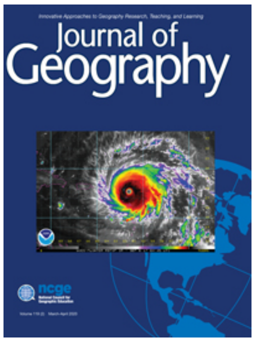

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Using Web-Based GIS to Assess Students' Geospatial Knowledge of Hurricanes and Spatial Habits of Mind

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ABSTRACT
Geospatial weather data is readily available to learners. However, the interpretation and understanding of this data requires the utilization of geospatial thinking skills. This study examined the impacts of a Web-based, collaborative inquiry Hurricane Irma GIS learning module on AP environmental science students' hurricane knowledge and spatial thinking skills. Study results showed significant improvement in knowledge about hurricanes, coastal impacts, and risks. A measure of spatial literacy found no changes in student self-assessment of spatial thinking skills resulting from the module. However, students did show significant improvement on hurricane knowledge questions associated with pattern recognition, spatial descriptions, and visualization.

KEYWORDS
GIS; spatial thinking; spatial habits of mind; collaborative inquiry; hurricanes

Introduction

In the classroom, Web-based Geographic Information Systems (GIS) provides the platform for students to engage as scientists, accessing and analyzing large datasets, displaying data and results in a spatial context, and synthesizing answers to driving questions related to real-world problems (Bodzin and Anastasio 2006). Hurricanes provide a unique opportunity for educators and students to utilize Web-based GIS not only to investigate these storms that can cause billions of dollars in economic damage, but also address issues faced by coastal residents each year during hurricane season.

Although hurricanes are a meteorological phenomenon, the hazards of landfalling hurricanes, such as damaging winds and storm surge, are also inherently geographic in nature. For example, a maximum sustained wind near 285 kilometers per hour was measured in Hurricane Irma in 2017 (Cangialosi, Latto, and Berg 2018). However, the maximum wind speed of a hurricane is not representative of the wind speed (or even potential wind speed) at every location within the storm's entire circulation, which can span hundreds of kilometers. Rather, the maximum wind in a hurricane is normally found at the inner edge of the eyewall (National Hurricane Center 2019). Thus, for students and the general public alike, a true understanding of hurricanes and the impacts of their hazards requires the utilization of geospatial thinking skills.

Communication of weather using maps have existed since the early 20th century with published weather charts of the northern hemisphere and the inclusion of weather maps in printed newspapers (Monmonier 1999). There is now instant and continuous access to geospatial weather data through the Internet, mobile devices, and 24-hour-a-day television weather networks, such as The Weather Channel. Indeed, television often becomes the primary source for public weather information during extreme weather events. During Hurricanes Isaac and Sandy in 2012, for example, most United States coastal residents received their information on storm impacts from television (Meyer et al. 2014). More recently, general public interest fueled record viewership of The Weather Channel during Hurricane Irma in 2017, with The Weather Channel posting higher cable/satellite television ratings than CNN, FOX News Channel, or MSNBC during the storm's landfall (FOX66, 2017).

On television, millions of viewers are exposed to the dramatic and extensive media coverage of extreme weather events, such as landfalling hurricanes. Media produced visualizations are geographic in nature, providing viewers with maps of a hurricane's expected track and effects such as wind gusts, storm surge inundation heights, and rainfall potential. The National Hurricane Center issues graphical and textual information on a hurricane every three to six hours that details the storm's position, intensity, and coastal hazards, with more frequent updates as a hurricane nears the coast. However, despite the abundance of available information, Meyer et al. (2014) found that U.S. coastal residents impacted by Hurricanes Isaac and Sandy overestimated the threat from the hurricanes' strongest winds and underestimated the threat from storm surge flooding. Misconceptions may arise not because there is not enough information, but rather because hurricane hazard information should be interpreted by in a geospatial context.

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This interpretation of hurricane hazard information is necessary because there is strong geographic variability in the wind and storm surge impacts along the path of a hurricane. For example, Hurricane Michael in 2018 made landfall as a Category 5 hurricane with sustained winds near 260 kilometers per hour (Beven, Berg, and Haven 2019). The eye of Michael passed between Panama City, FL, and Mexico Beach, FL, which are only about 30 kilometers apart, as it made landfall. The damage from wind and storm surge at Mexico Beach was much more severe than in the Panama City area, with the severity of the hazards changing rapidly over a relatively short geographic distance. (Beven, Berg, and Haven 2019).

This variability is influenced by a hurricane's wind radii, its distance from the coast, and its angle of approach to the coast. At a specific location, a hurricane's impact is influenced by the location's distance from the hurricane's center, its position relative to the hurricane's center, its distance from the immediate coast, and the surrounding terrain. In the case of Hurricane Michael, the center passed about 25 kilometers closer to Mexico Beach, FL, than Panama City, FL. Additionally, were was 4.48 meters of storm surge inundation at Mexico Beach on the east side of the storm, compared to only 1.62 meters of storm surge inundation at Panama City Beach on the west side of the storm (Beven, Berg, and Haven 2019). Thus, the impacts experienced at a particular location during a hurricane may be significantly different than a location just a few kilometers away. Because of the spatial gradients in meteorological variables of hurricanes and the resulting significant impacts and damage, hurricanes are therefore a particularly useful phenomena for educators seeking to develop their students' geospatial thinking skills. With hurricane related data readily available and easily displayed using Web GIS, educators have an exciting opportunity to incorporate geography lessons that focus on hurricane hazards.

Using hurricanes and GIS to develop spatial literacy

Formal secondary education on hurricanes can make use of maps, charts, diagrams, images, conceptual models, and simulations to aid in the visualization of the storm and its hazards. But because the concepts of hurricane development, intensity, tracks, and resulting wind and storm surge hazards are also inherently spatial in nature, they require utilization of geospatial thinking skills for proper understanding. GIS is one tool that educators can incorporate into lesson activities that can promote the development of geospatial thinking skills.

