A Community-Centric Intelligent Cyberinfrastructure for Addressing Nitrogen Pollution using Web Systems and Conversational AI

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Abstract

The Blue-Green Action Platform (BlueGAP) information system (IS) is an intelligent cyberinfrastructure framework designed to support large-scale water quality assessments in the context of demographic statistics and community stories about water issues. The system prioritizes collaboration with interested parties in three pilot watersheds with test cases implemented in US locations including Iowa, Tampa, and the U.S. Virgin Islands. The BlueGAP IS leverages Artificial Intelligence (AI) technologies with large language models based on regional nutrient management issues and community knowledge to provide access to water quality information. The current focus of the system is on nitrate in drinking water, rivers, and waterways, and can be expanded to incorporate other water quality information. BlueGAP identifies possible partnerships and promotes collaborations among diverse stakeholders to facilitate effective evaluation of nitrogen-related analytes, guide action to address possible pollution, and outline sustainable water management practices. The BlueGAP IS also emphasizes its educational mission by connecting water quality data with inclusive and accessible educational content through AI technology. By integrating nitrogen data and water quality issues into educational resources, BlueGAP fosters a deeper understanding of water quality issues across diverse communities, empowering users to make informed decisions and contribute to sustainable water management practices.

Keywords: web systems, information systems, AI agents, nitrogen pollution management, water quality, large language model, conversational AI

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1. Introduction

Watershed health and drinking water play crucial roles in the formation and upkeep of a strong and sustainable economy; an integrated approach to economic development and environmental sustainability must be used when dealing with water resources (Mount et al., 2023). One major problem negatively impacting watershed health, from spring sources to the estuary and ocean, is nitrogen pollution. This is a widespread problem that poses a significant risk to the health of impacted communities (Demir et al., 2009). Its harmful effects spread to nearby and more distant waters in a watershed resulting in elevated levels of unwanted bacteria, algae, and plants that have the potential to upset entire ecosystems (Baydaroglu et al., 2024). Nitrogen pollution can cause serious health problems for humans, fish, and wildlife.

The United States experienced a sharp increase in nitrogen pollution in the middle of the 20th century, which was correlated with the growing use of synthetic fertilizers in agriculture, farming practices (waste from CAFOs) and the development of industrial actions such as manufacturing, chemical production, and urban development (Davidson et al., 2012; Gilbert, P. 2020). Compounded environmental problems that exacerbate those caused by pollution and climate change developed over the next few decades. This is the focus of ongoing management efforts to address nitrogen pollution.

In 1972, the United States took a substantial step towards addressing water pollution with the passage of the Clean Water Act (Hines et al., 2013). The legislation aimed to regulate and reduce water pollution, particularly focusing on point source pollution originating from wastewater treatment plants and industrial facilities. By the late 20th century, nitrogen runoff from fertilized farmlands, CAFOs (Concentrated Animal Feeding Operations) and urban areas emerged as a dominant contributor to water pollution in rivers and streams. A majority of nitrogen pollution currently originates from diffuse, non-point sources that are more difficult to regulate. Among the most serious consequences of this nitrogen excess are coastal harmful algal blooms, areas of hypoxia, and general degradation of coastal ecosystems including coral reefs, seagrasses, and areas that otherwise are attractive to tourists (Rabalais et al., 2002). The reduction of nonpoint sources of nitrogen pollution remains a critical issue for many communities and additional resources are needed to inform how to address these challenges under existing regulatory frameworks, through best management practices or grassroots efforts.

The environmental degradation in water resources is a stark reminder of the consequences of excessive nitrogen pollution, affecting not only the balance of aquatic ecosystems but also the quality of drinking water sources. Craswell et al. (2021) noted that nitrogen pollution is not limited to surface water bodies alone. Groundwater, a crucial source of drinking water for many Americans, can also be contaminated by nitrogen pollution (Sit et al., 2021). This issue is especially pronounced in rural areas, where septic systems and agricultural runoff leach nitrates into aquifers, rendering well water unsafe for consumption. Nitrate contamination of groundwater remains a significant concern in Iowa, affecting drinking water sources and necessitating costly remediation efforts. The environmental and human health impacts resulting from this contamination are matters of concern. In coastal regions including Tampa Bay and the

U.S. Virgin Islands, nitrogen pollution, a large fraction from atmospheric deposition of nitrogen oxide from burning of fossil fuels, led to eutrophication, algal blooms, and fish kills, posing significant threat to aquatic ecosystems (Heil et al., 2021).

