Watershed Characterization to Enhance Student Learning and Build Capacity for Community-Led Watershed Planning and Management

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ABSTRACT The watershed characterization process involves compiling, synthesizing, and interpreting existing information to understand current watershed conditions, and uses narrative, maps, and other tools to tell the watershed's story. It is an important first step in guiding planning and management efforts. Because watershed management problems are complex, jumping straight into management solutions without fully understanding conditions on the ground can produce projects that are ineffective, unsustainable, and harmful. Every watershed is unique, and care must be taken to ensure that watershed maps effectively depict and communicate local issues. Academic partners can help build capacity for watershed work by using Geographic Information Systems (GIS) to create high-quality and customized maps, while community members provide local knowledge to inform map design and can use the characterization process to start critical conversations about the watershed. This case study reports on a watershed characterization project for the Fishkill Creek Watershed, a tributary to the Hudson River, New York. The case study describes the importance of watershed characterization, the value of completing the work through academic-community partnerships, and the role of expertise and specialized knowledge in capacity building and ensuring successful outcomes. The case study appendices provide resources to enable students to complete their own watershed characterization maps for summer research, a group course project, or as a guided independent study. KEYWORDS watershed planning, watershed management, capacity building, Geographic Information Systems (GIS), academic-community partnerships

KEY MESSAGE

Students will build GIS skills while gaining insights into the role of watershed characterization in the watershed planning and management process. Students will also learn how teams with diverse forms of expertise and knowledge can work together to compile information to tell a watershed's story, bring together stakeholders to start critical conversations about shared waters, and build capacity for community-led watershed work.

INTRODUCTION

Watersheds are areas of land from which rain or melting snow drains into a river, lake, ocean, or other waterbody. The water flows through forests, cities, farms, and other lands to create "a system of hydrologically connected people, places, and things" [1]. Thus, upstream activities, such as urban development and pollution generation, can impact water quality in downstream communities, and cause or exacerbate existing environmental justice harms [2]. Watershed hydrological systems cut across geopolitical boundaries and are the geographic unit best suited for restoring, protecting, and managing shared waters.

The watershed planning and management process involves bringing people together from across these municipal boundaries, including local governments, watershed groups, nonprofit organizations, property and business owners, the academic community, and more, to develop a shared vision for the watershed, document

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current watershed conditions, define realistic goals, and prioritize specific, strategic, implementable actions to improve their watershed's health [3]. The watershed management process is "integrated" in that it must address multiple challenges, including restoring and protecting water resources and ecosystems while also balancing socioeconomic development demands [3, 4] and meeting the needs of vulnerable and underserved populations [5]. Critical to the watershed planning and management process is that it is just that, a process. Heathcote [4 pp. 14–15] notes:

> *[A] good watershed plan is not a single product, such as a document that sits on an agency bookshelf. Instead, it is a framework for continued dialogue about water and the watershed. Ideas endorsed by the planning team must be revised and reviewed periodically to determine whether they are still acceptable or could be improved. New technology and management thinking must be incorporated into the evolving plan. Most of all, the watershed management plan must reflect the current societal consensus about the value of water as a resource, about responsibilities and social attitudes, and about the community vision of an ideal watershed state. Integrated watershed management is, therefore, a journey, not a destination.*

Because of this ever-changing nature of on-the-ground conditions and community needs, involving citizens and watershed stakeholders in the planning and management process is critical for successful outcomes [3, 4].[1] Participation can include serving on advisory councils [3, 5], providing local or citizen science data [7], ground-truthing large datasets or model results [8–10], and contributing an understanding of local needs and community dynamics [11, 12]. Furthermore, involving stakeholders in decision-making ensures the needs of those stakeholders are met during the implementation and policy-making process [5].

Though the watershed management process is often driven by a need to solve some problem such as water quality or flooding, an important first step is to develop a complete and shared understanding of that problem among stakeholders [13]. The watershed characterization process, or watershed inventory [4], compiles, synthesizes, interprets, and communicates existing information to understand current watershed conditions and to tell the story of the watershed, through narrative, maps, and other tools. Though watersheds are connected hydrological systems, biophysical and social processes impact and are impacted by the system, and "an understanding of these features and processes is an essential first step in assessing the condition of a watershed ecosystem and the impacts of management actions on it" [4]. The watershed characterization process can also help identify any gaps in or limitations of existing information. Watershed problems are complex, and implementing solutions without an accurate or complete understanding of those problems can produce projects that are ineffective, unsustainable, or harmful [13].

Therefore, the watershed characterization process needs to be more than *just* compiling and mapping existing data; it must be thoughtful, inclusive, and deliberate so the resulting watershed maps and images not only effectively represent and communicate current conditions (and values) but connect people to their watersheds and inspire action. And watershed characterization plays an important role in building partnerships and starting critical conversations about shared waters. Stakeholder involvement in the watershed planning process is critical not only for ensuring successful outcomes [3] but also for accurate and effective maps [8–10]. For example, stakeholders can help with ground-truthing and fact-checking errors, that is, correcting labels and locations that may be listed incorrectly within large state datasets. While academics or scientists might have access to water quality data that show pollution, local communities might have experienced the pollution directly, through sight or smell, for example, or have knowledge about contaminant spills or discharges [14]. Furthermore, community members have access to different knowledge and ways of knowing than academics, agencies, or regional nonprofits [15, 16]. The watershed characterization process helps bridge this divide by bringing together both the myriad of regional/state datasets and new tools like web mappers, while including critical context and local knowledge. The balance of these different ways of knowing will be unique in each watershed [15]. There should be, therefore, careful consideration of who is included in the characterization process and what role they will play. Teams are needed with not only technical experts and community members with local knowledge, but also project leaders who can provide vision and direction, project

1. Even the presence of a watershed group in a watershed can improve water quality. For example, [6] found that the presence of a watershed group, and the total amount of their donations and expenditures, is significantly correlated with better water quality (lower dissolved oxygen deficiency and more swimmable and fishable water bodies) in U.S.-based watersheds.

managers to help the team meet that vision, and effective listeners and communicators to both help translate technical information to diverse stakeholders and to tell the story of the watershed [11].

Geographic Information Systems (GIS) is an effective tool for supporting watershed management [17, 18] and can be used as part of the watershed characterization process to delineate watershed boundaries, collect and manage existing data, generate watershed maps as illustrations of key concepts, compute summary statistics such as percent land use or population density, and identify gaps in relevant geographic information. There are many publicly available mapping resources available to support watershed characterization, including GIS platforms such as Google Earth, R, and QGIS. Also, the U.S. Geological Survey's StreamStats application (https://www.usgs.gov/streamstats) can be used to delineate watershed boundaries and compute watershed characteristics such as percent forest cover. However, watershed stakeholders may not have access to the dedicated GIS staff, computing resources, time, or capacity to learn and work with the software [11, 19] and hiring a professional GIS consultant may not be feasible for an all-volunteer watershed group. Even the use of publicly available web mappers and dashboards, such as the New York State Department of Environmental Conservation Natural Resource Mapper, https://gisservices.dec.ny.gov/gis/erm/, will require expertise to interpret the data, and decisions must be made about what layers to include and at what extent. While geographic information may be more accessible than ever, there are still important steps to take before the information can be interpreted and used in watershed planning and management. While this may be second nature for environmental professionals who are familiar with the specifics of these datasets, watershed groups and volunteers may need support to interpret the maps.

Academic partners can support the watershed characterization process by compiling geographic information data and using GIS to create high-quality and customized watershed maps [1, 19] to depict and communicate local issues. Building these partnerships can be an effective way to support community planning efforts [11, 20], particularly when the academic-community partnership is mutually supportive [21–23]. Providing opportunities for students to learn through experiential, real-world projects is important for building academic and professional competencies such as critical thinking and analysis, problem-solving, and collaboration [24–26]. Moreover, faculty and students gain opportunities for professional development and networking, to engage in local planning, to build relationships in watershed communities, and to provide support for community projects and concerns. This is while also providing the needed skills for community members to move forward with prioritizing watershed work.