A mapping and spatial analysis tool such GIS assists the user in data collection, the visualization of the spatial relationships and patterns in that data, and promotes a better understanding of those relationships and patterns. (Baker et al. 2015). As such, GIS serves a wide spectrum of purposes, including utilization in educational, civilian, and military settings. Fleming et al. (2009) demonstrated how the United States Marine Corps used GIS to model sea level and shorelines, make vehicle mobility assessments, and provide aerial perspective scenes of areas of potential military operations. For urban planning, Stevens, Dragicevic, and Rothley (2007) used a desktop version of GIS to develop an urban tool that allowed the user to model land use changes and visualize their future neighborhoods using high-density, medium-density, and low-density residential and commercial development scenarios. In hazards geography, Mitchell, Borden, and Schmidtlein (2008) integrated GIS into a lesson on Hurricane Katrina in which students not only used GIS to analyze storm surge data from the National Hurricane Center's SLOSH model, but also used GIS to explore the social vulnerabilities from the perspective of age and poverty posed by the hurricane. With GIS, students were able to use to uncover relationships between different groups of people and hazardous locations that otherwise were not readily apparent (Mitchell, Borden, and Schmidtlein 2008).

Compared to paper maps, computer-supported GIS offers students a technology enhanced learning experience in which multiple data sets can be manipulated and visualized. Web-based GIS, or simply, Web GIS, differs from desktop GIS in that users access a suite of mapping tools through a Web browser. With desktop versions of GIS, users need to not only invest in potentially costly software, but also develop a significant level of expertise to navigate its complexities, and, as such, is more appropriate for industrial use (Bodzin, Anastasio, and Sahagian, 2015). Compared to desktop GIS, Web GIS requires less user skill, is more readily accessible, but still maintains many of the features of the desktop version (Reed and Bodzin forthcoming). In the classroom, the use of Web GIS is beneficial to both teacher and student. The training of teachers on using GIS becomes simpler and less time consuming, while students navigate a simpler interface with computational and mapping abilities that are more than sufficient for the types of activities and levels of analyses required in the classroom (Baker, 2005). Thus, teachers and students can focus on learning with GIS, as opposed to learning about GIS, which is more appropriate for learning in the K-12 classroom (Baker et al. 2015).

Web GIS use can promote the development of the spatial concepts of pattern recognition, spatial description, visualization, spatial concept use, and spatial tool use, collectively referred to as spatial habits of mind (Kim and Bednarz 2013). In the context of hurricanes, Web GIS allows students to develop these spatial concepts as they dynamically map and overlay multiple layers of relevant data, such as the track of the hurricane, surface observations along that track, and modeled storm surge inundation heights. For example, students can use the zoom feature of Web GIS to examine modeled storm surge inundation heights for a specific coastal county and overlay reported tidal observations from that county to make comparisons. Then students can quickly navigate to adjacent areas to analyze the same data while drawing conclusions about the geographic differences in the values of these observations.

There is ample data in the literature to not only support this notion that the incorporation of GIS into the geography can improve spatial literacy, but also that the use of GIS can improve content knowledge. In a study of eighth grade science students, Bodzin et al. (2015) found that the integration of Web GIS activities into the Earth science curriculum improved students' geospatial reasoning skills as well as their subject knowledge of plate tectonics. In a quasi-experiment involving third grade geography, Favier and van der Schee (2014) compared students in which GIS was part of the geography lesson to students in which the lesson used a traditional textbook without GIS. The students using GIS showed significant improvement on a geospatial thinking test whereas the traditionally taught students showed no significant improvement. In a study of middle school students, Goldstein and Alibrandi (2013) found that nonwhite students taking an elective GIS class or a social studies class which incorporated GIS into the curriculum achieved significantly higher scores in science and reading than students no receiving GIS instruction. Additionally, Kim and Bednarz (2013) examined higher education students' self-assessment of their spatial reasoning abilities. They found that students taking an introductory GIS course and exposed to spatial concepts and analyses showed a significant increase in their self-assessment of their spatial reasoning abilities. In contrast, despite a semester long course in geography, higher education students not exposed to GIS showed no significant change in their spatial reasoning abilities (Kim and Bednarz 2013). However, Marsh, Golledge, and Battersby (2007) caution that effective use of GIS requires strong foundational knowledge of the concepts of the subject matter on which GIS performs its analyses. Only then can GIS be used effectively for teaching, learning, and analyzing problems in a geospatial context.

Technology and collaborative inquiry as an instructional framework

The instructional approach for this study was designed utilizing technology, scientific inquiry, and student collaboration. The theoretical framework for instruction that fuses inquiry and collaboration is termed collaborative inquiry. Collaborative inquiry originates from the increasing practice of using inquiry as the method of science education as well as computer-supported collaboration (Bell et al. 2010). Through collaboration, learning occurs through the interactions with others, rather than as a solitary activity (Prince 2004). Meanwhile, through the inquiry process, students not only acquire knowledge, but also develop a deep understanding of scientific principles, concepts and theories (National Research Council 2000). The inquiry process teaches students to combine concepts and ideas which can later be applied outside the classroom (Linn et al. 2006). The National Research Council (2000) suggests that instructors provide some structure to students less experienced in inquiry-oriented tasks. Effective instruction using guided inquiry enables the instructor to interact with students, with the instructor providing investigative questions while the students develop their own data collection methods and interpretations of results (Blanchard et al. 2010).

