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Moving CyberGIS education forward: Knowing what matters and how it is decided

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Abstract

Maintaining educational resources and training materials as timely, current, and aligned with the needs of students, practitioners, and other users of geospatial technologies is a persistent challenge. This is particularly problematic within CyberGIS, a subfield of Geographic Information Science and Technology (GIS&T) that involves high-performance computing and advanced cyberinfrastructure to address computation- and data-intensive problems. In this study, we analyzed and compared content from two open educational resources: (1) a popular online web resource that regularly covers CyberGIS-related topics (GIS Stack Exchange) and (2) existing and proposed content in the GIS&T Body of Knowledge. While current curricula may build a student's conceptual understanding of CyberGIS, there is a noticeable lack of resources for practical implementation of CyberGIS tools. The results highlight discrepancies between the attention and frequency of CyberGIS topics according to a popular online help resource and the CyberGIS academic community.

1 | INTRODUCTION

The past two decades have seen significant development at the intersection of advanced cyberinfrastructure and Geographic Information Science and Systems (GIS) known as CyberGIS. CyberGIS represents an interdisciplinary field combining advanced computing and cyberinfrastructure (CI), GIS, spatial analysis and modeling, and many geospatial application domains (e.g., agriculture, emergency management, public health, and smart cities) to enable broad scientific and technological advances (Padmanabhan et al., 2011; Wang, 2010; Wang et al., 2013; Wang & Goodchild, 2019). Additionally, increasing accessibility to high-performance cloud-based computing systems has further encouraged the development and use of CyberGIS (Bowlick et al., 2018; Li et al., 2020; Liu et al., 2015; Michels, Padmanabhan, Xiao, et al., 2024; Padmanabhan et al., 2011; Shook et al., 2013, 2019; Wang & Goodchild, 2019; Zhang et al., 2018, 2020; Zhang, Zou, et al., 2021) in GIS research and education. CyberGIS has revolutionized previous approaches to geospatial problem solving because it addresses a key limitation of traditional desktop-based GIS environments, that is, limited computational resources that prevent the completion of computationally expensive tasks on large datasets in a timely manner. Advancing CyberGIS technology allows users to utilize advanced data science methods and work with large-scale datasets, broadening the accessibility of such work to users with the appropriate skills (Wang, 2016).

While access to the functionality and capacity of CyberGIS is at an all-time high (Chen et al., 2021), other knowledge and awareness barriers to entry persist, inhibiting a steady growth of competencies around CyberGIS knowledge. Moreover, how CyberGIS fits into the broader context of Geographic Information Science and Technology (GIS&T) has not been consistently documented or accepted (Wan et al., 2021), which has been reflected in other educational publications and training materials (Shook et al., 2021). Without instructional materials or examples of common CyberGIS use cases, achieving CyberGIS competencies is challenging for students as well as professionals in the GIS and computer science domains. What should be included in educational content or curricula for CyberGIS, how should that be decided, and does current content meet the needs of users? By definition, CyberGIS involves advanced cyberinfrastructure and computing workflows that evolve rapidly and require its users to maintain significant technological acumen. Would any single resource be adequate or appropriate as an authoritative source of CyberGIS knowledge and skills? The process of applying knowledge learned in a structured environment into practical problem solving represents a challenge for students within the CyberGIS domain. Despite a foundation of conceptual understanding achieved in learning CyberGIS, it is common for students to seek information and answers from applying learned skills in practice.

In this article, we share the results of evaluating and comparing two different sources of knowledge about CyberGIS within a GIS&T context:

1. a 2014 rating of GIS&T topics being considered at that time for retention in the UCGIS GIS&T Body of Knowledge (GIS&T Bok);
2. a 2022 analysis of content within the GIS Stack Exchange online platform.

Our comparison of these sources will highlight the variability in how CyberGIS has been defined, prioritized, and promoted by educators and learners. This analysis also highlights the diversity in the types and formats of GIS knowledge that is in demand by different audiences of learners. Formal and authoritative collections that cover basic conceptual knowledge are designed with particular objectives in mind, and more informal or crowd-sourced technical solutions meet a different type of demand. A systematic comparison will demonstrate how a blend of inputs may be best suited to address the needs of students formally pursuing a CyberGIS education.

2 | BACKGROUND

The GIS&T BoK, first published only as a hard-copy book in 2006, has long been recognized as a valuable educational resource for the geospatial community (Du et al., 2021; Johnson, 2019; Prager & Plewe, 2009; Sadvari, 2020). Decisions about the nature and extent of the original content were made over the course of several years, and there were several opportunities for input from diverse audiences (Johnson et al., 2006; Waters, 2013). Eventually, the project was completed under the auspices of the University Consortium for Geographic Information Science (UCGIS), led by the then-Chair of the UCGIS Education Committee, David DiBiase, who served as the lead editor. The publication consisted of 329 "topics" considered germane to the domain of GIS&T (e.g., "Proximity & Distance Decay", "Hierarchical Data Models", "Map Projection Properties") as well as multiple learning objectives for each topic (a total of 1660 learning objectives across the 329 topics). The topics were grouped into 10 Knowledge Areas. It was understood that the publication was valuable as a first version and would be revised and updated, though no funded plan existed at the time.