This case study reports on a watershed characterization project for the Fishkill Creek Watershed, a tributary to the Hudson River in New York State. The case study describes the importance of watershed characterization, the value of completing the work through academic-community partnerships, the role of expertise and specialized knowledge in capacity building and ensuring successful outcomes, and other lessons learned through watershed characterization projects in the Hudson River Watershed. We describe how the lessons learned from creating the Sparkill Creek Watershed and Punch Brook-Roeliff Jansen Kill (PB-RJ) watershed characterization reports then informed the community and student-led process of creating the Fishkill Creek watershed characterization maps. This first phase of the planning process is crucial for bringing stakeholders together and starting critical conversations about the watershed. The case study appendices provide resources to enable students to complete their own watershed characterization maps in support of watershed community goals.

CASE EXAMINATION

Hudson River Watershed Groups

There are over 30 watershed groups operating within the larger 13,400 square mile Hudson River Watershed, which begins at Lake Tear of the Clouds in the Adirondack Mountains and flows to New York City (figure 1). Hudson River watershed groups are defined as "community-based groups working to protect local waterbodies using a watershed framework and scale" [27]. While many Hudson River watershed groups want to undertake watershed planning, and understand the need for plans to direct their work, they often do not have the capacity to play their most impactful roles, such as compiling watershed-based information, supporting coordination across municipal boundaries, and implementing priority projects [27, 28]. For example, watershed groups working on a watershed characterization need to compile existing information about the watershed that contributes to an understanding of

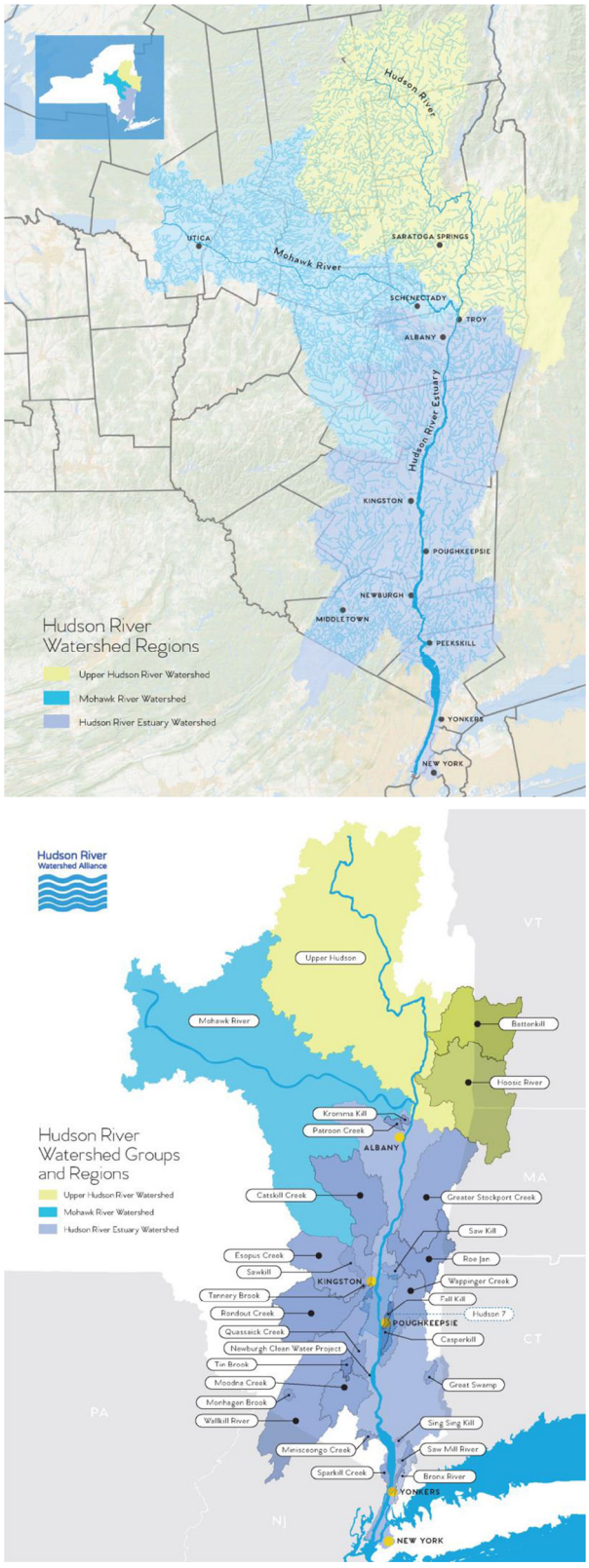

Figure 1. The Hudson River Watershed (top) and watershed groups within the Hudson River Watershed (bottom). Source: https://hudsonwatershed.org/wp-content/uploads/HRWA_Work-on-Watersheds_Report.pdf.

current watershed conditions. Before that process even begins, watershed groups connect and build relationships with researchers, municipalities, community members, or other stakeholders to compile more comprehensive information and incorporate knowledge and experience that would contribute to an understanding of watershed conditions. Having these relationships in place becomes even more important for an inclusive and equitable planning process and improves the work—by acknowledging past projects, not reinventing the wheel, understanding priorities of different groups/stakeholders, and valuing local knowledge. With enough operations capacity, watershed groups can compile information about current watershed conditions as those materials become available in an accessible location, building out institutional knowledge and laying the foundation for a stronger watershed characterization. If they have a clear organizational structure and financial procedures, watershed groups can apply for funding either directly or indirectly through a fiscal sponsor to support watershed characterization and planning. Once a watershed plan is complete, many actions fall to watershed groups to implement. Priority strategies from the plan may not be implemented if there is inadequate community support during the planning process or watershed groups do not have the ability to accomplish the work. Each of these pieces relies on watershed groups having a certain level of organizational capacity to achieve, and many groups need assistance to get there.

In response to the need for capacity building for watershed groups, the Hudson River Watershed Alliance (HRWA, hudsonwatershed.org), a regional nonprofit that supports watershed-based work by providing technical and education resources to watershed groups, municipalities, and others, developed a pilot watershed characterization project for the PB-RJ and Sparkill Creek Watersheds (Supporting Information 1) which, like the Fishkill Creek, are tributaries to the larger Hudson River Watershed. The reports are being used to engage with key partners to discuss the watershed and plan for next steps in the management process, such as developing a full watershed plan with strategic actions. One important goal of these characterization projects was to develop resources, lessons learned, and templates to support other watershed groups, like the Fishkill Creek Watershed Alliance (FCWA), in completing similar projects. While the HRWA worked with a professional GIS consultant to complete the PB-RJ and Sparkill Creek watershed

characterizations, not all watershed groups have the resources to hire GIS professionals for their characterizations. Completing this part of the watershed characterization process through academic-community partnerships provides a cost-effective, win-win approach to creating GIS maps, a critical part of the watershed characterization process, and provides a mechanism for watershed management in the region to be community-led and community-centered. Building these partnerships can help overcome barriers and be mutually supportive, providing students with opportunities to develop and practice GIS skills and to engage in local planning while providing GIS data management and mapping resources for community members in support of watershed work.

Fishkill Creek Watershed Alliance

One such watershed group looking to update a 20-year-old watershed management plan is the FCWA. The 500 km² Fishkill Creek Watershed (figure 2) encompasses 14 municipalities in upstate New York and two counties (Dutchess and Putnam counties). In response to rapid growth in Dutchess County, concerns about water quality, and a desire to balance economic growth with the health of the watershed, in 2002 the Fishkill Creek Watershed Committee (FCWC) formed as a grassroots organization of private citizens and municipal and agency representatives, with a mission "to encourage individuals and entities, both public and private, to work for the protection of the natural environment within the Fishkill Creek Watershed" [3]. Over the next 3 years, the FCWC developed the *Natural Resources Management Plan for the Fishkill Creek Watershed* [29], which includes a watershed characterization, watershed conservation objectives, management recommendations, and an implementation strategy. The group eventually became inactive and its successor, the FCWA, was formed in 2023 by coauthor and FCWA President Sergei Krasikov, the FCWA vice-president, and other stakeholders. The FCWA mission "is to protect, preserve and restore the natural resources of the Fishkill Creek watershed through collaborative efforts with local agencies, municipalities, non-governmental organizations, and citizens. [The FCWA aims] to promote sustainable land use practices, protect water quality, and enhance recreational opportunities while preserving the unique character of the watershed" (https://www.fishkillwatershed.org/our-group). Current projects include expanding water quality testing throughout the watershed and pursuing New York State Inland Waterway Designation, a program that provides funding and resources to help communities protect the designated waterbody and revitalize the community.