Numerous researchers have investigated knowledge acquisition in the context of inquiry, collaboration, and technology-enhanced learning. Among middle school students, for example, Jaakkola and Nurmi (2008) and Jaakkola, Nurmi, and Veermans (2011) found that the integration of technology with inquiry and collaboration was effective in knowledge acquisition. With technology, the addition of visualization and simulation experiences with complex scientific phenomena can bolster students' opportunity for success and understanding (Casperson and Linn 2006; Dede 2000). Compared to text or traditional lecture, visualizations generally offer more details and more opportunities for student interactivity (Varma and Linn 2012). Among high school students, Yildirim, Ozden, and Aksu (2001) found students exposed to the hypermedia environment of Web-based text, graphics, motion pictures, still pictures, sound, and video scored better than students denied this exposure on the measure of knowledge acquisition. A study conducted by Lee et al. (2010) found that inquiry activities that are well designed and enhanced with technologies such as interactive visualizations and collaborative online discussions are more effective than traditional instruction.

Additional research has shown that students benefit from collaboration when technology enhanced inquiry is used as the instructional method. Okada and Simon (1997) found that students working in pairs on a computer-enhanced inquiry project posted higher test scores, participated in more explanatory activities, entertained more hypotheses, and considered justification more so than students working alone. Similarly, Gijlers and de Jong (2009) found improvements in students' test scores resulting from technology supported collaborative inquiry. Thus, the literature supports that technology can bolster collaboration while also enabling the learner to address real-world problems using high-tech tools (Dede 2000).

Research focus and questions

The focus of this study was to examine the effects of instruction utilizing extensive geographical visualizations of numerical data with Web-based GIS. While there is strong support for the use of GIS as part of instruction, two knowledge gaps in the literature identified by Baker et al. (2015) include the evolution of students' geospatial skills as well as instructional practices that use geospatial technologies such as GIS. This study addresses both of these gaps by assessing students' spatial thinking skills before and after using a Web-based GIS module on hurricanes. For this study, students worked in small groups to engage in scientific inquiry to complete a Web-based GIS module on hurricanes that relies on the geographic representation of a hurricane's track, wind speeds, wind radii, and storm surge data. Students' geospatial skills were examined within a framework that specifically examines the spatial skills of pattern recognition, spatial description, visualization, spatial concept use, and spatial tool use (Kim and Bednarz 2013). The instruction integrated Web-based GIS and other technology tools such as video, simulations, and pictures into the module using a collaborative inquiry approach to learning. Thus, this study directly addresses both of the knowledge gaps identified by Baker et al. (2015).

The primary goal of this study is to provide insight into how 11th and 12th grade students' existing knowledge about hurricanes changes after learning with a Web-based GIS collaborative inquiry module. The secondary goal was to assess students' spatial habits of mind both before and after the Web-based GIS module. Specifically, this study addressed the following questions:

1. How do 11th and 12th grade AP environmental science students' understandings about the geographic nature of hurricane structure, spatial scale, climatology, and coastal impacts change after the completion of a collaborative Web-based GIS inquiry module on hurricanes?
2. What effect does the use of a Web-based GIS module have on 11th and 12th grade AP environmental science students' perceived spatial habits of mind?
3. What are student perceptions of their experience using a Web-based GIS module on hurricanes?

Method

Participants and setting

This study was conducted at a suburban public high school in northeast United States. The participants were a convenience sample of 11th and 12th grade students enrolled in an AP Environmental Science class. The AP Environmental Science class consisted of two sections taught by the same instructor, with 25 students in one section and 22 in the other. The instructor reported that all students had at least some previous experience with Web-based GIS in this class. Study participants ranged in age from 16 to 18 years, with 36 female and 11 male participants. Parental consent and student assent were obtained for students under age 18, while student consent was obtained for students aged 18.

Curriculum design and implementation

A Web-based GIS module on hurricanes was created for this study by experts in tropical meteorology and instructional design using the backwards design approach of Wiggins and McTighe (2005), with content developed and scaffolded within a geospatial context. Students used Web-based ArcGIS to access GIS data of the location, wind, barometric pressure, and storm surge of Hurricane Irma from 2017 to achieve three learning goals. Using empirical data collected during Hurricane Irma and analyzed using GIS, students were expected to accurately describe (a) the relationship between a hurricane's barometric pressure and sustained wind speeds, (b) the effect of land interaction on hurricane intensity, and (c) the difference between modeled storm surge inundation heights and verified inundation heights. The Web-based GIS module was designed to challenge the AP environmental students, and as such would also be appropriate as part of a college level general education meteorology course.

Hurricane Irma was chosen to be the focus of the Web-based GIS activity for several reasons. Hurricane Irma was one of the strongest and costliest Atlantic Ocean hurricanes on record, making landfall seven times across the islands of the Caribbean and United States (Cangialosi, Latto, and Berg 2018). Because the catastrophic hurricane affected so many land areas, there was a high density of meteorological observations taken along its path. This provides the opportunity for students to investigate the structure and effects of the hurricane using actual surface weather observations in addition to conceptual models. Additionally, because the hurricane made landfall in the United States, this study was able to make use of the National Hurricane Center's Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model. The SLOSH model depicts potential storm surge inundation heights, which students could then compare to the actual reported storm surge inundation heights. Web-based GIS is an ideal tool for the display and analysis of hurricane and storm data, given their geospatial nature.

The hurricane lesson material was organized on a website that students accessed through their school-provided laptops. The website consisted of six pages: Home, Introduction, Tracking Hurricanes, Wind, Storm Surge, and More on Storm Surge, and each page was accessed through a hyperlink displayed on a banner that was consistent across each page. Additionally, a live Twitter feed from the National Hurricane Center (@NHC_Atlantic) was displayed on the right-hand side of the page. The introductory material used 1989 data from Hurricane Hugo as a case study on storm surge and the Home page displayed alternating images of satellite images and newspaper headline from Hurricane Hugo to gain learners' attention to this authentic event. Hurricane Hugo was chosen as the case study due to its Category 4 intensity at landfall, high storm surge, and abundant satellite, radar, and surface data available for analysis.