By 2013, UCGIS began to design a path toward shifting the collection to a digital platform, a move that would facilitate updating and expand access, and John Wilson of the University of Southern California agreed to oversee the revision process. The first step was to solicit input through an online survey in which people were asked to rate the 329 original GIS&T BoK topics on their importance for continued inclusion in the collection, from a scale of 1 (high importance) to 5 (low importance), or even 6 (no longer relevant) (Wilson, 2014). They were also asked to suggest or identify additional topics that had either been excluded from the original collection - inadvertently or otherwise - or had emerged over the previous decade. The survey was distributed via list-serves managed by UCGIS and the American Association of Geographers, and thus largely only reached an academic audience. A total of 23 people completed the online survey, and those results were presented during a day-long workshop at the 2014 UCGIS Symposium in Pasadena, California (Wilson, 2014). Approximately 100 academics at this meeting were divided into five discussion groups and used the initial survey results as a starting point to provide further guidance. By the end of the day, several more workshop participants had completed the original survey, bringing the total number of surveyed responses across all 329 individual topics to 3750. All topics across the ten Knowledge Areas were subject to review, but respondents were 3- to 4-times more likely to cast their opinions about topics within the Analytical Methods Knowledge Area than GIS&T and Society, or Organizational & Institutional Aspects. The complete set of final ratings of the 329 topics, as well as detailed notes from the discussion groups, can be found in the appendices of Wilson's final report (Wilson, 2014).

Despite the technological advances infiltrating GIS&T by the 2010s, the concepts, skills, and practices required to utilize CyberGIS were not well defined in Wilson's (2014) report, nor were they appearing consistently in other educational resources or settings (Frazier et al., 2018; Wikle & Fagin, 2014).

In 2018, Bowlick et al. (2018) reviewed the CyberGIS literature to develop a set of 37 key CyberGIS concepts and used the Q-methodology to interview 20 GIS users to identify the components of CyberGIS that these individuals viewed as most applicable to their GIS practice. Based on their responses, Bowlick et al. (2018) categorized expert GIS users into three groups: the spatial analyst, the domain-specific problem solver, and the CyberGIS-enabled computer scientists. Bowlick et al. (2018) pointed out that there were confusing practices and contrasting visions of the nature of CyberGIS among these three groups of GIS users. Therefore, more detailed information about users' perspectives and instructional organization efforts were needed.

There has been little published discussion on effective ways to prepare students (or users) for competency in CyberGIS learning. The 2014 version of GIS&T BoK topic matrix (Wilson, 2014) and the survey results gathered by Bowlick et al. (2018) represent the viewpoints of educators but say little about the challenges that students have faced when implementing CyberGIS and the utility of CyberGIS for various research and education purposes. This is consistent with the recognized gaps between industry and academic practices (Hofer et al., 2020; Johnson, 2019). However, CyberGIS was neither a separate nor central topic of the 2014 UCGIS survey or the conference workshop.

Resources exist that bridge the gaps between foundational, conceptual knowledge, and applied technical practices. A notable example is the Geospatial Technology Competency Model (GTCM) from the United States Department of Labor (GTCM, 2019). The GTCM provides an important touchstone of the contemporary skills used and valued by industry professionals. Based upon industry professionals' responses to a survey developed by the GeoTech Center, the GTCM provides a broad, tier structured model of the skills and competencies required by geospatial professionals (Employment and Training Administration, 2019). Within GTCM's sections of technical content, references are made to the GIS&T BoK Knowledge Areas, providing further resources for learning skills. Updated periodically, the GTCM could serve as an important guide for professionals transitioning from an academic to a commercial environment, though its usage is uncommon in formal university-level curricula (Wikle & Sinton, 2020).

To gain a perspective on the information needs around CyberGIS methods and workflows outside of formal academic resources, we used the GIS Stack Exchange to solicit users' knowledge and opinions. The GIS Stack Exchange platform (https://gis.stackexchange.com/) is part of a large question-and-answer Stack Overflow system that is exclusive to GIS topics. Once a user posts a question and creates a thread, any other registered users may respond with answers. Users are encouraged to ask and answer questions through a system of reputation metrics that enhances interactivity within the platform. Given the wide range of user experience, this platform represents a broad swath of what general GIS users are expressing interest in and want or need to know. The questions tend to be of a technical and applied nature, and responses are likely to appear in a much more rapid manner than in traditional academic settings and resources (Wang et al., 2018). The online discussion, therefore, helps capture contemporary trends within professional and academic GIS.

3 | METHODS

We first identified key CyberGIS topics from the GIS&T BoK and conducted a literature review of the selected topics. After that, we developed a Python program using the Stack Exchange API to filter the discussion threads to collect information about views, votes, and scores for each selected topic. Finally, a summary report was developed to analyze the frequency of threads, the sum of views, votes, and score of each topic and compared to the results with other sources such as the GIS&T BoK. Figure 1 summarizes the project steps.

3.1 | CyberGIS keywords

The 2014 UCGIS BoK report was selected to provide insights from GIS academics and professionals in a conference setting. This survey context offers a unique dataset to compare quantitative rankings by GIS academics with popularity on GIS Stack Exchange. The topics from Wilson's (2014) GIS&T BoK report were used as keywords to filter CyberGIS-related articles on Google Scholar. For instance, the "Point Pattern Analysis" topic is listed under AM5-1 in the 2014 GIS&T BoK report. Additionally, Bowlick et al. (2018) was used to help refine keyword selection for relevant CyberGIS topics. Appendix A shows the filtered CyberGIS articles with topics from the 2014 UCGIS GIS&T BoK report.