Twenty years after the 2005 watershed management plan was completed, the group, realizing the need to update the plan to understand current conditions and how conditions have changed, and develop an updated long-term management plan, partnered with HRWA, Clarkson University, and Siena College to complete the watershed characterization (https://www.fishkillwatershed.org/projects). The 2005 plan identified several challenges to creek health, many of which remain, including runoff, stormwater, aquatic connectivity, encroachment on riparian buffers, and septic system effluent. New challenges have emerged in the forms of climate change, land use changes, emerging contaminants, and more intense episodic storms. A compelling need exists to create an up-to-date management plan, starting with watershed characterization maps, and supported by new monitoring and characterization efforts, taking advantage of major advances in research tools, data availability, mapping software, and communications. For example, GIS technology has improved considerably in 20 years and the maps in the 2005 plan are out of date, include federal and state but not local data, and are difficult to read at their published scale.

Fishkill Creek Watershed Characterization

The watershed planning and management process is typically initiated by some need of a government agency or community to address one or more predefined watershed problems or challenges such as poor water quality or climate change. The goal of the Fishkill Creek Watershed Characterization and Management Planning project is to engage scientists, community members, and elected leaders to create an up-to-date watershed characterization of the main stem of the Fishkill Creek to address current challenges and threats, and to develop guidance documents and factsheets to assist landowners and public agencies to adopt conservation best management practices. Here, we report on phase one of this project (figure 3), which employed a process following the framework for watershed planning in New York State provided by the New York State Department of State (NYDOS) and the New York Department of Environmental Conservation (NYSDEC)'s *Guidebook on Watershed Plans* [3] and the templates for watershed characterization developed by the

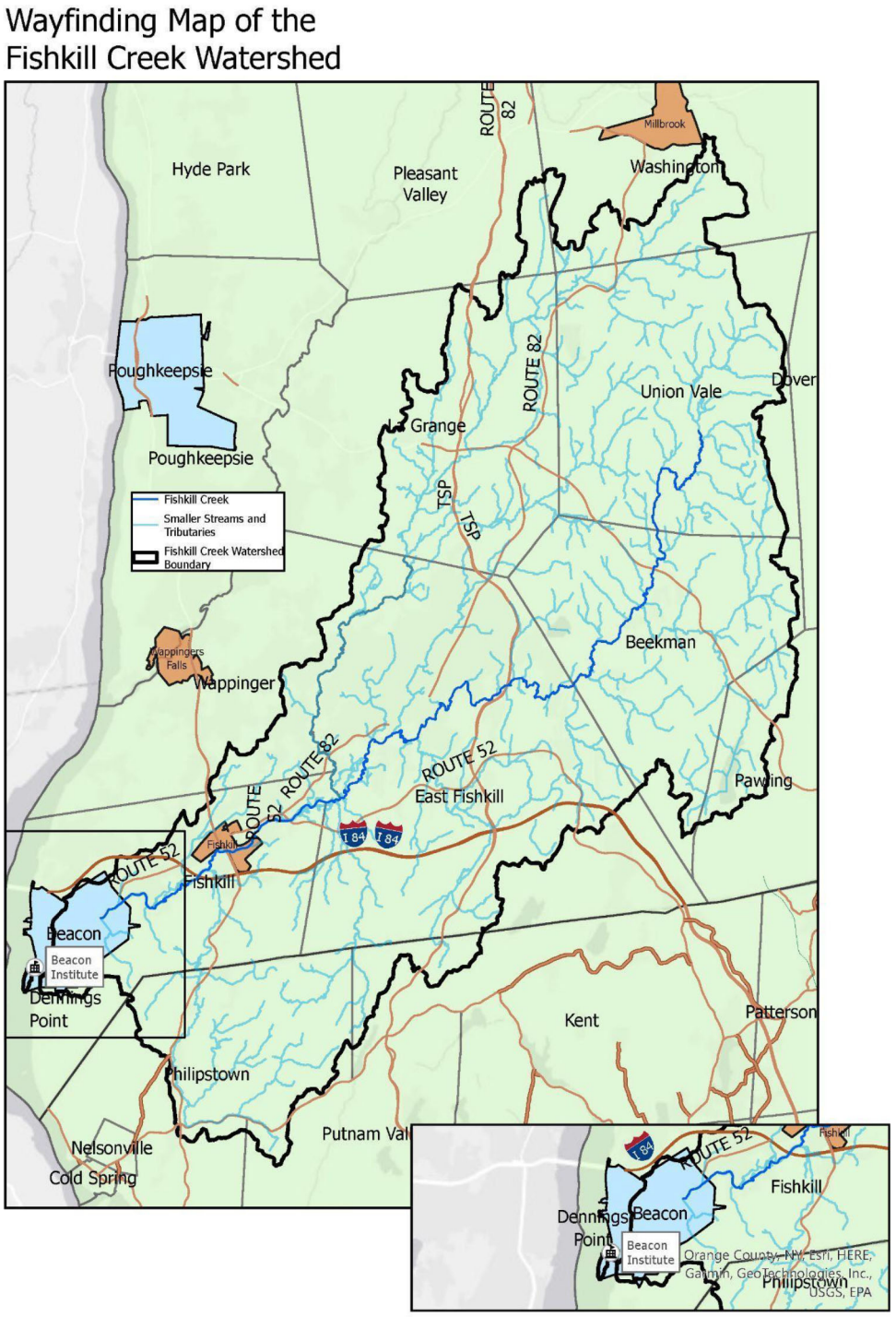

Figure 2. Map of the Fishkill Watershed created by student partner, Gaffney, as part of the watershed characterization process.

HRWA. The project team developed maps by focusing on accessible state, federal, and regional datasets. For the PB-RJ and Sparkill Creek watershed characterizations, we received more feedback on the maps at the end of the process than at the beginning and local data may take time to obtain. For these reasons, we decided to break up the watershed characterization process into these three phases, starting with the maps, working on the narrative, and coming back to finalize the maps within the context of the larger report. The Fishkill Creek maps will help start the characterization process and will be refined later in the project with more local data and local feedback. Local datasets that are not publicly available and take additional time or connections to access, such as

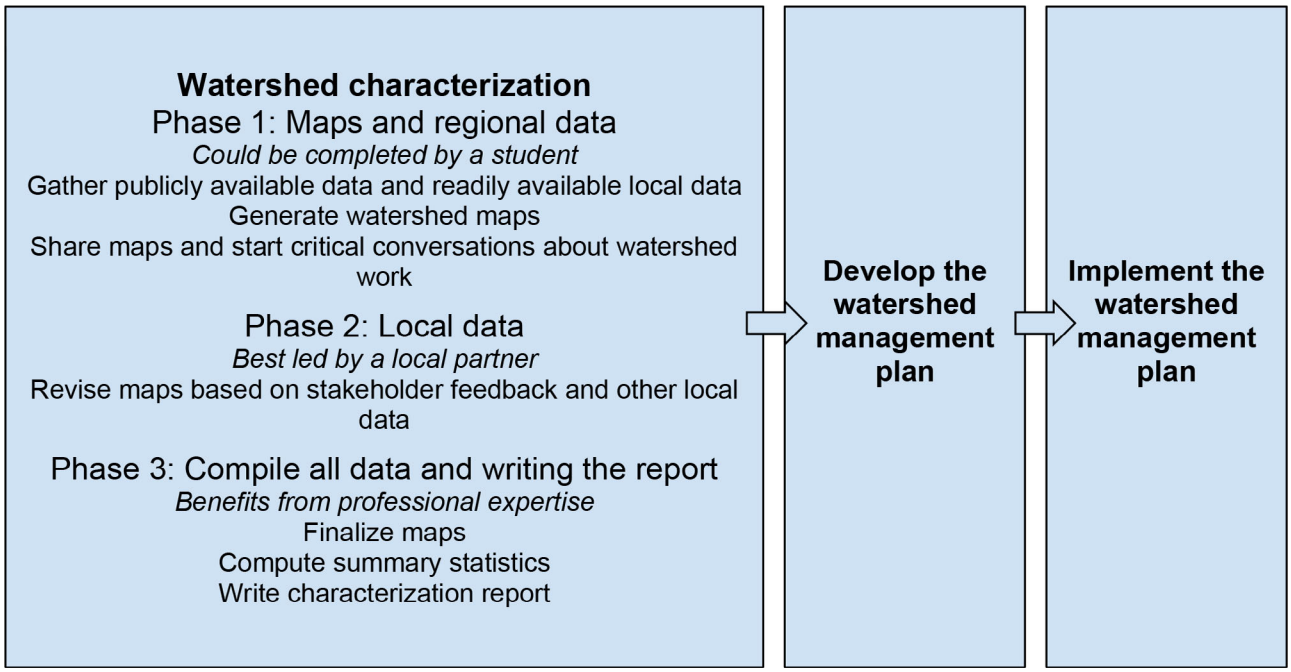

Figure 3. Phases of the watershed characterization and planning process.