The Introduction page provided basic information on hurricanes and storm surge, along with an instructional video that described hurricane development, life cycle, the Saffir-Simpson scale, storm surge, and landfall impacts. The Tracking Hurricanes page prompted students to access the global tropical cyclone data base through a Web GIS and to display historical hurricane tracks for a year of their choice. The learning materials also discussed the use of satellite images, radar, and aircraft reconnaissance to monitor the storms. The Wind page presented wind observations and an anemometer trace from Hurricane Hugo and prompted students to answer several questions based on the data. For example, the anemometer trace from Charleston, South Carolina during Hurricane Hugo showed winds dropping from near 80 knots to near 10 knots then increasing again to over 70 knots over the course of an hour. Students were asked to determine if the eye moved overhead and, if so, when. The Storm Surge page examined storm surge in more detail through diagrams, animations, and Weather Channel produced videos. The More on Storm Surge page introduced students to storm surge modeling using Storm, Lake, and Overland Surges from Hurricanes (SLOSH), and prompted students to examine the SLOSH model output from

Hurricane Hugo's landfall in South Carolina. The instructor led the students through material on each page of the website, allowing time for the completion of the instructional activities. The instructor also led a discussion based on the questions students had from the Website content. After completion of the More on Storm Surge page, students then accessed material that focused on a storm surge activity.

The second part of the module introduced students to Hurricane Irma, explained the SLOSH model used by the National Hurricane Center to forecast storm surge in more detail, and directed students to Web GIS to complete five instructional tasks. The Web GIS used in this study was preloaded with extensive data on Hurricane Irma. This included (a) data layers from each advisory listed issued by the National Hurricane Center which included coordinates in latitude and longitude, maximum wind speed, barometric pressure, and radius of hurricane and tropical storm force winds; (b) surface observations of maximum wind gusts and storm surge values for reporting stations across the southeastern United States; and (c) SLOSH model output for the United States for each Saffir-Simpson Hurricane Category. Students were provided detailed instructions on how to display the different data layers, and these instructions guided students through the module.

The module was designed to encompass four 43-minute class periods. The instructor spent one class period presenting the hurricane material, prompting the class with prewritten questions embedded in the lesson, and introducing students to the Web-based GIS module. Students spent the remaining three class periods working through five Web-based GIS learning tasks. Classroom observations were conducted to evaluate the instructor's fidelity of implementation and monitor student engagement in the learning module.

In the module, students worked collaboratively with one or two partners. Teams were challenged to determine the accuracy of SLOSH model predictions through comparison of geospatial data of SLOSH model output to storm surge observations from Hurricane Irma using Web-based GIS. Teams were also tasked with using geospatial data in Web-based GIS to (a) determine the Hurricane Irma's maximum intensity and deduce the pressure-wind relationship found in hurricanes; (b) determine Hurricane Irma's intensity at the storm's two landfall locations in Florida and the resulting effects of land interaction on storm intensity; and (c) compare maximum wind speeds measured across Florida during the storm to wind speeds expected from the structure of the storm's wind radii. Teams had two additional tasks directly related to Hurricane Irma's storm surge. First, using data provided in Google sheets, teams constructed a graph of the storm tide measured at the Caribbean Island of Barbuda as Hurricane Irma passed over the island.

In the second more extensive task, teams were tasked with evaluating the performance of SLOSH model predicted storm surge inundation heights near Hurricane Irma's two landfall locations in Florida. Students first imported two Google sheets into a Web GIS that contained tidal data from eleven locations across Florida and the Caribbean. One Google sheet contained data of reported storm *surge* values, while the second Google sheet contained data of reported storm *tide* values, which included the contribution of both storm surge and the astronomical tide to actual water levels. For each data set, students then created two new layers in Web GIS, with colored circles of various sizes depicting the height of the storm surge and storm tide levels at each station.

Students then needed to evaluate the performance of the SLOSH model at Key West and Naples, Florida. To compare SLOSH model predictions to actual reported values, students needed to create two maps, each with three layers. For each map, one layer was the best track data for Irma to determine landfall location and intensity (Category 4 for the Florida Keys and Category 3 for the southwest coast of Florida) and the second layer SLOSH model output for the appropriate landfall category for each location. The third layer was storm surge values for one map (Figure 1) and storm tide values for the second map. Students then needed to discuss any differences between predicted SLOSH values and actual reported values of storm surge and storm tide. Answers to each part of the module using Google Docs which were submitted electronically to the instructor.

Instrumentation and data collection

Data was collected using two quantitative assessments and one qualitative measure. One quantitative assessment measure was designed to evaluate students' knowledge of hurricanes and the geographic nature of their structure, spatial scale, climatology, and coastal impacts. Specifically, 25 out of the 30 items referenced geographic maps and images. The second quantitative assessment measured students' perceived spatial skills, using the 28 items from the Spatial Habits of Mind Inventory (SHOM) self-assessment (Kim and Bednarz 2013). Each of these measures was completed by students both before starting the module and immediately after its completion. The qualitative measure was designed to gather feedback from the students on their Web-based learning experience and was administered after they completed the module.