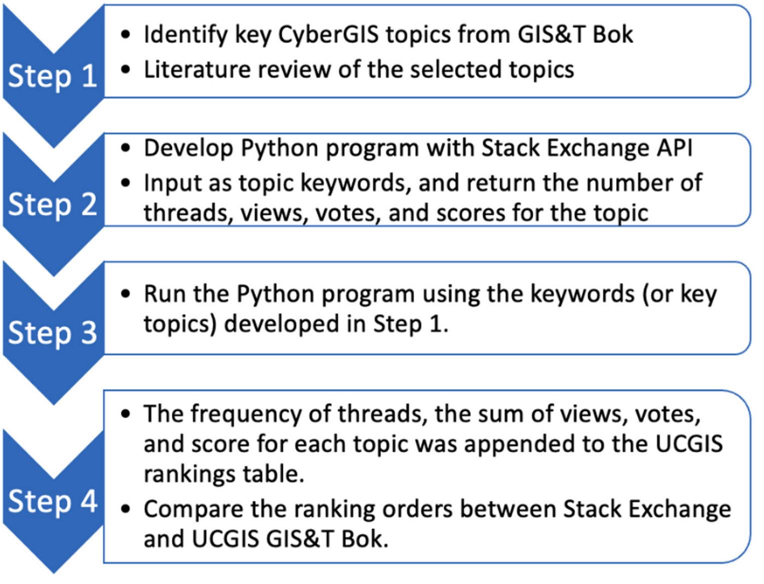

FIGURE 1 Flowchart of study methodology.

3.2 | Comparing the topic list between the GIS&T BoK and stack exchange

Using Google Scholar and Bowlick's work (2018), we first identified CyberGIS literature relevant to the topics listed in the 2014 GIS&T BoK report. Google Scholar aggregates publications from a variety of literature databases, including closed and open journals. After that, we developed a text mining process to analyze the GIS Stack Exchange discussion threads to identify the popularity of the topics based on the keywords identified in the 2014 GIS&T BoK Report and the CyberGIS literature. Finally, we compared the ranking results derived from GIS Stack Overflow with those in the 2014 GIS&T BoK report.

The most popular concepts and keywords found within the reviewed CyberGIS literature guided the choice of the 2014 GIS&T BoK topics to analyze. The eligibility of CyberGIS-related topics for comparison was determined by searching key terms in the "Web of Science" (Clarivate, 2023). The 2014 GIS&T BoK report topics and supporting CyberGIS studies are summarized in Appendix A. A search query for a topic on Stack Exchange yields all discussions (i.e., "threads") containing the search terms. On GIS Stack Exchange, a broad search term, such as "Web Mapping", returns thousands of threads that contain the term. Expectedly, the subjects covered in the discussion within returned threads are diverse, yet all are related through the inclusion of a search term.

Text mining was accomplished with a Python program developed to interface with the Stack Exchange API. The Stack Exchange API can provide information on both users and posts across the Stack Exchange platform. A program was designed to use the capabilities of the API to understand which keywords are being discussed the most (Stack Exchange, 2022). To measure keyword popularity, data from threads were used. In forum nomenclature, a thread is defined as an individual post and its responses. The data from threads determined to be relevant for assessing keyword popularity were the number of views, answers, and the score. The score, as defined in the Stack Exchange, is the number of votes a given thread receives. For example, if a user has the same question as an existing thread, they may up vote the thread, increasing its visibility and likelihood to be answered. Votes are a direct indication of the community's preference or approval of a thread, while scores may aggregate different metrics, including upvotes and downvotes. Together, these data points may then be used to measure the popularity and engagement of a topic on Stack Exchange. Due to request limits and other API limitations, our Stack

Exchange API requests prioritized user engagement data including elements with the greatest weight on the overall popularity index.

We sought to simulate the results a GIS Stack Exchange (GIS SE) user receives when making a search on the website. As such, a two-step API request was necessary. The first step was to pass the topic keyword(s) to the first API query function, *search/excerpts*. The query returns the same results as if the keyword was typed into the website's search bar. This API query, however, only provides a thread's question ID, and does not contain the views, votes, and answers data. The second step was to acquire the data for each of the threads using the question ID. After being checked for duplicates, the question IDs were vectorized, and sent to the API with the *questions/{ids}* query function. The returned data contained the desired data points for analysis of topic popularity in JSON (JavaScript Object Notation) format. The data were then tabulated, and the process was repeated for each topic.

The frequency of threads, sum of views, votes, answers, and score were calculated for each topic and were then assigned ranks in ascending order and appended to a table. Survey respondents in the 2014 GIS&T BoK report were asked to score the importance of a topic on a scale from 1 to 6, 1 being of high importance and 6 being no longer relevant. The average score for each topic was calculated and assigned a rank. The tabulated survey responses were taken from the 2014 GIS&T BoK report and incorporated into the dataset. After completing the table containing the ranks of the three GIS SE fields and the GIS&T BoK report rankings, the data were visualized and compared. Disagreement of topic importance (average difference) was determined by subtracting the GIS&T BoK report rank from the average of the three GIS SE fields. Basic summary statistics were calculated for the average difference field. Following the completion of data acquisition, information had been collected from 3753 Stack Exchange threads with a total of 56,097,767 views. This represents a much larger and likely more diverse audience than the 100+ academics captured by the GIS&T BoK survey (Wilson, 2014).

4 | RESULTS

Recall, CyberGIS was not a central topic of the 2014 UCGIS survey. Its relevance was evident despite few explicit references in the report. Participants pointed out that cyberinfrastructure is a critical piece of GIS education and cannot be ignored or missing in the curriculum. Though not explicitly identified as "CyberGIS", numerous data-intensive GIS approaches, such as agent-based modeling and spatial clustering methods, were noted in the 2014 GIS&T BoK report (Wilson, 2014).