community monitoring locations and land trust acquisitions, will be added during phase two.

Even in these early phases, the watershed characterization process must include not only technical experts (with GIS skills and knowledge) but community members with an understanding of local needs, regional partners, government (municipal, county, regional, and/or state) agencies, and other stakeholders. These stakeholders can take on many roles from leading the process, serving on an advisory council, or support (by providing county datasets, for example). The Fishkill Creek watershed characterization team includes University staff (Clarkson University's Beacon Institute staff), a regional watershed partner (HRWA staff), a GIS student and faculty mentor, and volunteer members of the FCWA (table 1). The project team was convened by the HRWA who had existing relationships with each team member with the exception of the student partner who was brought on board by his faculty mentor. The team followed best practices and ethical guidelines for collaboration and academic-community partnerships such as centering community needs, valuing each member's expertise, being clear about expectations and transparent about capacity constraints, and acknowledging power differences [30, 31]. The project was initiated by the FCWA who secured funding through a private donor. Planning began during the spring of 2024 with a review of the pilot PB-RJ and Sparkill Creek maps and discussions of the scale, scope, logistics, and the goals of the Fishkill Creek characterization.

One of the first decisions about the scale and scope of the project was to decide on the watershed boundary. The watershed boundary is determined by its watershed outlet. The choice of the watershed outlet will impact the size of the watershed and which subwatersheds to include, and is as much a political decision as a technical or scientific one [32, 33]. For example, choosing what to use as the watershed boundary will impact not only what data will be included in the characterizations but also what municipalities, counties, states, or countries are stakeholders in the planning and management process. Aside from scientific and political implications, the choice of the size of the watershed will impact what data can be mapped and how much generalization is needed [34]. For example, showing a building footprint vector layer may be possible for smaller watersheds, while a percent impervious or land use raster may be more appropriate for larger watersheds. To illustrate certain datasets, larger watersheds may need to be broken down into subwatersheds, which is another important mapping and decision-making process. There also may be value in aligning the watershed delineation with other local plans, so they are referencing the same area. Supporting Information 3 provides additional considerations and guidance for choosing a watershed boundary. For the Fishkill Creek Watershed, we chose to use the

Table 1. Project Team Roles, Expertise, and Responsibilities.

Team Member	Expertise, Role, and Responsibilities
Charles Gaffney, rising senior and environmental science major, Siena College	Gaffney provided technical expertise in GIS and cartography, and capacity to find and compile available data, and generate and edit watershed characterization maps.
Emily Vail, Executive Director, Hudson River Watershed Alliance	Vail contributed expertise in collaborative processes and project management, setting the structure for meeting agendas and facilitating team meetings. She provided institutional memory and shared lessons learned and experiences from the Sparkill and PB-RJ watershed characterization pilot projects. Vail also provided access to a regional network, which can provide valuable information, resources, and potential partners. Vail helped connect Gaffney to local data.
Kate Meierdiercks, faculty member, Siena College	Meierdiercks mentored student partner, Gaffney, and contributed expertise in GIS and working with students and community partners on GIS and watershed-based work. She also served as a "technical translator" between the language of GIS and watershed work.
Sergei Krasikov, President, Fishkill Creek Watershed Alliance	Krasikov provided local leadership and local knowledge of watershed group needs and planning priorities, local knowledge of "markers" to include in the maps, and served as a liaison to the rest of the Fishkill Creek Watershed Alliance.
Asher Pacht, Director of Environmental Programs, School(s) Institute for STEM Education, Beacon Institute for Rivers and Estuaries at Clarkson University	Pacht provided local leadership and local administrative and management support. As staff at the Beacon Institute, Pacht provided the organizational capacity and resources, including human resources staff and systems to compensate team members through Clarkson University's payroll (which a volunteer group like FCWA did not have access to). Pacht also provided local knowledge of watershed group needs and planning priorities, and local knowledge of "markers" to include in the maps.
Advisory Council	Unlike the previous Sparkill and PB-RJ watershed characterization projects, due to the compressed timeline of the Fishkill watershed characterization, the team did not have a kickoff meeting or advisory committee. Instead, as above, Krasikov served as the FCWA liaison. We anticipate that next steps would include a more formal advisory committee, which could be the FCWA as a whole or subset, along with other key partners. Meetings with an advisory council are where additional feedback and reflection would help in refining the maps, understanding local priorities, and determining what stories/scales are more important to highlight. The Fishkill Creek watershed characterization maps provide an important foundation to build support for next steps, including creating an advisory committee to inform and complete the next phases of the watershed characterization and management process.

boundary that Dutchess County[2] uses for their mapping purposes. This boundary closely corresponds to both a Hydrologic Unit (HUC10)[3] watershed and the boundary that is delineated by topography (choosing the watershed outlet as the point just upstream of where the mainstem Fishkill Creek joins the Hudson River).

The student partner, coauthor Gaffney, having completed a one-semester introductory GIS course, was hired to complete the watershed characterization maps during the 2024 summer (approximately 120 hours over 8 weeks) for course credit. After meeting to discuss the goals of the watershed characterization process, the student partner and his faculty mentor began by gathering publicly available datasets from state databases (such as NationalMap.gov), county planning agencies, and local sources (table 2). The links to these datasets were gathered as part of the PB-RJ and Sparkill Creek characterizations and are available in a spreadsheet (Supporting Information 1). These data layers were organized into themes to make a series of 17 maps. The student partner used the PB-RJ and Sparkill Creek characterizations as templates following the layouts of the PB-RJ and Sparkill Creek maps (Supporting Information 1). He completed the mapping remotely using ArcGIS Pro version 3.3, meeting with his faculty mentor at least once per week to discuss progress, troubleshoot, and review draft maps. Draft maps were shared with the project team twice during the summer to solicit feedback, and subsequent adjustments were made to what layers were included, map scale/extent, symbology, labels, and locations. During these meetings, the student partner and his faculty mentor also inquired about the availability of local data. However, most local data, due to logistical and technical constraints, could not be added to the maps during the timeframe of this phase of the project; as above, these data were noted and will be included in phase two (figure 2).