SHOM self-assessment

Prior to the start of the lesson, students completed the SHOM assessment. Because the SHOM measures students' self-assessed spatial skills, a baseline of students' perceived spatial literacy was established. The SHOM includes five subdimensions with each focusing on a particular spatial habit of mind: pattern recognition, spatial description, visualization, spatial concept use, and spatial tool use. The reliability of SHOM was Cronbach's alpha $= 0.93$, with subdimensions ranging from $\alpha = 0.68\text{-}0.82$ (Kim and Bednarz 2013). While Kim and Bednarz originally developed the SHOM for students learning about GIS, the instrument has also been applied to an educational setting where students learn with GIS. In public health education, for example, Reed and Bodzin (forthcoming) used the SHOM to show that the use of Web-based GIS significantly improved students' spatial abilities overall, as well as in the

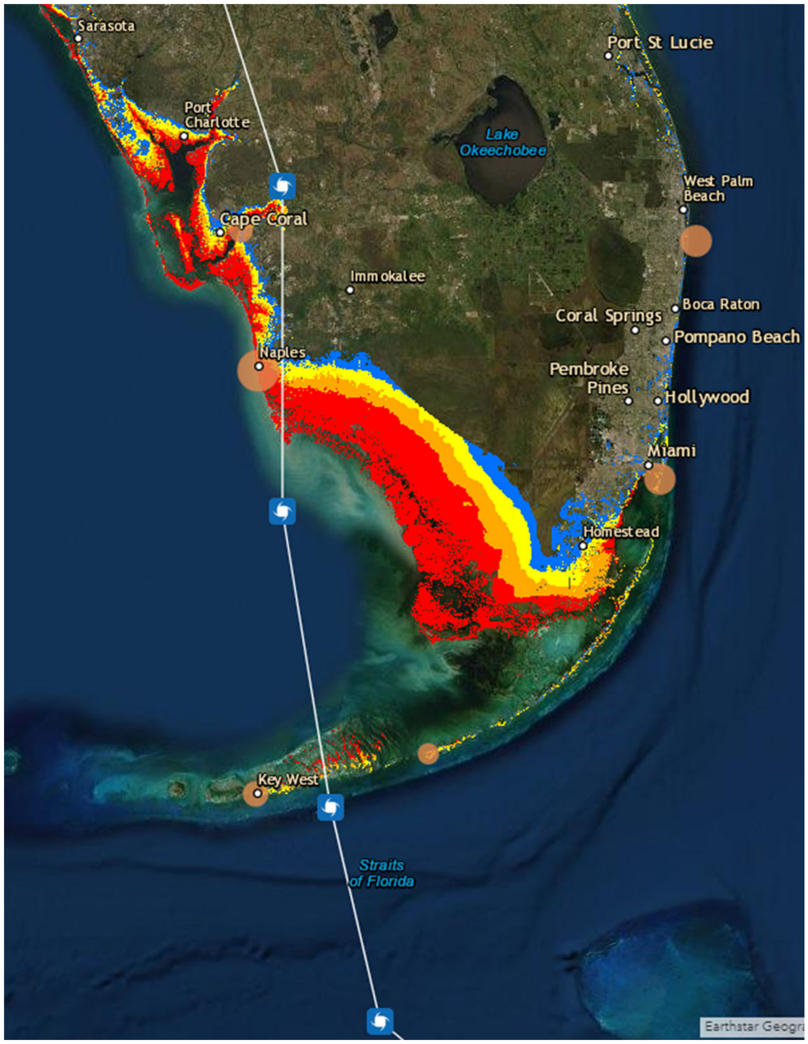

Figure 1. Web GIS map of south Florida displaying three layers of data: SLOSH model output, Hurricane Irma storm track, and reported storm surge values. Circle sizes correspond to the height of the storm surge.

subdimensions of pattern recognition and spatial description. Thus, the SHOM was an appropriate choice to measure changes in students' spatial literacy resulting from the hurricane lesson and Web-based GIS module.

The SHOM was distributed and completed outside of class and collected prior to the start of the hurricane lesson. Students manually filled in their self-assessment on the questionnaire form, which provided a Likert scale for their responses. When scoring the SHOM, five points were assigned to responses indicating "strongly agree", and one point for responses indicating "strongly disagree". Questionnaire items that were negatively worded were reversed scored and the total possible scores ranged from 28 to 140 points. All 47 students completed the SHOM at the end of the module.

Hurricane knowledge assessment

Students also completed the 30-item multiple choice hurricane knowledge assessment measure outside of class and returned the assessment to the instructor prior to the start of the module. Content validity was established by two reviewers: a professor of atmospheric science and an expert in GIS curriculum development. One point was assigned for each correct answer, for a maximum possible score of 30 points. Twenty-five of the 30 knowledge assessment items were specifically designed to make use of geographic maps and images with alignment to one or more of the SHOM subdimensions - pattern recognition, spatial description, visualization, spatial concept use, and spatial tool use. The assessment items were aligned to the content and activities of the hurricanes curriculum module instead of relying on assessment items that may be unrelated to the hurricane concepts or generic spatial thinking skills. Alignment between curriculum and assessment strengthens interpretation of learning results from the curriculum by increasing the sensitivity of the outcome measures (Lee et al. 2010). As such, students needed to apply spatial habits of mind to answer these 25 items. A sample of assessment items are found in Appendix A. All 47 students completed this same assessment after completing the module.

Open-ended assessment

Finally, after submitting the two post-test assessments, students were asked to complete the open-ended survey to

Table 1 Results of the hurricane knowledge assessment analyzed with questions aligned to SHOM subdimension.

SHOM Subdimension	Items	pretest *M* (*SD*) Raw Score	Post-test *M* (*SD*) Raw Score	*p*-value	Effect size
All items	1–30	13.66 (3.96)	15.17 (4.15)	0.012*	0.372
Geospatial Items Only	1–25	10.91 (3.28)	12.32 (3.09)	0.004*	0.443
Non-Geospatial Items	26–30	2.74 (1.18)	2.85 (1.46)	0.649	0.083
Pattern Recognition	5, 6, 7, 8, 9, 10, 11, 13	2.72 (1.54)	3.29 (1.55)	0.045*	0.375
Spatial Description	1, 2, 3, 4, 8, 9, 10, 11, 22	5.43 (1.73)	6.09 (1.67)	0.022*	0.389
Visualization	1, 2, 3, 4, 20, 21, 23, 24, 25	5.06 (1.72)	5.80 (1.47)	0.007*	0.469
Spatial Concept Use	5, 6, 7, 12, 14, 22, 23, 24, 25	3.17 (1.48)	3.51 (1.40)	0.139	0.237
Spatial Tool Use	15, 16, 17, 18, 19, 23, 24, 25	2.66 (1.49)	2.96 (1.37)	0.168	0.209