One of the most difficult issues in addressing nitrogen pollution is the limited information available to the public about conditions in drinking water and local water bodies, and information about the consequences of nitrogen pollution. We have created a cyberinfrastructure framework that allows spatial and temporal analysis and visualization of water-quality data. Another unique feature of the Blue GAP Information System is the capacity to connect data with engaging and educational content, significantly contributing to enhancing nitrogen pollution literacy for everyone. By providing local communities testimonies and experiences with water quality issues and clear explanations of fundamental concepts and processes related to nitrogen pollution, our community comprehends the serious impacts of nitrogen pollution.

This understanding is crucial for addressing the environmental challenges posed by nitrogen pollutants effectively. We tested the technology in Iowa, the Tampa Bay watershed, and in the U.S. Virgin Islands to exemplify locations with different but potentially complementary contexts in addressing nitrogen pollution. These areas also exemplify the challenges in both the quantity and quality of data and existing regulatory, political, and social infrastructures to manage nutrient pollution. The framework provides users with seamless access to data pertaining to various nitrogen-related analytes, using various data sources distributed across different counties and zip codes. Users can access detailed demographic information about the selected regions. Furthermore, the system allows users to explore the stories of numerous community "Champions" and experts across various fields, providing a bridge between the data and community to inform action in addressing nitrogen pollution.

Through the interactive platform, users can engage with AI representations of these individuals from within the three regions, as well as an AI 'Expert' trained on extensive vetted technical documents related to nitrogen and water quality. This engagement facilitates the resolution of queries from local residents in a manner that brings local knowledge to communities. The system generates action plans to address specific concerns, leveraging the expertise of Champions and experts. By combining data access, demographic insights, and direct interaction with AI representations of local figures, the system streamlines the process of obtaining information and resolving queries related to water quality.

The organization of this paper is described as follows. Section 2 introduces the methods used to create the framework for the information system. Section 3 introduces the functionality of BlueGAP IS with detailed description of both the frontend and backend Application Programming Interface (API). Section 4 and Section 5 introduce the overall results and conclusions of the project.

1.1. Literature Review

With increasing demands on limited water resources from urbanization and population growth, water quality management is an important aspect of environmental protection. The necessity for effective data management strategies in the monitoring and management of water resources has led to the development of numerous web-based systems for the administration and display of data linked to water quality and management (Yesilkoy et al., 2023).

The integration of web technologies in environmental science has revolutionized the way data is managed (Demir et al., 2022), analyzed, and communicated, marking a significant leap forward in efficiency and effectiveness. In the realm of water quality management, these advancements have proven particularly vital. Web technologies facilitate the seamless aggregation, storage, and retrieval of vast amounts of environmental data from disparate sources, enabling comprehensive datasets to be easily consolidated and made accessible to diverse stakeholder groups. Analytical tools powered by web technologies allow for sophisticated data modeling (Li and Demir, 2022), visualization, and interpretation, transforming raw data into actionable insights that drive informed decision-making (Alabbad et al., 2024). This is crucial for water quality, where timely and accurate analysis can significantly impact public health and ecosystem management. Additionally, web-based platforms enhance communication channels (Sermet and Demir, 2022), providing real-time updates and fostering interactive engagement among researchers, policymakers, and the public. By leveraging the connective power of web technologies, environmental scientists can share critical findings more broadly and rapidly, ensuring that communities and decision-makers are equipped with the knowledge needed to address water quality challenges effectively and sustainably.

Yang et al., (2010) stress urgency in addressing problems of data quantity for watershed monitoring. The study focuses on the evolution of web-based technologies for visualization and analysis in response to the growing maturity of computer-assisted data analysis (Ramirez et al., 2022). The creation of a prototype system that integrates data analysis and visualization is the BlueGAP project's main objective. The result of this effort is a web-based data visualization and analysis system that enhances the effectiveness of watershed management activities by simplifying the usage of data exploration, analysis, and downloading (Shahid et al., 2023).

Simultaneously, Cham et al., (2020) stress the significance of data visualization for the effective interchange and understanding of water quality information. The authors developed a real-time web-based water quality monitoring system using Google Earth, based on the National Water Quality Index of Malaysia (NWQI). The study demonstrates how web-based water quality index systems may identify sources of contamination and assess regional differences in water quality trends.

Furthermore, surface water quality analysis is examined by Bernatska et al., (2023), particularly in relation to mining and chemical companies. The study emphasizes the need for an information and analytical monitoring system to store, process, and analyze data on environmental contamination. A web application based on an interactive map of the sites where water samples are collected, a display of the results of hydro-chemical monitoring, and an evaluation of the state of the water environment are the recommendations made by the researchers. The methodology provides a valuable tool for forecasting changes in the domain's environment of the chemical and mining sectors.