Table 2. Summary of GIS Data Used in the Hudson River Watershed Characterization Projects (See Supporting Information 2b for Links to the Data).[†]

Federal	• Watershed Boundary Dataset • 1/3rd arc-second Digital Elevation Models (DEMs)—USGS National Map 3DEP Downloadable Data Collection • National Hydrography Dataset • NLCD 2021 Land Cover (CONUS) • National Wetlands Inventory • National Flood Hazard Area
State	• Civil Boundaries • Water Wells • Aquifers • State Regulated Freshwater Wetlands • Hudson River Estuary Tidal Wetlands • Hudson Valley Forest Patches and Condition • Chemical Bulk Storage Facility • Inactive Solid Waste Landfills • Permitted and Reclaimed Mines • Petroleum Bulk Storage Facility • Transfer Facilities • Remediation Sites—Rockland • Remediation Parcels—Rockland • Riparian Buffers • Priority Waterbody List—Lakes, Priority Waterbody List—Estuaries, Priority Waterbody List—Streams • Aquatic Biological Monitoring • Water Quality Data Exchange (WQDE) Monitoring Locations in New Jersey • Natural Heritage Communities • Natural Heritage Important Areas in the Hudson River Valley • Natural Heritage Grid Map for New Jersey • Hudson Valley Significant Biodiversity Areas • Terrestrial Core Network in New Jersey • Sea Level Rise Certainty
Local	• Aquatic Biomonitoring Sites • Professional External Evaluations of Rivers and Streams (PEERs) Sampling Sites • Community Sampling Points • Dutchess County Subwatersheds • Dutchess County Villages • Dutchess County Cities and Towns • Roads • Putnam County Centerlines • Union Vale National Resource Inventory Layers • Agricultural Districts, Dutchess County

[†]While local data are likely to be unique to each community, many New York State datasets listed here may also be available for other U.S. states.

2. We have found that counties in the Hudson Valley have robust GIS programs and county-scaled data, and provide a valuable intermediary between local and state or federal scale watershed mapping (i.e., in cases they have corrected larger dataset to match local conditions).

3. Many watershed maps will use a Hydrologic Unit for the watershed boundaries, publicly available through the U.S. Geological Survey's Watershed Boundary Dataset, "a nationally consistent watershed dataset that is subdivided into 6 levels (12-digit [Hydrologic Unit Codes, or] HUCs) and is available from the USGS and USDA-NRCS-National Cartographic and Geospatial Center (NCGC)" https://water.usgs.gov/GIS/huc.html. Hydrologic Units are hierarchical and break down the United States into different size areas from regions to subregions, watersheds to subwatersheds, each representing smaller watershed areas. For example, a "HUC2 watershed," representing the largest areas, is, on average, 177,560 square miles, compared to a "HUC12 watershed" which is, on average, 40 square miles [35]. Thus, even using this readily available and standardized dataset requires a decision about what size HUC to use and whether to map at the subregion, watershed, or subwatershed scale.

The student partner generated 17 watershed characterization maps for the Fishkill Creek: Watershed Boundary, Watershed Map (with key location markers), Subwatersheds (HUC12), Agriculture, Aquifers and Wells, Built Environment, Dams and Culverts, Floodplains and Riparian Areas, Forest, Land Use and Land Cover, Population Density, Recreation, Significant Aquatic Habitats, Significant Habitats, Topography, and Water Quality and Wetlands. The choice of what maps to make was based on the templates available through the PB-RJ and Sparkill Creek characterization templates and community needs. A subset of these maps is shown in figures 4–7; all maps and links to data layers included in the maps are provided in Supporting Information 2. Supporting Information 3 provides additional details and guidance on starting and completing the watershed characterization process. The maps are shared with the broader community through the FCWA website and are being used as the first stage in the

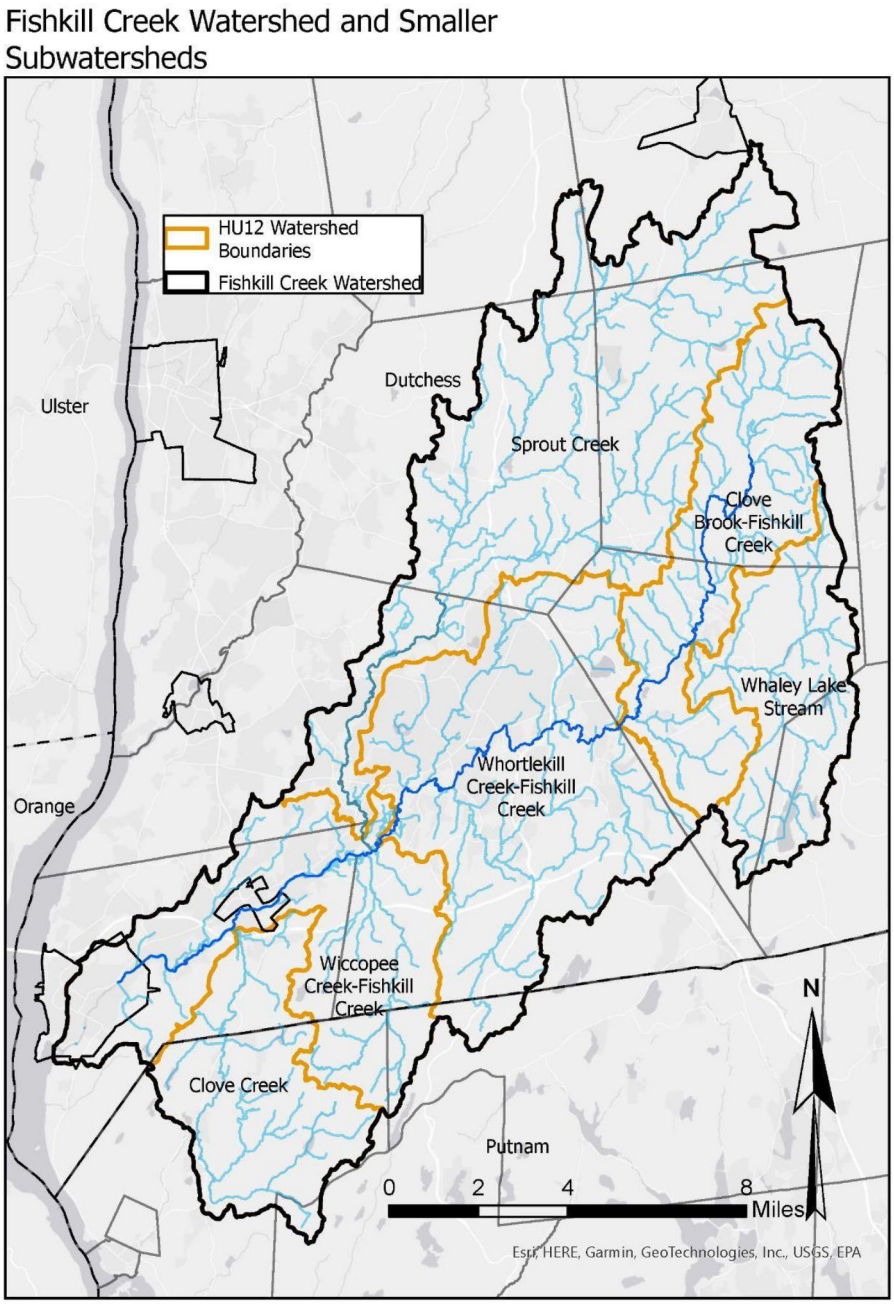

Figure 4. Subwatersheds (HUC12) watershed characterization map (see Supporting Information 2a for all maps).