Notes: *significant at the $p < 0.05$ level. Effect size: $d = \frac{M_2 - M_1}{\sqrt{\frac{\sigma_1{}^2 + \sigma_2{}^2}{2}}}$.

provide feedback on their Web-based GIS learning experience. Students were asked to the respond to the following four questions:

1. How was your Web-based learning experience about hurricanes different than other science learning experiences you have previously had?
2. What was the best part of this experience?
3. What was the most frustrating part of this experience?
4. How did the lesson on hurricanes affect your motivation to learn about other weather systems, such as thunderstorms, tornadoes, and winter storms?

A total of 38 students provided written responses to the survey which were subsequently collected by the instructor.

Results

Classroom observations were conducted by the researchers to evaluate the instructor's fidelity of implementation and monitor student engagement in the learning module. The instructor was the regular instructor for the AP environmental science class but was teaching this material for the first time. Although not a content knowledge expert in meteorology, the instructor adhered to all aspects of the instructional sequence, working through the learning materials during the single class period allotted to that part of the module. The instructor prompted students to individually watch the videos included in the lesson and to complete the embedded mini-activities in the lesson. This included the generation of a GIS map of hurricane tracks for a year of the students' choice. The classroom observations noted that students were engaged with the instruction materials, watched the videos using headphones for the audio so as not to interfere with other students, and generated the GIS hurricane track maps as assigned. As the module progressed to the Web-based GIS activity on Hurricane Irma, students were observed to collaborate not only with their lab partner, but also with other teams, particularly when using GIS. Additionally, the instructor provided guidance to students who had questions about the concepts and procedures of the Hurricane Irma activity.

All data from the two quantitative assessments was analyzed using SPSS. A paired-sample t-test was used to compare the pretest and post-test means for the overall SHOM score as well as the score in each of the five SHOM subdimensions of pattern recognition, spatial description, visualization, spatial concept use, and spatial tool use. A paired-sample t-test was also used to compare the pretest and post-test means of the hurricane knowledge assessment. A paired-sample t-test was then used to compare pretest and post-test means for each group of questions from the knowledge assessment that align to each of the five SHOM subdimensions.

Table 2. Results of the SHOM questionnaire.

SHOM Subdimension	pretest *M* (*SD*) Raw score	Post-test *M* (*SD*) Raw score	*p*-value	Effect size
All items	94.89 (12.70)	94.77 (12.40)	0.917	−0.009
Pattern recognition	20.23 (3.50)	20.36 (3.82)	0.730	0.035
Spatial description	16.51 (3.35)	16.34 (3.42)	0.648	−0.050
Visualization	27.85 (4.54)	27.68 (4.67)	0.757	−0.037
Spatial concept use	13.42 (2.78)	13.21 (2.25)	0.542	−0.083
Spatial tool use	16.87 (3.49)	17.17 (3.06)	0.490	0.091

Notes: *significant at the $p < 0.05$ level. Effect size: $d = \frac{M_2 - M_1}{\sqrt{\frac{\sigma_1{}^2 + \sigma_2{}^2}{2}}}$.

The results showed that there was a statistically significant gain in student knowledge about the geographic nature of hurricane structure, spatial scale, climatology, and coastal impacts. These results are summarized in Table 1. On the 30 item hurricane knowledge assessment, the 47 students had an average increase in the number of questions answered correctly from pretest to post-test of $M = +1.51$ ($SD = 3.95$), $t(46) = 2.62$, $p = 0.012$, $d = 0.38$. However, the significant gain in student knowledge occurred almost exclusively from the 25 assessment items that required students to apply spatial thinking to determine an answer. For the 25 assessment items specifically designed to make use of geographic maps and images, students had an average increase in the number of questions answered correctly from pretest to post-test of $M = +1.40$ ($SD = 3.17$), $t(46) = 3.03$, $p = 0.004$, $d = 0.44$. Furthermore, students demonstrated significant knowledge gains from pretest to post-test on the hurricane knowledge assessment items specifically aligned to the SHOM subdimensions of pattern recognition, spatial description, and visualization. On the five non-geospatial questions, there was no significant difference in the number of questions answered correctly from pretest to post-test ($M = +0.11$ ($SD = 1.59$), $t(46) = 0.46$, $p = 0.649$, $d = 0.08$).

Analysis of the SHOM questionnaire responses indicated no significant changes in students' overall self-evaluation of their spatial thinking skills. There were also no significant changes in students' self-evaluation of their spatial thinking

Table 3. Cronbach's α for the pretest and post-test administrations of the SHOM assessment, overall and by subdimension.

SHOM Subdimension	Cronbach's α Pre-test	Cronbach's α Post-test
Overall	0.869	0.870
Pattern recognition	0.687	0.750
Spatial description	0.732	0.789
Visualization	0.739	0.772
Spatial concept use	0.769	0.548
Spatial tool use	0.657	0.676

skills for each SHOM subdimension. The results for each SHOM subdimension are shown in Table 2. Additionally, Cronbach's alpha was calculated for the overall SHOM assessment as well as for the five subdimensions, for the pretest assessment and post-test assessment (Table 3). The overall reliability for the SHOM assessment for the pretest was $\alpha = 0.869$ and $\alpha = 0.87$ for the post-test. Reliability scores for the SHOM subdimensions ranged from $\alpha = 0.657$ to $\alpha = 0.769$ for the pretest and $\alpha = 0.548$ to $\alpha = 0.789$ in the post-test. While several reliability scores for the SHOM subdimensions fell below the standard reliability threshold of $\alpha = 0.7$, all of the SHOM subdimensions only contained between four and eight items. The reliability scores found in this study are similar to those found elsewhere when the number of items available for analysis is small (Kim and Bednarz 2013; Nori and Giusberti 2006).