The advent of conversational AI systems and large language models has marked yet another transformative shift in environmental education (Pursnani et al., 2023), communication and public awareness, with opportunities to address challenges such as water quality, flooding, and drought. Conversational AI systems, powered by these advanced language models, provide an intuitive and accessible means for the public to engage with complex environmental data. These systems can interpret and respond to user queries in real time, demystifying scientific terminology and presenting information in a user-friendly, understandable format (Sajja et al., 2023). This capability is crucial in raising awareness, educating the public, and fostering informed communities, particularly regarding water quality issues that have direct and immediate implications for public health and safety (Sermet and Demir, 2021).

Moreover, conversational AI will eventually be able to disseminate critical information during environmental hazards like flooding and drought, providing timely guidance and resources. By offering personalized and context-specific insights, these AI systems empower individuals and communities to take proactive measures, thereby enhancing resilience and adaptive capacity. The integration of conversational AI and large language models represents a significant advancement in environmental communication (Vald et al., 2024), bridging the gap between scientific data and public comprehension, and facilitating a more engaged, educated, and responsive society in the face of environmental challenges (Samuel et al., 2024).

Ultimately, these studies highlight the importance of data synthesis and visualization to solve a variety of environmental issues. The public's ability to obtain knowledge about the quality of the water resources in their immediate surroundings is greatly facilitated by the availability of this information. It also acts as a catalyst for raising consciousness and encouraging accountability for protecting the aquatic species found in these water resources. The integration of different tools and features highlights the possibility for effective data processing, visualization, and public participation in environmental conservation initiatives. Active participation of stakeholders in the preservation and improvement of aquatic environments can be facilitated by utilizing integrated web-based platforms that distill data into actionable information.

2. Methods

2.1. Purpose and Scope

The Blue-Green Action Platform (BlueGAP) brings together diverse academic and government scientists, environmental and community organizations, and individuals to address the problem of aquatic nitrogen pollution, inclusive of underestimated communities. The BlueGAP IS was created and designed to support this objective by facilitating education, communication, and collaboration among its users. The BlueGAP IS provides unrestricted access to water quality data that is often difficult to obtain and interpret. While the data integrated into the BlueGAP IS is publicly available, comprehending data from various repositories, such as the United States Geological Survey (USGS) National Water Information System and the Environmental Protection Agency (EPA) STOrage and RETrieval database, including their parameter codes and data processing methods, is essential to transform environmental observations into easily understandable formats. Additionally, the system provides an interface to explore a wide range of stories from local and community partners with different areas of expertise (referred as "Champions" in the interface). Subsequently, if users wish to interact with AI agents representing their chosen Champions, they can ask questions about their issues, and the AI agent will provide a detailed action plan tailored to the user's specific needs.

The IS is also designed to enhance educational outreach and capacity building through the integration of AI-driven resources. It offers users the ability to explore fundamental concepts and processes related to nitrogen pollution via AI agents and the AI Action Planner tool. These tools enable users to make inquiries and receive tailored guidance, particularly within the "Capacity Building and Education" problem domain. This aspect of the IS is dedicated to improving educational efforts and expanding outreach, empowering users to better understand and address nitrogen pollution challenges. This paper primarily focuses on the front-end interface and backend systems that contribute to the functionality of the BlueGAP IS.

The BlueGAP IS aggregates and enhances water quality data from existing repositories, including USGS NWIS, USEPA STORET, Iowa Water Quality Information System (IWQIS), IADNR – Iowa Department of Natural Resources, SDWA – Iowa (Safe Drinking Water Act), PWS – Tampa Bay (Public Water Supply), PWTS – Iowa (Public Well Tracking System), EPC – Tampa Bay (Environmental Protection Commission of Hillsborough County, Tampa Bay Coastal Sites) and TBW – Tampa Bay (Florida Department of Health). Furthermore, additional data sources can be incorporated to encompass information from other federal, state, regional, and local entities, as well as data collected by individuals or groups.

The BlueGAP IS offers the following functionality:

- A unified platform for discovering information about various champions in selected regions and engaging with their AI agent counterparts.
- Access to extensive datasets spanning various spatial and temporal scales.
- Visual representation of time series data sourced from USGS, EPA, SDWA, PWS, PWTS, and IWQIS.
- Access to demographic data (Ebi, 2019) specific to the chosen regions, including information at the county, zip code, and census tract levels from EPA Environmental Justice Screening and Mapping Tool (EJScreen).
- Access to both data and analytical tools in one location, eliminating the need for manual downloading and processing of substantial data volumes from multiple providers.
- Interact with AI agents serving as water quality expert, data expert, community champion, sensor data agent, and knowledge expert.

