings for SI, a contingency plan to handle the issue of possibly missing required environmental data used in the computation of the SI, and website usage statistics of the cyberinfrastructure developed in this paper.

Methods

Site description

The Mainland Sea Caves study site, comprising a 3.5 km stretch of sheer sandstone cliffs that rise approximately 15 m above the water surface (Kraft et al., 2007), is located at the western edge of the APIS on the southwestern shore of Lake Superior (Fig. 1). Water depths are typically 2–5 m at the base of the cliffs. Atop the cliffs is a hiking trail in a deciduous forest that is managed by the National Park Service (NPS). Typically visitors kayak to the Sea Caves from Meyers Beach (Fig. 1), which is located approximately 2 km southwest from the start of the Sea Caves with typical round trip duration about 3 h. Meyers Beach is the main motor vehicle access point for sea kayakers at any time of the day or year (Fig. 1). During the busy kayak season from July–August and on weekends until the end of September, staff from the NPS are stationed at Meyers Beach.

Wind and wave climatology at the study site is dominated by westerly winds and wave directions (Anderson et al., 2015). Monthly averaged winds and waves are at their annual low during July and August (Kraft et al., 2007), but energetic wind and wave conditions can occur from synoptic scale weather systems over a daily time scale or convective storms over an hourly time scale. As a result, summer wave heights can reach as large as 3 m near the Sea Caves (Anderson et al., 2015), and wind gusts >20 m/s have been measured by the NOAA real-time meteorological station DISW3 (Fig. 1), located at Devils Island. At the westerly location of the APIS, the study site is sheltered from strong northeast wind events that dominate the wave climatology at most other areas in the APIS (Anderson et al., 2015). Meyers Beach is further sheltered by the shoreline geography when waves approach from the northeast, which can deceive kayakers that are examining conditions at Meyers Beach and planning to visit the Sea Caves.

Safety Index

A Safety Index (SI) is devised to be a points-based skill level by considering multiple environmental factors that characterize navigational safety for kayakers. A SI of 100 corresponds to the safest conditions. As the SI decreases, water conditions become more hazardous for kayakers. Calculating SI involves assigning conditional point totals to multiple variables, summing the total (T), and applying the equation $SI = 100 - T$. Table 1 shows the variables considered in the computation of the SI and an example calculation. The point weightings of each category were originally based on the relative danger posed to kayakers. The method to combine each category into a composite skill level index was determined by experts and was tested under multiple scenarios in the ocean (Soares and Powers, 1999). The SI scale is based upon a rescaling of the original SCRS so that thresholds >70, 50–70, 30–50, and <30 of SI correspond to the expert determined skill levels beginner (I), intermediate (II), advanced (III) and expert (IV), respectively (Lull, 2013). In addition, we further modify the SRCS method for breaking waves and add a new variable of radar reflectivity to characterize atmospheric moving storms. Details of each variable and the associated conditions for point allocation are described below.

Environmental factors are classified into three categories (Table 1). Base category is considered to have no direct effect on navigation. First, swim distance to safety has a maximum distance of 2 km (Fig. 1) at the study site as the sheer cliffs provide no escape from the water. Swim distance is assumed constant at 2 km in the calculation of SI which limits the maximum SI to 90. Second, entering the sea caves is