The average ranks of the GIS SE items were subtracted from the UCGIS mean ranks to determine rank distance. A negative average rank difference indicates a prominent UCGIS ranking, and positive values indicate a prominent GIS SE rank. Table 1 displays the ranking of topic popularity based on the mean rankings in the GIS&T BoK report, and the rankings of the GIS SE results according to the fields views, answers, and score as well as the average rank difference (Avg Diff). The AM11-3 (Least-cost path) and GC2-1 (High-performance computing) topics showed the least (zero) differences. The average differences ranged from −13 to 10, with a standard deviation of 5.67. The topic DM5-3 (Modeling three-dimensional (3-D) entities) provided the largest positive rank difference, favoring the 2014 GIS&T BoK report, at −13. The topic GC2-9 (Neural Network Schemes) had the largest negative rank difference, favoring the GIS SE, at 7.

The bar chart reproduced in Figure 2 shows the difference between the 2014 GIS&T BoK and GIS SE mean ranks. When there is no bar displayed, the 2014 GIS&T BoK and GIS SE ranks are equivalent. The differences in ranks between the GIS SE fields were calculated to test the strength of each field against the GIS&T BoK report rankings. There were no discrepancies between the ranking of the GIS SE *view* and *answer* fields. The GIS SE results ordered by *score*, however, varied from the previous ranks. Figure 3 demonstrates the fluctuation between views and score per each thread. Topic AM7-7 (Bayesian Methods) had a *score* rank of 18 with a *view* and *answer* rank of 21 and although the score follows a similar path as views, it trends above views for most threads.

TABLE 1 BoK topic popularity on Stack Exchange (SE) ordered by mean UCGIS survey rank.

Topic ID	Topic	UCGIS mean rank	Views (SE)	Answers (SE)	Score (SE)	Avg diff
CV4-5	Web mapping and visualizations	1	2	2	2	−1
AM5-3	Spatial cluster analysis	2	1	1	1	1
CV4-3	Dynamic and interactive displays	3	10	10	10	−7
AM6-2	Interpolation of surfaces	4	3	3	3	1
DM5-3	Modeling three-dimensional (3-D) entities	5	17	17	20	−13
AM11-3	Least-cost (shortest) path	6	7	7	4	0
CV4-2	Multivariate displays	7	18	18	17	−10.7
AM8-1	Spatial sampling for statistical analysis	8	6	6	6	2
AM5-1	Point pattern analysis	9	5	5	7	3.3
AM5-7	Multi-criteria evaluation	10	15	15	19	−6.3
AM5-2	Kernels and density estimation	11	4	4	5	6.7
DM5-1	Spatiotemporal GIS	13	12	12	8	2.3
DM3-1	Grid representations	13	9	9	13	2.7
CF6-2	Mathematical models of	13	8	8	9	4.7
AM9-2	Spatial autoregressive models	15	19	19	21	−4.7
DM5-2	Modeling uncertainty	16	22	22	15	−3.7
AM10-4	Pattern recognition and	17	14	14	12	3.7
AM5-5	Analyzing multidimensional attribute	18	13	13	11	5.7
AM7-7	Bayesian methods	19	21	21	18	−1
GC5-2	Genetic algorithms and artificial genomes	20	23	23	22	−2.7
GC2-1	High-performance computing	21	20	20	23	0
GC2-9	Neural network schemes	22	11	11	14	10
GC4-1	Greedy heuristics	23	16	16	16	7

5 | DISCUSSION AND CONCLUSION

The results indicate a moderate rate of disagreement between the popularity of GIS&T BoK topics on the GIS SE and the rankings provided by the survey respondents in the 2014 BoK 2.0 report. Topics such as Web Mapping, Spatial Clustering, Interpolation Methods, Least-Cost Path, Spatial Sampling, Bayesian Methods, and High-Performance Computing were ranked similarly (≤2 in average difference). However, topics such as Neural Networks, Multivariate Display, and 3D Modeling show large differences in rankings (≥10 in average difference) and may indicate elevated interest over time (given 39 of the 51 articles listed in Appendix A were published after 2014). Topics that had a higher GIS SE score, as shown by the results in Figure 3 indicate higher rates of user interaction among a smaller sample of threads. Conversely, a lower GIS SE score rank indicates a lower amount of user interaction relative to the sample of threads.

Topics that tended toward higher GIS SE rankings include Neural Network Schemes, Greedy Heuristics, and Kernels and Density Estimation. Neural networks are commonly used in cloud and high-performance computing