2.2. Cyberinfrastructure Design

The web-based cyber infrastructure system is designed to efficiently handle high-dimensional spatiotemporal water quality-related data by optimizing resource utilization. The primary tools employed in the construction of the system include:

- Frontend: React, MUI, JavaScript, HTML, CSS
- Backend: Python, Unicorn and FastAPI
- Web server: Nginx
- Database: PostgreSQL with PostGIS spatial extensions

Frontend: Modern component-based software architecture has been employed to ensure a highly modular codebase with exceptional adaptability. The BlueGAP IS is constructed on the React framework and utilizes the Material-UI (MUI) design library, which adheres to best UI/UX practices such as consistent and component-based design. Map visualization and interaction are facilitated through the Google Maps API. This interface supports interactive raster, polygon, advanced marker views, and point data with geospatial filtering. Furthermore, it offers dynamic plotting and visual navigation across different geospatial scales and data types. Apart from emphasizing sustainability and modularity, the system has strong error-handling features, especially when using API calls to get data from various sources. For large data requests, asynchronous calling has been enabled to optimize efficiency and guarantee seamless operation. By taking this proactive step, possible system performance lags are avoided, which improves user experience.

In addition, the system uses careful state management in React to guarantee consistency in data presentation across various components and interfaces. The system's ability to remain organized allows it to provide a unified and dependable user interface, which improves the overall effectiveness of data display. In order to ensure long-term sustainability and modularity, our system has been designed with a focus on incorporating various components. This approach aligns with fundamental coding principles such as SOLID (Single Responsibility, Open-Closed, Liskov Substitution, Interface Segregation, and Dependency Inversion) and DRY (Don't Repeat Yourself). By adhering to these principles, we ensure that our codebase remains organized, scalable, and easy to maintain.

This deliberate design enhances the system's stability and fosters adaptability to future changes. The utilization of distinct components ensures a high degree of flexibility, allowing seamless integration of new features or modifications. As technology evolves and requirements shift, our system can embrace these changes without compromising its structural integrity. This commitment to a modular and principled approach underscores our dedication to delivering a robust and future-proof solution.

Backend: PostgreSQL is a stable and open-source database that has been used across many sectors over the past 25 years. It is distinct from other object-relational databases by offering a flexible architecture that can be expanded by developers and regular users, in addition to complying with numerous SQL standards. PostGIS, an essential addon that enables PostgreSQL to manage operations like generating, saving, and altering spatial data, is an illustration of this extensibility. Data transformation, data export, and geometric and geographic analytical techniques are also supported. For most of the data in the BlueGAP IS, PostgreSQL is the primary data storage system.

Nginx is an open-source, high-performance web server, load balancer, proxy, and gateway. Its architecture is non-blocking, and it can manage high concurrency levels of incoming requests. Nginx serves as both the routing mechanism to the gateway API and the standard web page in the context of BlueGAP IS. Uvicorn, which is an ASGI (Async Server Gateway Interface) web server implementation for Python, serves as BlueGAP IS's application server, and collaborates closely with Nginx. Nginx smoothly transfers any HTTP requests involving the API route to Uvicorn for processing.