Student feedback from the open-ended survey provided several insights into their Web-based GIS experiences. Each of the four questions from the open-ended student survey was analyzed independently. The researchers read through each line of the responses to identify the emergent themes for each question. Responses were not more than a sentence or two and many responses to the same questions used similar or identical language. Individual responses were then grouped by theme for each question and tallied.

Students indicated that this learning experience was different than other science learning experiences in that it was online (23.4%), highly visual (10.6%), and involved in-depth hurricane knowledge (14.9%). However, a significant number of responses also indicated that the experience was more complicated and frustrating (31.9%) than other science learning experiences. Students indicated that they enjoyed the visualizations and use of technology (17.0%) and learning about hurricanes (44.7%). Multiple students (12.8%) also reported that collaborating with a partner during the module was the best part of the experience.

Despite indicating that they enjoyed using technology in this module, students also expressed a great deal of frustration with its heavy use. Multiple students indicated they did not like having to record all their answers electronically as opposed to using paper and pencil ($n = 6$) and having to switch tabs and access multiple weblinks to gather information ($n = 15$). Overall, despite its complexity, students reported that the learning experience had a neutral effect on their motivation to learn more about other destructive weather systems. A summary of student responses is listed in Table 4.

Table 4. Summary of student responses to the open-ended survey.

Question number	Response summary		Number of responses
How experience was different	a.	Complicated/Frustrating	a. 15
	b.	Online	b. 11
	c.	In-depth hurricane knowledge	c. 7
	d.	Highly visual	d. 5
Best part of experience	a.	Learning about hurricanes	a. 21
	b.	Visualization and technology	b. 8
	c.	Collaboration	c. 6
Most frustrating	a.	Use of technology	a. 21
	b.	Directions	b. 12
	c.	Everything	c. 4
Motivation to learn more	a.	Neutral	a. 28
	b.	Positive	b. 6
	c.	Negative	c. 2

Discussion

This study provided mixed results as students showed significant knowledge gains but no significant changes in spatial literacy. On the hurricane knowledge post-test, students made significant gains with geospatially oriented questions and specifically within the sub-groups of questions aligned to the pattern recognition, spatial descriptions, and visualization spatial habits of mind. However, despite these increases, there were no significant changes in students' overall SHOM scores nor within each of the SHOM subdimensions. Additionally, while overall hurricane knowledge test scores improved significantly from 13.7 to 15.2 points, post-test scores remained below the expectations of the researchers and class instructor and well below the maximum possible score of 30 points.

One of the possible reasons for the less than expected increase in post-test scores was the amount of time the learning unit devoted to content. The learning unit spanned four class periods, yet only one of those class periods was devoted to content knowledge. Scores on the knowledge pretest indicated poor prior knowledge of hurricanes, which was expected. With a low baseline test score, however, spending only 25% of the time on content, especially given its level of rigor, was clearly insufficient for students to develop deep understanding of the material. Indeed, survey responses indicated that students found that this module was more in-depth and more difficult than their previous science learning experiences.

The rigor of the module likely led to the expression of frustration and difficulty in the survey responses. While students were given extremely detailed instructions on how to navigate through GIS, a summary of student responses indicated that students still found some of the tasks daunting and confusing. While the instructor reported that students had prior exposure to GIS in their environmental science class, students indicated frustration with the extensive use of GIS. Despite this frustration, however, all lab groups did complete the module in the allotted time. Classroom observations also indicated that students were engaged in the module and collaborated extensively with their peers. Additionally, survey responses indicated that students enjoyed the topic and the collaboration with their partners. The collaborative effort likely made this module more "doable" than if students had worked independently alone, given its complexity.

Because the module made extensive use of GIS features that were new to the students, such as importing raw data files to create new layers, GIS likely became an impediment to more significant learning and spatial literacy development. Marsh, Golledge, and Battersby (2007) contend that the use of complex software, such as GIS, can often result in students focusing on learning the software at the expense of the spatial analysis concepts and procedures that GIS performs and displays. Based on observations in this study, the collaborative effort in the classroom focused more on navigating the intricacies and challenges of using unfamiliar GIS tools than the interpretation of the data it analyzes and displays. A future iteration of this module would curtail some of the GIS activities, particularly the mining of large data sets, in favor of more time spent on fundamental content knowledge.

Additionally, complex Web-based GIS activities were combined with multimedia instruction that made extensive use of videos, animations, pictures, charts, and schematics. Considering the cognitive multimedia learning theory of Mayer and Moreno (2002), the intensive Web-based multimedia and GIS module may have caused a visual cognitive overload. While Mayer (2003) maintained that instruction using visuals that are too complex or excessive may impede learning, the effects of cognitive overload on the development of spatial literacy is unknown and an area for future research. Nonetheless, instructional designers should be mindful of cognitive overload when incorporating highly visual elements, including GIS, into classroom instruction.

The lack of improvement in SHOM scores likely stems from the short implementation period over the module, which was completed over the course of three school days. Favier and van der Schee (2014) contend that geospatial thinking skills take time to develop. Based on their results from a three-day GIS lesson in geography, three days is insufficient to expect substantial changes, and data from this study supports that notion. Additionally, in a five-day implementation study, while Reed and Bodzin (forthcoming) did find significant increases in overall SHOM scores, those significant improvements occurred in only two of the five SHOM subdimensions.