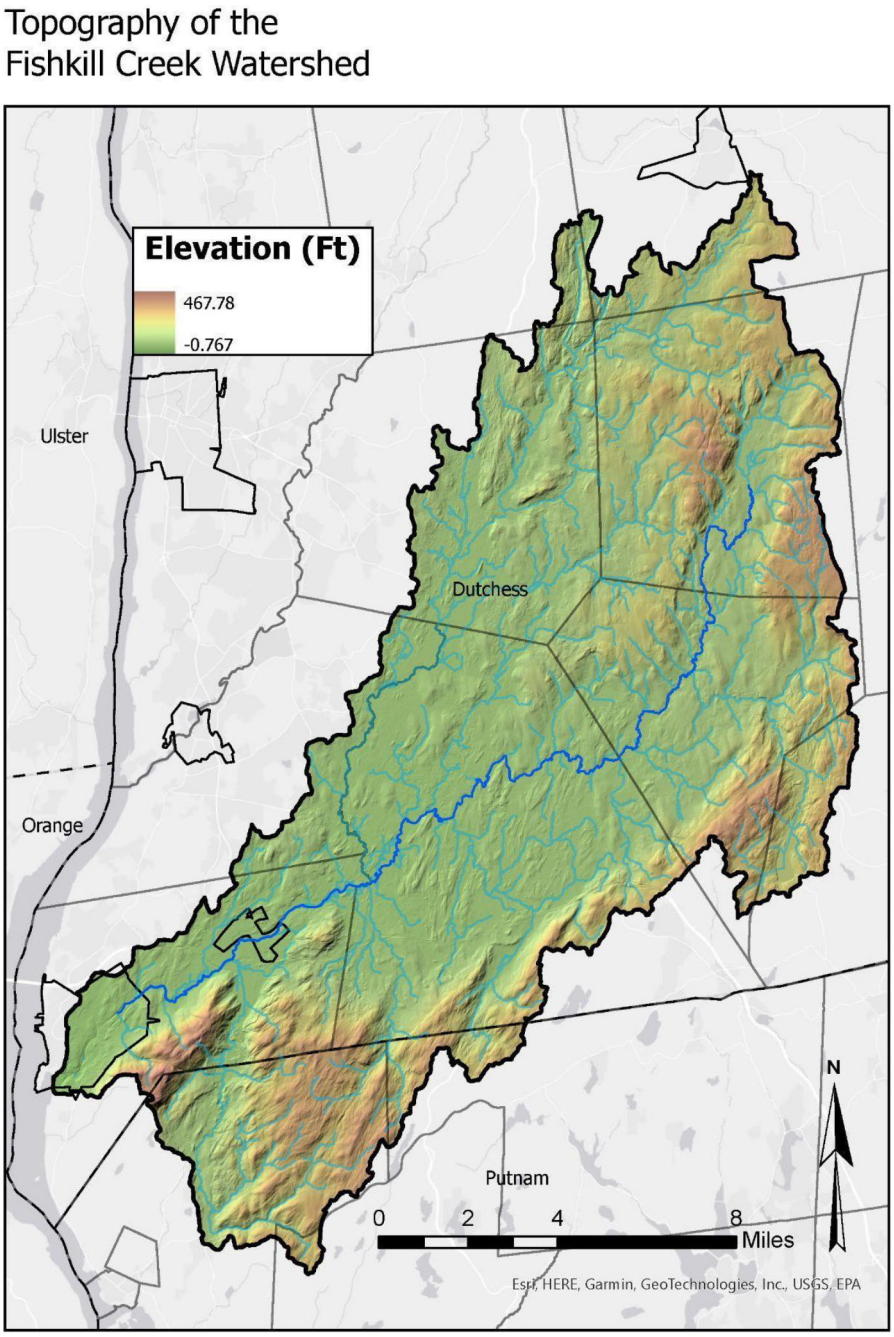

Figure 5. Topography watershed characterization map (see Supporting Information 2a for all maps).

FCWA watershed planning and management process. Though one summer was not enough time to gather all available data, or feedback that will be needed, these maps have already been used to start critical conversations about the watershed and lay the foundation for future planning and implementation. The maps have been used as part of grant applications to support watershed work; used to educate local residents, students, staff; and shared with donors boosting stewardship and engagement in the management process. FCWA members report that the maps act like magnets during community events, drawing the public in and allowing an opening to engage with people.

Discussion

While not every watershed group has access or funds to hire a GIS professional, we found that with HRWA guidance documents and templates, a student through

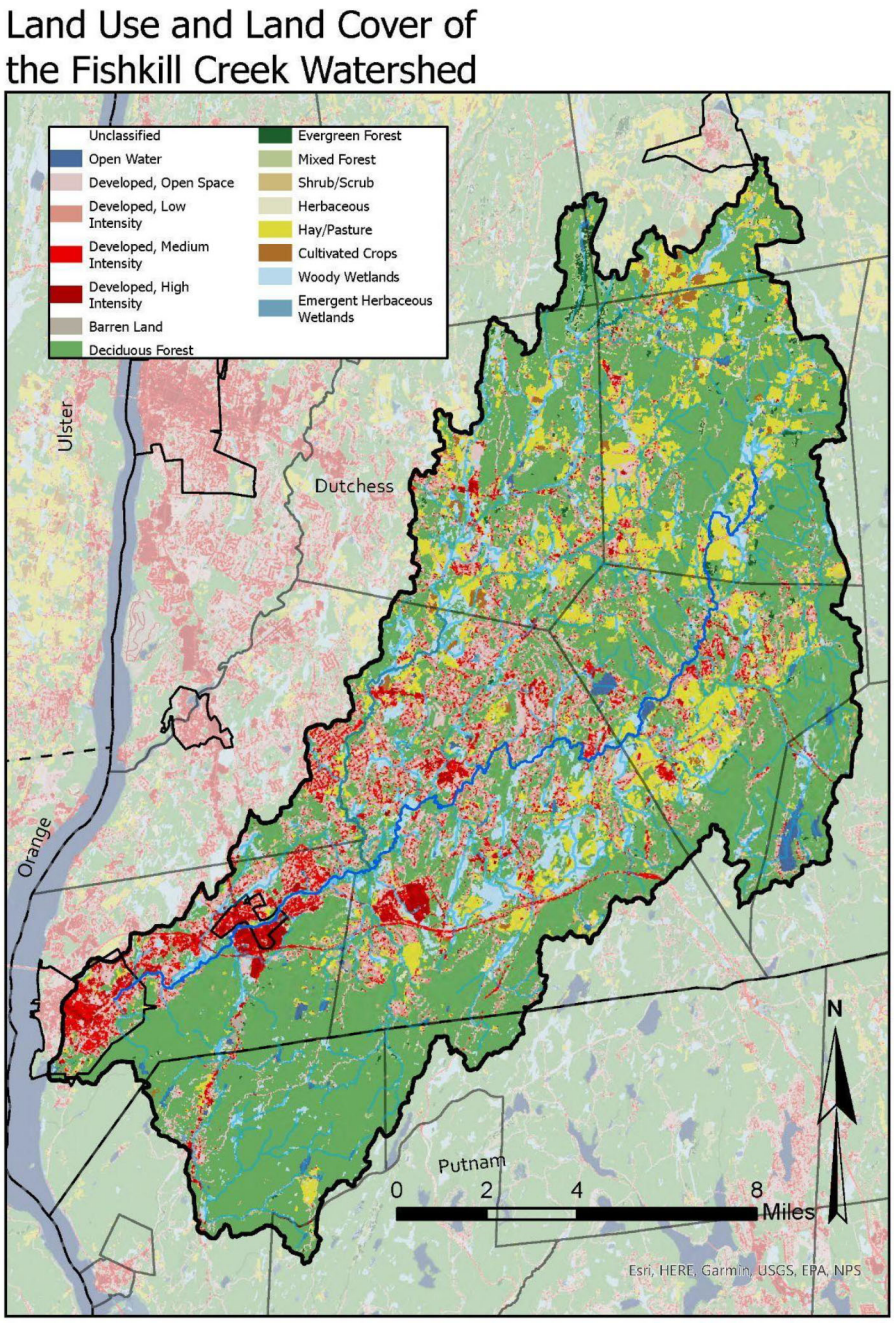

Figure 6. Land Use and Land Cover watershed characterization map (see Supporting Information 2a for all maps).

a summer internship could successfully and efficiently complete phase one of the watershed characterization. The project was mutually beneficial, with the student partner gaining important academic and professional skills, while providing technical GIS services to the community-led FCWA. Furthermore, with many academic institutions already partnering with local watershed groups, involving students with some GIS experience in these partnerships provides cost-effective technical support for low-resourced watershed groups, and may be a mechanism for creating high-quality and customized watershed maps at a scale necessary to meet the planning and management needs in the region. Yet, there are key lessons learned, summarized below, that should be considered during the watershed characterization process.