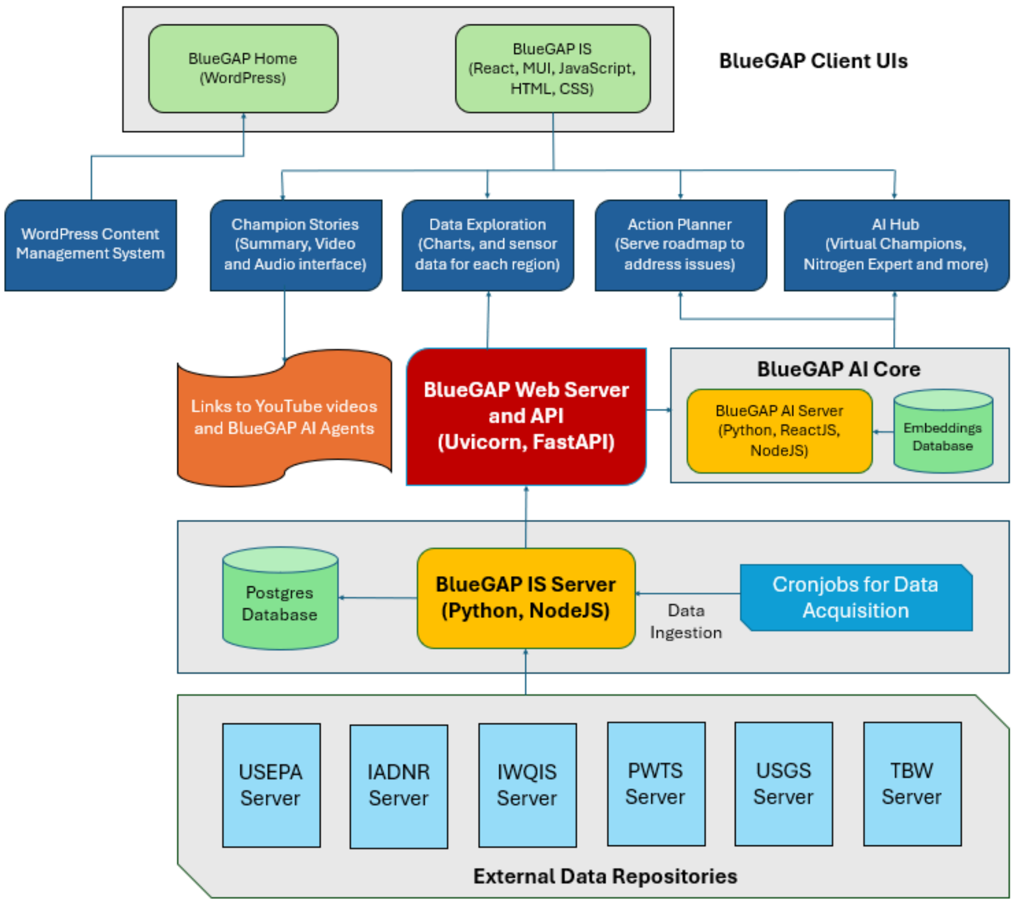


Figure 1. System architecture and components for BlueGAP IS

The overall architecture for the BlueGAP IS is shown in Figure 1. The BlueGAP Web Server and API act as the gateway to BlueGAP clients, for the entire system's functionality. This server ensures a secure connection and defines the correct query syntax needed to retrieve information. The architecture includes endpoints that provide isolation between user requests and the database, enforce rules for non-ambiguous queries, ensure resilient and common access protocols, and tailor results to the specific requests made by clients or the system. The system relies on periodically fetching updated data from external repositories. The BlueGAP server handles the necessary data ingestion process, storing this data in the PostgreSQL database. This design ensures that the BlueGAP IS remains functional even if there are issues with external data repositories, maintaining a robust and reliable system for users.

The AI agents are designed to facilitate intuitive, natural language-based interactions with complex water quality data, forming a part of the greater BlueGAP Information System. The system employs a multi-tier architecture, integrating several technologies to achieve data retrieval, processing, and interaction. The core components include a Data Aggregation Layer (BlueGAP Web Server and API) that consolidates data from sources like the National Water Information System (NWIS) and the EPA's STORET system, categorized into public drinking water, private drinking water, recreational waters, and ocean recreational waters. The AI Services Layer provides essential functionalities such as Named Entity Recognition (NER), geocoding, and sentiment analysis, leveraging OpenAI's GPT models for sophisticated natural language understanding and response generation. These services are supported by a vector database, Chroma, which stores embeddings for contextual conversations. The backend, primarily developed in Python, utilizes frameworks like Flask and Langchains to handle web requests and natural language processing tasks. The frontend, developed using ReactJS, provides a user-friendly interface, with NodeJS managing asynchronous operations to ensure a responsive user experience.

2.2.1. Watershed Stories

The system actively works to educate stakeholders about nitrogen-related water pollution and aims to improve the overall quality of water from multiple sources by bringing together a broad collection of professionals and community experts from different sectors. These "Champions" in the BlueGAP framework represent the regions: Iowa, Tampa Bay watershed, and the U.S. Virgin Islands. Every Champion makes a distinct contribution to the project, and each are involved in a variety of initiatives meant to alleviate the problems associated with water pollution. The system provides access to a platform that highlights these Champions and gives them a thorough overview of their contributions. Two major sections comprise the information about the Champions:

Champion or Community Stories: Users can obtain succinct but informative summaries of each community champion by location, emphasizing their training, experience, and unique contributions to the goal of reducing nitrogen pollution. For users requiring a brief summary of the profiles of the Champions or a story about a community, this section is a useful resource. The platform provides access to a vast library of informative video interviews with the Champions. These videos offer a personal look at their activities, comprehensive information about their work, and insights into addressing water pollution challenges. Viewers can delve into the video archive to acquire a more sophisticated comprehension of the Champions' proficiency and the effects of their actions. The system also provides in-depth biographies of each Champion, including background information beyond their career pursuits. These narratives offer a comprehensive viewpoint by integrating the individual and occupational facets of the

Champions' experiences. This strategy allows users to connect with the people bringing about a positive change in addition to understanding the technical issues of managing water pollution.

2.2.2. Data Resources

Within the BlueGAP IS, our primary data types are geospatial and aspatial data representing water quality and demographics datasets. These data sets undergo thorough processing, such as data transformation, schema imports, creating lookup tables, and spatial joins, before being integrated into the system. Once processed, they are overlaid on Google Maps, offering a visual representation of specific regions or the distribution of data points within those chosen areas. This visualization is achieved by leveraging the time and position (longitude and latitude) metadata associated with the data.