However, when the use of Web-based GIS spans an academic semester and is not limited to only a few days clustered together, the results are more promising. Jo, Hong, and Verma (2016) found significant improvements in students' spatial thinking ability when three Web-based GIS activities were incorporated into world geography courses over an academic semester compared to the students that did not use Web-based GIS. Xiang and Liu (2019) also found significant improvements in geospatial thinking ability when Web-based GIS was incorporated into a teacher education program over the course of an academic semester. To test its validity, the SHOM questionnaire itself was also implemented over the course of an academic semester (Kim and Bednarz 2013). Further research is needed to not only examine the temporal component of changes in spatial literacy, but also to determine if spatial literacy shows progression, in which the SHOM subdimensions defined by Kim and Bednarz (2013) develop at different rates.

A starting point for this future research may be rooted in pattern recognition, spatial descriptions, and visualization. In the current study, student ability to correctly answer pattern recognition, spatial description, and visualization questions did show significant improvement in just three days. Similarly, in Reed and Bodzin (forthcoming), students showed significant improvement in the SHOM subdimensions of pattern recognition and spatial description in five days. Enhancing a course for a full, or even half, semester with Web-based GIS activities, then applying the SHOM at regular intervals during the semester, would allow researchers to measure the progression of changes in spatial literacy in each subdimension. Additionally, the development of SHOM subdimension-specific learning modules would also allow instructors to appropriately scaffold content based upon spatial skill development. Both of these ideas support the GIS research agenda described by Baker et al. (2015).

There are several limitations to this study. One is the previously discussed short implementation time for evaluating changes in spatial literacy. Another limitation is that the instructor was not a content knowledge expert in tropical meteorology or GIS. While the instructor was observed to satisfactorily cover the instructional material and activity, it was covered without the rich, content-enhancing details often provided by subject matter experts. Other limitations involve the timing of the implementation of the module. As discussed, the module was implemented over three days. It was originally designed as a four-day implementation, but due to a mandatory school field trip school, the implementation period and hurricane content instruction was shortened by one day. This may have contributed to the lower student content knowledge gains about hurricanes. Additionally, the module was presented near the end of the school year, after students had completed their AP exams and were preparing for the last day of class and, for some, graduation. This may have impeded a deep level of student engagement in the material, especially when preparing for the post-test hurricane knowledge assessment. Finally, for students in the United States, a module on hurricanes is more relevant in September and October, near the peak of the Atlantic Ocean hurricane seasons. Learning modules with significant meteorological content are more pertinent near the times of their climatological occurrence and could impact student interest.

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Authors notes

Part one of the learning module can be accessed at https://hurricanes-tormsurge.wordpress.com/. Part two of the learning module can be accessed at https://hurricaneirmastormsurge.wordpress.com/.

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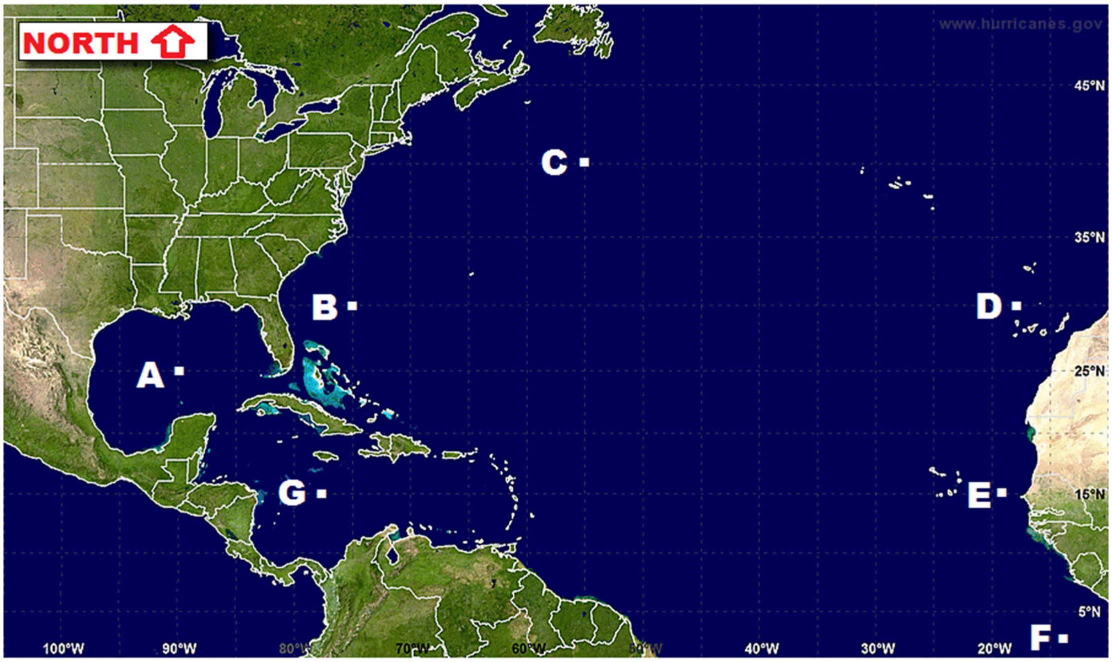

Figure A1.

Appendix A

Sample Knowledge Assessment Items. Correct answer is shown in italics.

Questions 8, 9, 10, and 11 refer to the map: (Figure A1)

8) Hurricanes are least likely to be observed at ____________.

a. Point A
b. Point C
c. *Point F*
d. Point G

9) Which of the following statements is TRUE?

a. *Hurricanes occur with less frequency at Point D than at Point C.*
b. Hurricanes occur with similar frequencies at Point B and Point D.
c. Hurricanes occur with greater frequency at Point E than at Point G.
d. Hurricanes occur with equal frequencies at all points except Point C.

10) If a hurricane was centered at Point G, the system that spawned the hurricane most likely had previously crossed over __________.

a. Point A
b. Point B
c. Point C
d. *Point E*

11) The path of a hurricane is most likely to move from ______________.

a. Point A to Point G
b. Point B to Point E
c. Point D to Point C
d. *Point G to Point A*