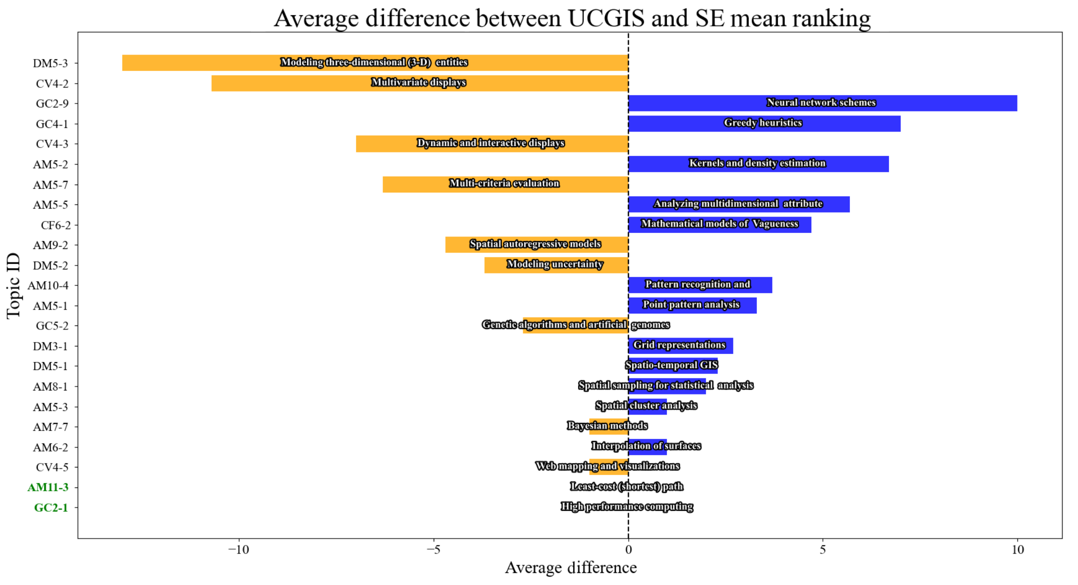

FIGURE 2 Bar chart summarizing the differences between the 2014 GIS&T BoK report and the GIS SE mean rankings. Topic IDs with no difference are highlighted in green.

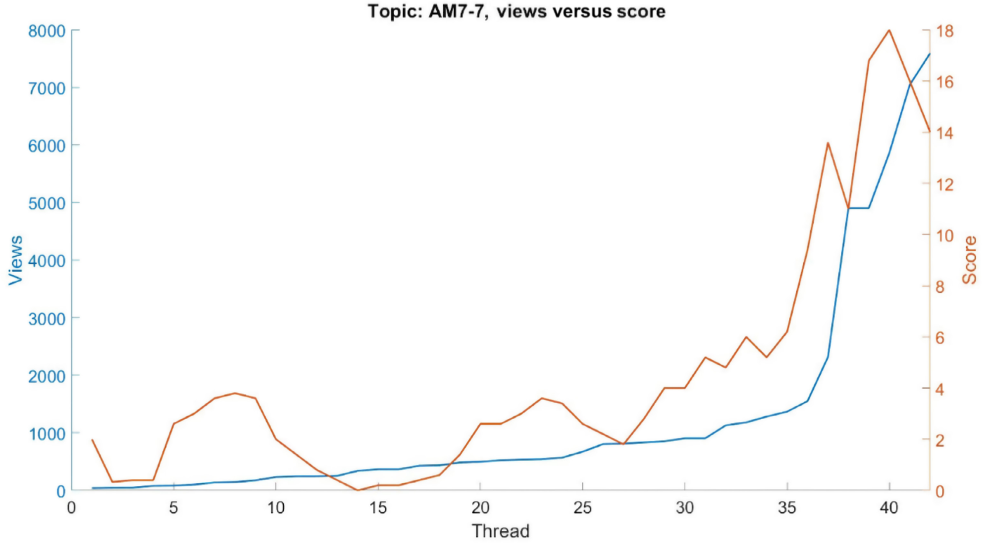

FIGURE 3 The relationship between views and score for topic AM7-7, Bayesian methods.

applications (Armstrong et al., 2019; Zhang, Zou, et al., 2021; Zhao et al., 2019). Additionally, the advent of open-source AI and machine learning has increased the accessibility of cyberinfrastructure in GIS applications (Janowicz et al., 2020). Conversely, the GIS&T BoK report rankings favored Modeling Three-Dimensional Entities, Multivariate Displays, and Dynamic and Interactive Displays. While these concepts are foundational to GIS, questions related to basic GIS skills are seldom posted on the GIS SE.

Measuring the frequency of threads provides the greatest insight into emerging or evolving trends, rather than static, foundational GIS concepts. The user base of the GIS SE is more likely to post questions when information on a topic is limited. Users are encouraged to ensure their question has not been previously asked, and existing threads of similar content are actively recommended when a user authors a post. This enables data from text mining forums to serve as a dynamic indication of the popularity of new and emerging topics within GIS. An additional attribute not included in the study is the temporal component of data from forum text mining. The rate of change in the discussion of a topic is experiencing can serve as a signal to authoritative GIS knowledge sources of topic importance.

This study illustrates a novel way to evaluate the interest in and potential need for education and training materials. One explanation for our results is that foundational topics such as Modeling Three-Dimensional Entities are sufficiently well-established, and sufficient educational materials are easily accessible such that experts and novices alike can find answers to their questions without needing to post questions on SE. An alternative explanation is that certain topics are not well-adopted or interesting in non-educational settings. Perhaps more interestingly, newer topics such as Neural Nets result in many more questions and discussion threads. This may suggest that there is insufficient education and training materials for these topics. Alternatively, the results in this article may indicate that the available education materials are not keeping pace with advances in the field, notwithstanding the 8+ year gap between the 2014 GIS&T BoK report rankings and those gathered from the GIS SE metrics. Highly technical topics for which a user expects information rapidly lends itself to online platforms such as SE rather than lengthy routes of peer-reviewed publications.

This said that the results provide two important takeaways. The first is the need to limit the gap between what topics are promoted as important and what practices are most prolific among common users. Scientific advances and technological innovation are progressing in leaps and bounds, and the GIS&T BoK continues to be developed and expanded on its digital platform (UCGIS, 2023) (https://gistbok.ucgis.org). Data from the 2014 survey and workshop served as valuable initial input to starting the revision process, and many of the topics suggested then have since been incorporated. Yet there continue to be gaps between the knowledge needs of common GIS users and BoK contributors within academia. The rapid development of CyberGIS presents an opportunity to create additional topics and entries. The methods utilized in this study provide an example of how community-based forums can be leveraged to provide additional insight into growing trends of CyberGIS topics. The structured approach to building a framework for CyberGIS education through survey and expert opinions, as has been the status quo, provides an explicit direction for shaping curriculum. Our results, however, provide an implicit view of current trends that can serve as a substantial addition to informing the structure of GIS knowledge amid a rapidly changing environment.