Spatial Data: In the BlueGAP IS, the predominant data type is spatial data, commonly known as geospatial data. This term encompasses any data linked to or containing information about a specific location on the Earth's surface. The system relies heavily on two primary types of spatial data: points and polygons. Geographical entities, such as counties and zip codes, are represented on maps as polygons, adapting to the spatial extent of the data being visualized. Locations where water quality data are collected are depicted as points, offering a visual representation of their geographical distribution.

These spatial data play a central role in the system, providing a foundation for mapping, analysis, and visualization activities related to water quality and nitrogen-related analytes across diverse geographical regions. To manage and organize this spatial data, the system relies on spatial tables within PostgreSQL that support various functionalities within the BlueGAP IS. Additionally, the system has the flexibility to analyze spatial data on-the-fly, dynamically adapting to the specific requirements of its functionality.

Non-Spatial Data: Non-spatial data, or data lacking geographical specificity, is also used in the BlueGAP IS. One example from the system is the sensor data, which is categorized as non-spatial since it is at a fixed location. A common identifier is used to connect this non-spatial data with spatial data that is location specific. For example, even though data on stream gage locations may not be essential to water quality datasets, these datasets can be linked to gage sites using a common identifier, like a gage ID. A key factor in improving the contextual richness of the system is non-spatial data, such as time series observations of water analytes and other characteristics. There are several uses for this non-spatial data integration such as chart and graph creation, and map symbolization within the BlueGAP IS. Combining spatial and non-spatial data gives the system additional depth and complexity, enhancing its analytical and representational flexibility.

Sites: In BlueGAP IS**,** sites are treated as 0-dimensional objects with their location defined as a coordinate pair using the 1984 World Geodetic System. Site data is ingested into the database from multiple data sources including the USGS, EPA, and state and regional agencies. Each data source for BlueGAP provides basic information about the site location, an associated identifier (ID) and other data. Most of the site data in BlueGAP was obtained through API queries (e.g., USGS, STORET) however some were ingested from flat files (e.g. Excel and CSV). Ingestion is an automated process conducted through python scripts.

Table 1: Data types and how they are used in the BlueGAP system.

Data Type	**Data Usage**
Spatial data	Spatial selection (county, zip code, census block) Relational joins with aspatial data
Aspatial data	Time series data storage and retrieval Informal metadata Relational joins with spatial data Temporally based aggregation statistics

The site data is very heterogeneous and requires standardization of data fields for comparison. Standardization occurs through a series of spatial joins between each site location and other spatial datasets including state, county, zip code, hydrologic unit codes, urban areas, and place polygons. The spatial join assigns values from each of the intersecting polygons (e.g., state, county) to the site table so data from different sources all have the same fields in the database.

Water Quality Monitoring: Water quality sensors are devices that measure different environmental parameters at a specific frequency. All the sensors that measure and record the observations in situ. A parameter is the type of variable being measured. In the BlueGAP IS we are focusing on the following parameters mainly containing any form of nitrogen. While these parameters are acquired from real-time sensors in Iowa, these sensors are not widely available in the US. Most of the nutrient data for Tampa Bay and USVI are from routine monitoring programs or project-based discrete samples with less frequent sampling intervals. The list of parameters that we are collecting are shown in Table 2 below:

Table 2: Data sources and parameters for water quality monitoring.

Data Source	**Analytes**
IWQIS	Phosphorus concentration (mg/l), Discharge (cfs), Dissolved Oxygen concentration (mg/l), Chlorophyll v, Nitrate concentration (mg/l), pH, Dissolved Oxygen saturation (mg/l), Turbidity (NTU), Dissolved oxygen concentration ds5x v2 (mg/l), pH ds5x v2, Water temperature ds5x v2 (°c), Chlorophyll concentration
NWIS	Discharge (cfs), Nitrate (mg/l)
STORET/ US VI	Nitrate (mg/l), Nitrate as N (mg/l), Nitrate + Nitrite (mg/l), Inorganic nitrogen (nitrate and nitrite) (mg/l), Inorganic nitrogen (nitrate and nitrite and ammonia) (mg/l), Nitrogen (mg/l), Nitrogen-15 (mg/l), Ammonia-nitrogen (mg/l),