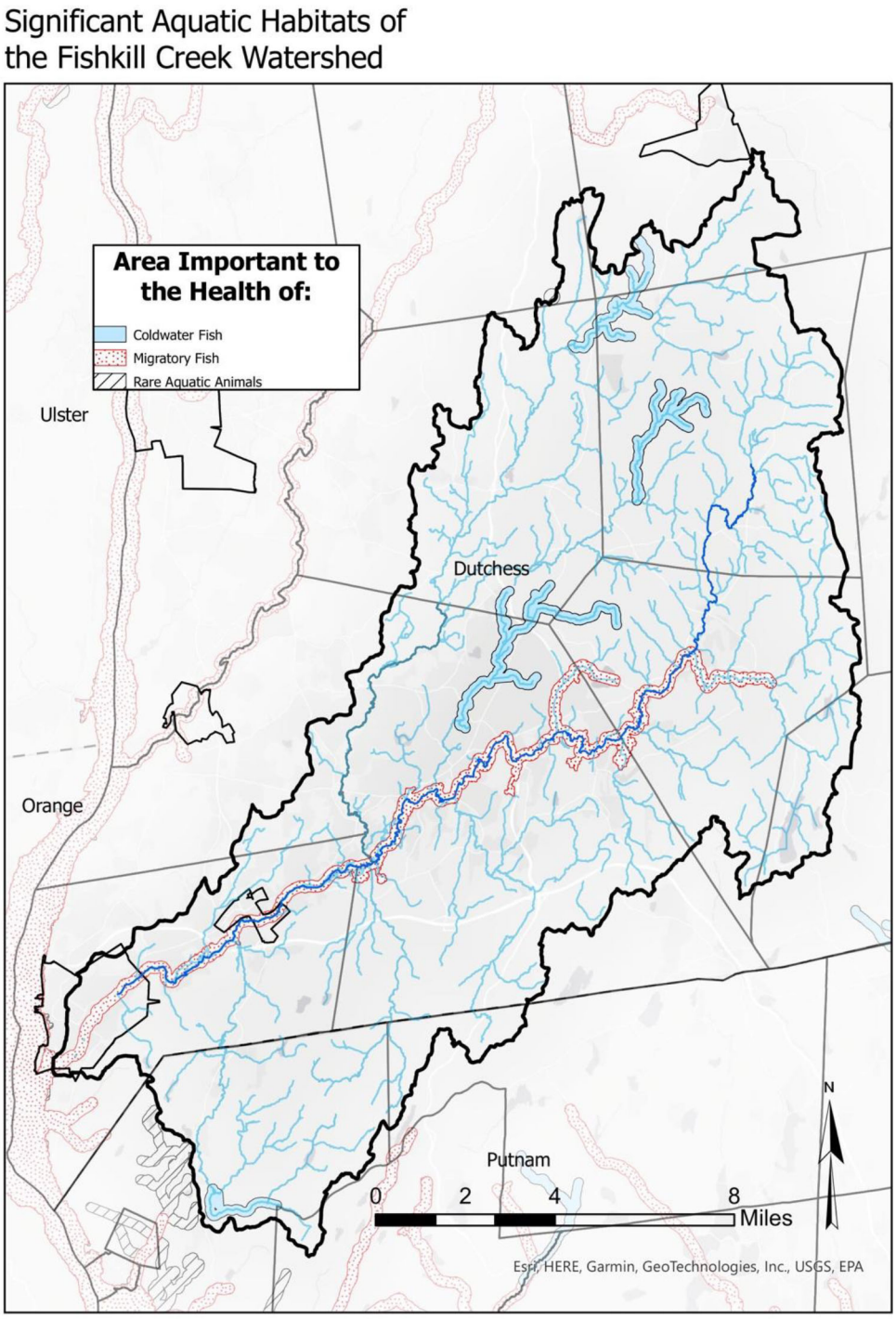

Figure 7. Significant Aquatic Habitats watershed characterization map (see Supporting Information 2a for all maps).

UNDERSTANDING PROBLEMS, AND FINDING AND TELLING WATERSHED STORIES. We may assume we know the most pressing problems a watershed faces, but a closer look can reveal key information that may be missing, or not understood by the entity guiding the planning and management process. Watershed characterization supports open-minded inquiry and helps stakeholders discover and understand watershed challenges. If the watershed management process is too solutions-driven without taking the time to understand the watershed from multiple perspectives, watershed problems may be understood incorrectly or inadequately.

Watershed characterization is not simply gathering information and making maps (although that is central), but also needs to involve organizing and structuring information to develop a shared understanding of the watershed and the problems the watershed group wants to address [13]. For example, during the Sparkill Creek watershed characterization process, there was careful consideration of how the data were organized into themes and which layers to include. Previous Sparkill watershed maps had more often highlighted natural elements such as forests and wetlands. But through the watershed characterization project, a map of the built environment was made to include Superfund sites, revealing the extent to which these sites were contributing to groundwater contamination, and possible surface water contamination. Though the community had known of the Superfund sites, including them in the map with other elements of the built environment helped them clarify for themselves and regional partners, the connection between the sites and groundwater and surface water quality.

The Sparkill Creek built environment map (Supporting Information 1) is an example of how compelling visuals like maps can be powerful tools for finding and telling watershed stories [11]. They can help make the invisible visible [12], revealing new information, insights, perspectives and stories about the watershed that the group had not considered before, and illustrate and provide visual evidence of local knowledge [11]. But in order to be used as tools to tell watershed stories and to engage diverse audiences in watershed science and conservation, watershed maps need to be customized and interpreted based on local understandings of a place. Using templates from past watershed characterizations is a starting point, but ongoing engagement among the project team and the broader community is needed to ensure the watershed characterization process is iterative and maps are updated as new stories emerge. For example, though the PB-RJ and Sparkill Creek watershed characterization maps provided templates as starting points, the "stories" of these two watersheds are very different from those of the Fishkill Creek. To start, the Fishkill Creek Watershed includes a mix of land use types, while the PB-RJ is more rural than the Fishkill and the Sparkill is generally more urban, creating three very different stories about how land use and development impact flooding and water quality. Thus, even with these templates, a lot of decision-making needs to happen about how to organize map themes and what layers to include, especially by the watershed group members and other local stakeholders. And this feedback is crucial for the student to create maps that are customized to local needs. Templates provide a helpful starting point so more time and energy in decision-making conversations can focus on adapting the templates to better address local needs, interests, and stories, rather than creating them from scratch.

ACADEMIC-COMMUNITY PARTNERSHIPS. Creating maps that accurately reflect and communicate local conditions requires community knowledge and input, and cannot be completed by technical experts alone. Subsequently, to do well, watershed planning and management takes a lot of time and resources. For community-led watershed planning, this can often mean running out of time or resources before the implementation phase begins [27]. The question arises, then, how can we do community-led and community-centered watershed planning and management at the scale necessary to meet regional and state watershed management needs? One approach is to use GIS-based academic-community partnerships, also called community-engaged learning, community-engaged scholarship, or academic service learning, where students and their faculty mentors complete GIS data management, mapping, and/or spatial analysis work for a community partner (e.g., municipality, not-for-profit, community-based group). These partnerships can help build capacity [36], by, for example, freeing-up time and resources, so watershed groups can focus on other elements of the planning and management process. Moreover, GIS software can be expensive and often it is not feasible for a local non-government organization or small government agency to purchase licenses or hire experienced GIS personnel. Though publicly available GIS tools exist, these require time, capacity, and technical resources that may not be readily accessible to non-GIS professionals [11, 20, 37]. In GIS-based academic-community partnerships, students complete GIS work for the community partner, with the partner needing to invest fewer financial resources. This was the case for the Fishkill Creek watershed characterization project. The FCWA is an all-volunteer watershed group without staff or members with GIS expertise. The student partner completed watershed maps with significantly less funding than would have been required if the FCWA had hired a professional GIS consultant.

GIS-based academic partnerships can be beneficial to not only watershed groups but also students and their faculty mentors as well [21, 22, 36]. Working with a community partner provides opportunities for students to learn through experiential, real-world projects, helping build academic and professional competencies, particularly those needed to address the sustainability challenges of today and the future, such as critical thinking and analysis, collaboration, and problem-solving [24–26]. In particular, when GIS skills are practiced through applied, hands-on, real-world projects, it enhances learning, problem solving skills, engagement, and employability [38–40], and students better understand how their GIS skills address community needs [36]. During the Fishkill Creek watershed characterization project, the student partner was able to practice his GIS skills while gaining valuable experience that informed his decision to apply to graduate school and will help with future job prospects. For faculty, these projects provide opportunities for innovative and effective teaching [23], and rewarding service and scholarship [22]. Supporting Information 3 provides alternative models for completing watershed characterizations through academic-community partnerships and resources for building collaborative and equitable academic-community partnerships.