The second is the continued need for those in the academy and the practice communities to give back so that their work and experiences are captured and used to guide the construction of the UCGIS BoK as well as other education and training materials. To ensure we can prepare today's students to contribute in meaningful ways upon graduation, the education we provide must not only be informed by formal perspective but also additionally with data acquired from online discussion. We find that this data may not be used in lieu of formal GIS knowledge collections, but rather to substantiate the organization and content of such collections. The use of software tools to interface with popular web platforms provides an exciting opportunity to incorporate a new perspective in the design of CyberGIS education.

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CONFLICT OF INTEREST STATEMENT

The Authors of this article have no conflicts of interest to declare that may influence or alter the outcome of this research.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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APPENDIX A

THE LISTS BELOW ARE SUBSETS OF TOPICS WITHIN THEIR RESPECTIVE ORIGINAL KNOWLEDGE AREAS THAT ARE PARTICULARLY RELEVANT TO CyberGIS

Geographic Information Science & Technology

Body of Knowledge 2.0 Project Final Report

2014 University Consortium for Geographic Information Science Symposium, Pasadena, California

Table A3.1 Ratings for importance of analytical methods knowledge area topics included in 2014 GIS&T BoK (Wilson, 2014).

1. AM5-1 point pattern analysis
- Tang, W., Feng, W., & Jia, M. (2015). Massively parallel spatial point pattern analysis: Ripley's K function accelerated using graphics processing units. *International Journal of Geographical Information Science*, *29*(3), 412–439.
2. AM5-2 Kernels and density estimation
- Zhang, G. (2022). Detecting and Visualizing Observation Hot-Spots in Massive Volunteer-Contributed Geographic Data across Spatial Scales Using GPU-Accelerated Kernel Density Estimation. *ISPRS International Journal of Geo-Information*, *11*(1), 55.
3. AM5-3 Spatial cluster analysis
- Hu, C., Kang, X., Luo, N., & Zhao, Q. (2015, August). Parallel clustering of big data of spatio-temporal trajectory. In *2015 11th International Conference on Natural Computation (ICNC)* (pp. 769–774). IEEE.
- Neukirchen, H., (2016). Survey and performance evaluation of DBSCAN spatial clustering implementations for big data and high-performance computing paradigms. Engineering Research Institute, University of Iceland. Available from web: https://helmut.hi.is/publications/VHI-01-2016.pdf (accessed 05.01.2023)
- Armstrong, M. P., Wang, S., & Zhang, Z. (2019). The Internet of Things and fast data streams: prospects for geospatial data science in emerging information ecosystems. *Cartography and Geographic Information Science*, *46*(1), 39–56.
4. AM5-5 Analyzing multidimensional attribute
- Gao, Y., Li, T., Wang, S., Jeong, M. H., & Soltani, K. (2018). A multidimensional spatial scan statistics approach to movement pattern comparison. *International Journal of Geographical Information Science*, *32*(7), 1304–1325.
- Wright, D. J., & Wang, S. (2011). The emergence of spatial cyberinfrastructure. *Proceedings of the National Academy of Sciences*, *108*(14), 5488–5491.
5. AM5-7 Multi-criteria evaluation
- Zhang, Z., Hu, H., Yin, D., Kashem, S., Li, R., Cai, H., Perkins, D., and Wang, S. (2018). A cyberGIS-enabled multi-criteria spatial decision support system: A case study on flood emergency management. *International journal of digital earth*, 12 (11), 1364–1381.
6. AM6-2 Interpolation of surfaces
- Zhao, J., Zhang, Z., & Sullivan, C. J. (2019). Identifying anomalous nuclear radioactive sources using Poisson kriging and mobile sensor networks. *PLoS ONE*, *14*(5), e0216131.
7. AM7-7 Bayesian methods
- Hu, H. (2018). CyberGIS-enabled spatial decision support for supply chain optimization with uncertainty quantification (Doctoral dissertation, University of Illinois at Urbana-Champaign), Accessed July 10, 2023 from: https://core.ac.uk/download/pdf/161953729.pdf.
- Bowen, G. J., Liu, Z., Vander Zanden, H. B., Zhao, L., & Takahashi, G. (2014). Geographic assignment with stable isotopes in IsoMAP. *Methods in Ecology and Evolution*, *5*(3), 201–206.
8. AM8-1 Spatial sampling for statistical analysis
- Zhu, Z., & Stein, M. L. (2006). Spatial sampling design for prediction with estimated parameters. *Journal of Agricultural, Biological, and Environmental Statistics*, *11*(1), 24–44.

- Liu, S., McGree, J., Ge, Z., & Xie, Y. (2015). *Computational and statistical methods for analysing big data with applications*. Academic Press.

9. AM9-2 Spatial autoregressive models

- Evans, M. R., Oliver, D., Yang, K., Zhou, X., Ali, R. Y., & Shekhar, S. (2019). Enabling spatial big data via CyberGIS: Challenges and opportunities. *CyberGIS for Geospatial Discovery and Innovation*, 118, 143–170.

10. AM10-4 Pattern recognition and matching

- Sudhira, H. S., Ramachandra, T. V., & Jagadish, K. S. (2003). Urban sprawl pattern recognition and modeling using GIS. *Map India*, 28–31.
- bin Ibrahim, A. L., & Sarvestani, M. S. (2009, May). Urban sprawl pattern recognition using remote sensing and GIS-Case study Shiraz city, Iran. In Proceeding of *2009 Joint Urban Remote Sensing Event* IEEE, 1–5.