	Organic nitrogen (mg/l), Kjeldahl nitrogen (mg/l), Nutrient nitrogen (mg/l), Ammonia nitrogen as N (mg/l), Total Kjeldahl nitrogen (mg/l), Total particulate nitrogen (mg/l), Carbon/nitrogen molar ratio (c/n ratio)
IADNR	Nitrate (mg/l), Nitrite (mg/l), Nitrite as N (mg/l), Nitrate as N (mg/l), Nitrate as NO3 (mg/l), Organic Nitrogen as N (mg/l), Organic Nitrogen (mg/l), Inorganic nitrogen (nitrate and nitrite) as N (mg/l), Inorganic nitrogen (nitrate and nitrite) (mg/l), Ammonia as N (mg/l), Ammonia as NH3 (mg/l), Ammonia (mg/l), Kjeldahl nitrogen (mg/l), Kjeldahl nitrogen as N (mg/kg), Ammonia-nitrogen as N (mg/l)
PWTS	Nitrate (mg/l), Nitrite (mg/l)
TBW	Nitrate (mg/l), Nitrite (mg/l)
PWS	Nitrate (mg/l), Nitrite (mg/l)
TBB	Nitrate (mg/l), Nitrite (mg/l), Organic nitrogen (mg/l), Kjeldahl nitrogen (mg/l), Total nitrogen (mg/l)

2.2.3. Data Acquisition

Data ingestion in the BlueGAP IS is orchestrated through cronjobs (tasks used to perform regular scheduled actions like periodic update of the database with latest data) operating on predefined intervals to ensure systematic updates with new data. These cronjobs are primarily responsible for invoking external API calls or retrieving data from files stored on external servers. Several external API sources are integral to the data acquisition process whereas for the case of Florida some of the data were obtained via email from researchers (Table 3) of that area in the BlueGAP IS, including:

Table 3: Data Source Reference

Data Source	**References**
IWQIS – The Iowa Water Quality Information System	Iowa Water Quality. (IWQIS, 2024; Jones et al., 2018)
NWIS – The National Water Information System	The National Water Information System. (2024)
STORET – EPA STOrage and RETrieval data warehouse	Water Quality Data Home. (2024)
IADNR – Iowa Department of Natural Resources	Iowa Department of Natural Resources. (2024)
SDWA – Safe Drinking Water Act	Environmental Protection Agency. (2024)
PWS – Public Water Supply	Florida Department of Environmental Protection Geospatial Open Data. (2024)

PWTS – Private Well Tracking System	PWTs. (2024)
TBW – Tampa Bay Well Dataset	Groundwater. Tampa Bay Water. (2022, June 2)
EPC – Tampa Bay Ocean Sites	EPCBOCC. (2024)

Each of these external APIs serves as a valuable source for different datasets pertinent to water quality and related information. The systematic and periodic execution of cronjobs ensures that data in the BlueGAP IS is current, facilitating comprehensive and timely data availability for users. The Iowa Water Quality Information System (IWQIS) offers data on various analytes that are present in the water sources, for the entire state of Iowa. IWQIS downloads data from different sensors that IWQIS has carefully put along rivers. All users can view real-time statewide trends in stream conditions and water quality on this open platform, or they can explore individual sites to look at historical data. The BlueGAP IS can use some of the API's queries, but most of it is restricted.

The USGS provides API access to the NWIS (National Water Information System) data, which provides historical and real-time stream data covering the whole country. The NWIS API makes it easier to retrieve data in different formats depending on particular user requirements. Spatial parameters, such state or territory, hydrologic unit code, watershed, spatial boundary box, or county, can be used to customize queries. Site name, date ranges, contributing agency, status, altitude, etc. are examples of aspatial query parameters.

In order to track the state of the nation's water quality, EPA STORET data is gathered from federal, state, tribal, and individual sources. Via the Water Quality Portal (WQP), more than 900 partners exchange their data on water quality. The WQP may show sparse information with large gaps in collecting dates due to the variety of data sources. It is difficult to select parameters that are pertinent for users of the BlueGAP IS when there are so many collecting sites and parameters accessible in the WQP. To facilitate data extraction for users of the BlueGAP IS, efforts have been taken to align parameters with those available in other queried systems.

IADNR data was obtained from an exported database that was ingested into the server and then exported into tables following the existing schema for BlueGAP. PWTS and SDWA data were ingested into the system following the BlueGAP schema. TBW data were partially obtained from flat files. However, ancillary data was obtained from the web data listed above. USVI data also came from the STORET API, however, the query parameters were altered to include coastal sites beyond land boundaries. Only the USVI and TBB data are found outside of county boundaries in surrounding water bodies. TBB data, made available at the URL listed above, were originally obtained from flat files sent by email. Additional data was obtained from the URL listed above.

2.2.4. Data Ingestion

Data ingestion into the database occurs in two phases, the first is site ingestion and the second is analyte observation ingestion. Site data is stored in separate tables from observation data so either can be updated independently without affecting the other. In addition, each data source has its own site and observation tables. The majority of data ingested into BlueGAP is from API queries to IWQIS, NWIS, and STORET. Each API has methods to obtain site data independently of observation data. The rest of the data sources, including IADNR, SDWA, PWS, PWTS, TBW and EPC, come from flat files that were downloaded or obtained through email request to relevant government agencies. All of these are loaded programmatically and preprocessed for consistency in format, units, and precision. In some cases, site information and observations are stored in the same file, so they are separated into two tables on loading.