EXPERTISE AND ROLES. While GIS professionals may have technical expertise, they may not have an understanding of local needs or knowledge of what GIS data are needed or available to tell the watershed's story. At the same time, while there are free and publicly available GIS resources available to community groups, watershed group members may not have the time, computing resources, capacity to learn or use the software, or familiarity with datasets and approaches to watershed-scale mapping. One of the powerful things about completing watershed characterization through academic-community partnerships is the ability for the watershed community to be in the right role, for example, uplifting local feedback in support of local goals, rather than trying to manage this GIS work on their own. They can focus on developing scopes of work on specific projects or studies based on the characterization. For example, the characterization process might reveal that water quality data are outdated, and watershed groups can work with colleges/universities or other partners to update that information. This approach might be particularly well-scaled for the work of watershed groups in moving forward with their goals, even without a full, formal watershed management plan.

In addition to GIS technical knowledge provided by the student partner and knowledge of community needs provided by the FCWA, other forms of knowledge and expertise were crucial for ensuring successful project outcomes. The student partner was able to create the Fishkill Creek watershed maps using the expertise and knowledge generated through the 2-year PB-RJ Kill and Sparkill watershed characterization guidance and templates. Including Beacon Institute and HRWA staff as part of the project team provided not only local but regional knowledge, institutional memory, and project management support. Furthermore, the administrative and management support they provided meant the student partner and his faculty mentor could focus on mapping. Meanwhile, the FCWA focused on providing iterative feedback to ensure the maps were accurate and useful for education and planning. Students may not be able to access all relevant data, especially in the available time frame, such as culverts or Municipal Separate Storm Sewer System (MS4) mapped outfalls. Other team members with regional connections may be better positioned to inquire and follow up on those datasets than a student.

BUILDING CAPACITY FOR WATERSHED WORK. Developing watershed characterizations through academic-community partnerships can build capacity for community-led watershed work in a number of ways. In addition to working in teams with diverse expertise and ensuring everyone is in the right role, the approach described here is systematic and scalable to meet the watershed planning and management needs of the region. In the case of the PB-RJ watershed characterization, the municipalities involved in the project had not previously worked together at the watershed scale. Working on the watershed characterization project, brought these municipalities together to start critical conversations about the watershed. Because the HRWA completed the watershed characterization process, the group could focus on other watershed-scale planning and management priorities.

One of the most important lessons learned through the Hudson River watershed characterization projects is a better understanding of the number of decisions that need to be made throughout the process, such as what to use as the watershed boundary and what layers to include and how they should be organized and symbolized.

During the Fishkill Creek watershed characterization process, decisions included how much of the Hudson River mainstem should be shown and what places should be included in the maps. Starting with templates and direct links to datasets helped reduce workload burdens and "decision fatigue" at the beginning of the planning process. The consequences of decision fatigue, that is, mental and physical fatigue that can result from repeated decision-making, include inaction and can negatively impact executive functioning and reasoning [41]. Using templates and links to available data meant that a student could easily create general maps to share with the team, allowing most of the decision-making energy, as well as project time and budget, to be spent on customizing these maps (rather than what maps to make) and illustrating key points. These types of decisions can be undervalued and are often invisible to those outside of the project team, but are crucial for ensuring users understand and connect with the watersheds the maps depict.

CONCLUSION

While strong watershed plans can help groups build capacity, the reverse is also true. Strong, high-capacity watershed groups result in better watershed plans, including more inclusive community engagement, a more thorough understanding of current watershed conditions, and deeper relationships with stakeholders to prepare for implementation projects [27, 28]. The Fishkill Creek watershed characterization project demonstrates that watershed groups have unique and specialized knowledge of local watershed issues, are strong advocates for their waters and their communities, and are well positioned to be leaders in the watershed planning and management process. However, watershed groups, particularly all-volunteer groups like the FCWA, need more capacity to do this work so that it is impactful, strategic, and sustainable. Academic partners can provide technical resources, like GIS mapping expertise, to support planning efforts, highlight local knowledge and identify watershed problems at multiple scales, but must be done through strong partnerships and in ways that center community needs. When students complete watershed characterization maps, they build their GIS skills through a real-world project, gaining the academic and professional competencies they will need to address today's water sustainability challenges and those of the future.

CASE STUDY QUESTIONS

1. What is a watershed characterization and why is it an important first step in the watershed planning and management process?
2. What role can students with GIS skills and knowledge play in the watershed characterization process? What role can communities play in the process and what skills and expertise do they contribute?
3. What are the benefits to community groups of working with academic partners to complete the watershed characterization process? What are the benefits to students?
4. The maps presented in this case are traditional static maps. What online mapping tools could be used to communicate and deepen engagement with watershed characterization? Do some research and suggest hardware, software, and interface designs that could be used.
5. Research a watershed of your choice. Can you find watershed characterization maps, and if so, what information is included and how does it compare to the Fishkill Creek watershed characterization maps? What watershed or community groups who might participate in watershed characterization, if any, can you identify? What data sources can you identify that would be a basis for an initial or extended watershed characterization?

AUTHOR CONTRIBUTIONS

KM, EV, SK, and AP conceptualized the project. CG completed the watershed characterization maps. EV and KM cowrote the original paper draft. Subsequent paper revisions were edited by all authors co-equitably.

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COMPETING INTERESTS

The authors have declared that no competing interests exist.

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DATA ACCESSIBILITY STATEMENT

All GIS data used in this project are listed in Supporting Information 1d, 1h, and 3.

SUPPORTING INFORMATION

- Supporting Information 1a. Punch Brook-Roeliff Jansen Kill (PB-RJ) Watershed Characterization Report. https://hudsonwatershed.org/wp-content/uploads/Punch-Brook-Roe-Jan-Watershed-Characterization-Report.pdf
- Supporting Information 1b. Punch Brook-Roeliff Jansen Kill (PB-RJ) Watershed Characterization Community Presentation. https://youtu.be/f1oryinv1Ss?si=cVwWDv292g7aabSF
- Supporting Information 1c. Punch Brook-Roeliff Jansen Kill (PB-RJ) Watershed Characterization map templates. https://drive.google.com/file/d/1FeI4dHdtXICcvXVW QSqQGJY6LDOhQNxt/view?usp=sharing
- Supporting Information 1d. Punch Brook-Roeliff Jansen Kill (PB-RJ) Watershed Characterization links to GIS datasets. https://docs.google.com/spreadsheets/d/1DrrWXrYeclFJ7vudxLB7_i6i7aYzPOyU/edit?usp=sharing&ouid=107080153821620487060&rtpof=true&sd=true
- Supporting Information 1e. Sparkill Watershed Characterization Report. https://hudsonwatershed.org/wp-content/uploads/Sparkill-Creek-Watershed-Characterization-Report.pdf
- Supporting Information 1f. Sparkill Creek Watershed Characterization Community Presentation. https://youtu.be/NfVZju1KbnE?si=wU8I5m45I5TctRAQ
- Supporting Information 1g. Sparkill Creek Watershed Characterization map templates. https://drive.google.com/file/d/1Fcyw9dihQc0gjmAjdPyZ7-cDsfL6UHMm/view?usp=sharing
- Supporting Information 1h. Sparkill Creek Watershed Characterization links to GIS datasets. https://docs.google.com/spreadsheets/d/1iE80PitgPWi7AHfTUNevJDfxdlTbGx5p/edit?gid=1285770084#gid=1285770084
- Supporting Information 2a. The student-generated Fishkill Watershed Characterization maps. https://doi.org/10.5281/zenodo.15121403
- Supporting Information 2b. Links to GIS datasets: Fishkill Watershed GIS Data Spreadsheet. https://docs.google.com/spreadsheets/d/1irsZKuWtRQlSbtYrVBq0OL849PxRLGNL3uLNlcJ2Yro/edit?usp=sharing
- Supporting Information 3. Student/faculty mentor guidance document. https://docs.google.com/document/d/e/2PACX-1vSbc7xjXNjG8EAPsUB4RJmPourak2SwK8wNTARAh17VrgNP0Dolp10GueDr6Iui35gvaRRZi8dSZebD/pub

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