11. AM11-3 Least-cost (shortest) path

- Bachmann, D., Bökler, F., Kopec, J., Popp, K., Schwarze, B., & Weichert, F. (2018). Multi-objective optimisation based planning of power-line grid expansions. *ISPRS International Journal of Geo-Information*, *7*(7), 258.

Table A3.2 Ratings for importance of conceptual foundations knowledge area topics included in 2014 GIS&T BoK (Wilson, 2014).

1. CF6-2 Mathematical models of vagueness: Fuzzy sets and rough sets

- Zhang, Z., Demšar, U., Wang, S., & Virrantaus, K. (2018). A spatial fuzzy influence diagram for modelling spatial objects' dependencies: a case study on tree-related electric outages. *International Journal of Geographical Information Science*, *32*(2), 349–366.

Table A3.3 Ratings for Importance of Cartography & Visualization Knowledge Area Topics Included in 2014 GIS&T BoK (Wilson, 2014).

1. CV4-3 Dynamic and interactive displays

- Zhang, Z., Hu, H., Yin, D., Kashem, S., Li, R., Cai, H., Perkins, D., and Wang, S. (2018). A cyberGIS-enabled multi-criteria spatial decision support system: A case study on flood emergency management. *International journal of digital earth*, 12 (11), 1364–1381.

2. CV4-5 Web mapping and visualizations (include Keywords JavaScript, Leaflet, WebGIS, CyberGIS Jupyter, cloud computing)

- Liu, Y. Y., Maidment, D. R., Tarboton, D. G., Zheng, X., & Wang, S. (2018). A CyberGIS integration and computation framework for high-resolution continental-scale flood inundation mapping. *Journal of the American Water Resources Association*, *54*(4), 770–784.
- Yin, D., Liu, Y., Hu, H., Terstriep, J., Hong, X., Padmanabhan, A., & Wang, S. (2019). CyberGIS-Jupyter for reproducible and scalable geospatial analytics. *Concurrency and Computation: Practice and Experience*, *31*(11), e5040.
- Yin, D., Liu, Y., Padmanabhan, A., Terstriep, J., Rush, J., & Wang, S. (2017). A CyberGIS-Jupyter framework for geospatial analytics at scale. In *Proceedings of the Practice and Experience in Advanced Research Computing 2017 on Sustainability, Success and Impact* (pp. 1–8).

3. CV4-6 Virtual and immersive environments

- Guo, M., Huang, Y., & Xie, Z. (2015). A balanced decomposition approach to real-time visualization of large vector maps in CyberGIS. *Frontiers of Computer Science*, *9*(3), 442–455.

4. CV4-8 Visualization of temporal geographic data
5. CV5-1 Computational issues in cartography and visualization

- Guo, M., Huang, Y., & Xie, Z. (2014). An Efficient Approach to Load Balancing of Vector Maps in CyberGIS Cluster Environment. *Geomatica*, *68*(2), 129–134.

- Riteau, P., Hwang, M., Padmanabhan, A., Gao, Y., Liu, Y., Keahey, K., & Wang, S. (2014, June). A cloud computing approach to on-demand and scalable cybergis analytics. In *Proceedings of the 5th ACM workshop on Scientific cloud computing* (pp. 17–24).
- Guo, M., Huang, Y., Xie, Z., & Wu, L. (2017). An effective approach to estimating computing time of vector data spatial computational domains in WebGIS. *Geomatica*, *71*(1), 21–26.
- Yang, C., Wong, D. W., Yang, R., Kafatos, M., & Li, Q. (2005). Performance-improving techniques in web-based GIS. *International Journal of Geographical Information Science*, *19*(3), 319–342.

Table A3.4 Ratings for importance of data modeling topics included in 2006 GIS&T BoK.

1. DM3-1 Grid representations

- Wang, S., Wilkins-Diehr, N. R., & Nyerges, T. L. (2012). CyberGIS-Toward synergistic advancement of cyberinfrastructure and GIScience: A workshop summary. *Journal of Spatial Information Science*, (4), 125–148.

2. DM3-5 The Triangulated Irregular Network (TIN) model

- Lyu, F., Xu, Z., Ma, X., Wang, S., Li, Z., & Wang, S. (2021). A vector-based method for drainage network analysis based on LiDAR data. *Computers & Geosciences*, *156*, 104,892.
- Wilson, J. P. 2018. Environmental applications of digital terrain modelling. Oxford, UK: Wiley-Blackwell.

3. DM5-1 Spatiotemporal GIS

- Kang, J. Y., Aldstadt, J., Vandewalle, R., Yin, D., & Wang, S. (2020). A CyberGIS approach to spatiotemporally explicit uncertainty and global sensitivity analysis for agent-based modeling of vector-borne disease transmission. *Annals of the American Association of Geographers*, *110* (6), 1855–1873.
- Padmanabhan, A., Wang, S., Cao, G., Hwang, M., Zhang, Z., Gao, Y., … Liu, Y. (2014). FluMapper: A cyberGIS application for interactive analysis of massive location-based social media. *Concurrency and Computation: Practice and Experience*, *26*(13), 2253–2265.
- Lyu, F., Kang, J. Y., Wang, S., Han, S. Y., Li, Z., & Wang, S. (2021). Multi-scale CyberGIS Analytics for Detecting Spatiotemporal Patterns of COVID-19. *Mapping COVID-19 in Space and Time* (pp. 217–232). Springer.
- Goodchild, M. F. (2013). Prospects for a space–time GIS: Space–time integration in geography and GIScience. *Annals of the Association of American Geographers*, *103*(5), 1072–1077.
- Armstrong, M. P., Wang, S., & Zhang, Z. (2019). The Internet of Things and fast data streams: prospects for geospatial data science in emerging information ecosystems. *Cartography and Geographic Information Science*, *46*(1), 39–56.
- Zhang, Z., Yin, D., Virrantaus, K., Ye, X., & Wang, S. (2021). Modeling human activity dynamics: an object-class oriented space–time composite model based on social media and urban infrastructure data. *Computational Urban Science*, *1*(1), 1–13.
- Zhang, Z., Laakso, T., Wang, Z., Pulkkinen, S., Ahopelto, S., Virrantaus, K., … Sheng, Z. (2020). Comparative study of AI-based methods—application of analyzing inflow and infiltration in sanitary sewer subcatchments. *Sustainability*, *12*(15), 6254.

4. DM5-2 Modeling uncertainty

- Hu, H., Lin, T., Wang, S., & Rodriguez, L. F. (2017). A cyberGIS approach to uncertainty and sensitivity analysis in biomass supply chain optimization. *Applied Energy*, *203*, 26–40.
- Kang, J. Y., Aldstadt, J., Vandewalle, R., Yin, D., & Wang, S. (2020). A CyberGIS approach to spatiotemporally explicit uncertainty and global sensitivity analysis for agent-based modeling of vector-borne disease transmission. *Annals of the American Association of Geographers*, *110*(6), 1855–1873.

5. DM5-3 Modeling three-dimensional (3-D) entities

- Shirowzhan, S., Tan, W., & Sepasgozar, S. M. (2020). Digital twin and CyberGIS for improving connectivity and measuring the impact of infrastructure construction planning in smart cities. *ISPRS International Journal of Geo-Information*, *9*(4), 240.

• Felemban, E., Majid, A. R. M. A., Rehman, F. U., & Lbath, A. (2021). Low-Cost Digital Twin Framework for 3D Modeling of Homogenous Urban Zones. In *Intelligent Computing* (pp. 1106–1114). Springer, Cham.

Table A3.5 Ratings for importance of geocomputation knowledge area topics included 2014 GIS&T BoK (Wilson, 2014).

1. GC2-1 High performance computing

• Wang, S., Anselin, L., Bhaduri, B., Crosby, C., Goodchild, M. F., Liu, Y., & Nyerges, T. L. (2013). CyberGIS software: a synthetic review and integration roadmap. *International Journal of Geographical Information Science*, *27*(11), 2122–2145.
• Evans, M. R., Oliver, D., Yang, K., Zhou, X., Ali, R. Y., & Shekhar, S. (2019). Enabling spatial big data via CyberGIS: Challenges and opportunities. Edited by Wang and Goodchild. *CyberGIS for geospatial discovery and innovation*, Springer, 143–170.
• Wang, S. (2016). CyberGIS. *International Encyclopedia of Geography: People, the Earth, Environment and Technology: People, the Earth, Environment and Technology*, 1–10.
• Wang, S., Liu, Y., & Padmanabhan, A. (2016). Open cyberGIS software for geospatial research and education in the big data era. *SoftwareX*, *5*, 1–5.
• Liu, Y. Y., Maidment, D. R., Tarboton, D. G., Zheng, X., & Wang, S. (2018). A CyberGIS integration and computation framework for high-resolution continental-scale flood inundation mapping. *JAWRA Journal of the American Water Resources Association*, *54*(4), 770–784.

2. GC2-9 Neural network schemes (many articles are available in this topic, only listed some)

• Cai, Y. (2019). *Data-intensive crop knowledge discovery in the era of cybergis and machine intelligence*. Accessed July 10, 2023 from: https://www.ideals.illinois.edu/items/113767
• Cai, Y., Wang, S., Guan, K., & Peng, J. (2019). Improving Crop Type Classification for Large Geographic Areas. Accessed July 10, 2023 from: https://cybergis.illinois.edu/wp-content/uploads/2018/04/YapingCai.pdf
• Azad, A., & Wang, X. (2021). Land Use Change Ontology and Traffic Prediction through Recurrent Neural Networks: A Case Study in Calgary, Canada. *ISPRS International Journal of Geo-Information*, *10*(6), 358.
• Gharehghani, A., & Pourrahmani, H. (2019). Performance evaluation of diesel engines (PEDE) for a diesel-biodiesel fueled CI engine using nano-particles additive. *Energy Conversion and Management*, *198*, 111,921.

3. GC4-1 Greedy heuristics

• Laura, J., Li, W., Rey, S. J., & Anselin, L. (2015). Parallelization of a regionalization heuristic in distributed computing platforms–a case study of parallel-p-compact-regions problem. *International Journal of Geographical Information Science*, *29*(4), 536–555.
• Xie, Y., Eftelioglu, E., Ali, R. Y., Tang, X., Li, Y., Doshi, R., & Shekhar, S. (2017). Transdisciplinary foundations of geospatial data science. *ISPRS International Journal of Geo-Information*, *6*(12), 395.

4. GC5-2 Genetic algorithms and artificial genomes

• Xiao, C., Hu, C., Chen, N., Zhang, X., Chen, Z., & Tong, X. (2022). A Genetic Algorithm–Assisted Deep Neural Network Model for Merging Microwave and Infrared Daily Sea Surface Temperature Products. *Big Earth Data Intelligence for Environmental Modeling*, 9, 421.