When sites are ingested, each site is spatially joined to other datasets including state, county, and zip code polygons. Attributes from the other spatial data are joined to the site data so, regardless of the data source, each site table has identical fields when inserted into the database. Observation data consists of time-series values for analytes from each data source. After site and observation data has been ingested from a data source, spatiotemporal statistics were created in the database. These statistics are used on the front-end to save computation on the client-side.

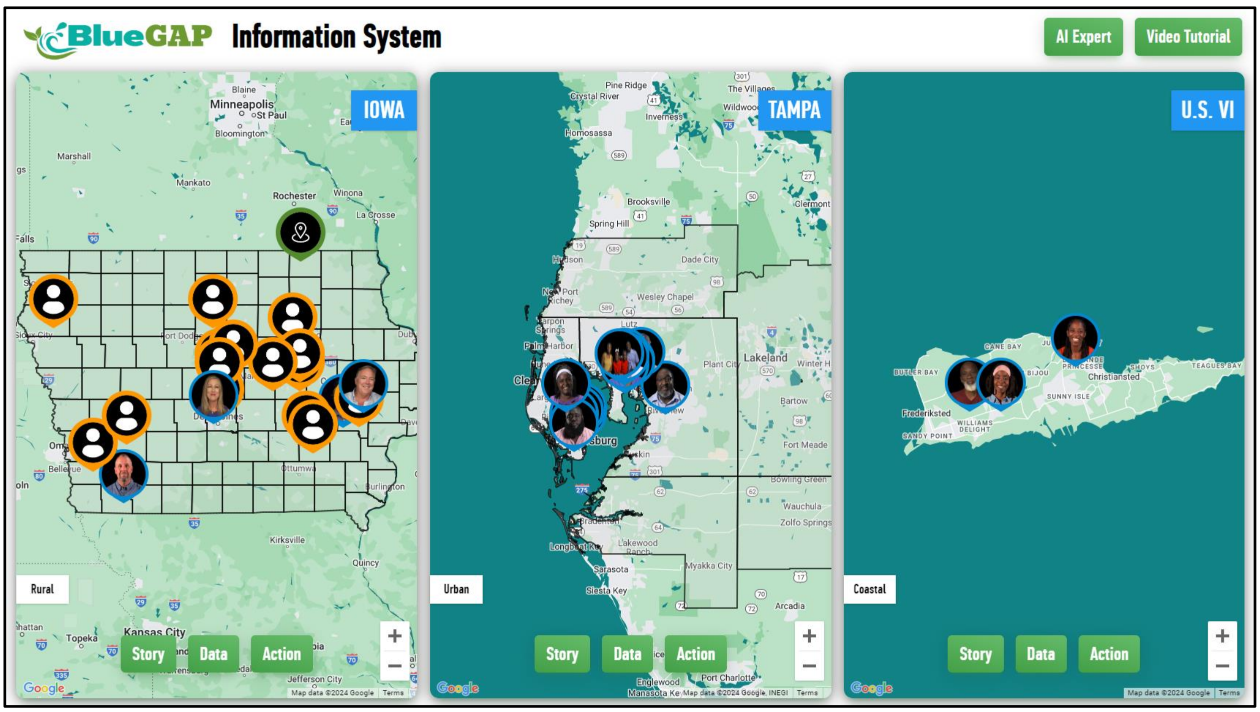


Figure 2: Entry page for 3 test regions with community champions, data and action platform connections

3. Results

3.1. Watershed Stories

The landing page highlights the three BlueGAP pilot regions to facilitate user geographic orientation. Each region is shown as a map. County political boundaries are indicated for Iowa and Tampa Bay for reference. There are links to tutorials on the use of the IS, and to an 'AI Expert' trained to assist the novice IS user navigate the system and find required information. The "Story" section within the Information System offers users a dynamic platform for exploring detailed information about the various communities and champions associated with the selected region. Users have the option to directly access champion profiles by interacting with the image linked to each specific champion. This approach allows users to quickly immerse themselves in the individual narratives and contributions of each champion.

The users can also utilize the "Story" section of the platform. This feature lets users navigate through the diverse stories of Champions as shown in Figure 3. Within this section, users can interact with video, audio, or text content on the champion's page. The additional features shown in Figure 2 include AI Hub and Video Tutorials. In the AI Hub, users can make inquiries to nitrogen expert AI agent and initiate an in-depth discussion about nitrogen and its impacts. On the other hand, the Video Tutorials section links to YouTube video tutorials on the usage of the system. These video tutorials provide a comprehensive demonstration of how to use the entire IS system.

Hyperlinked thumbnail photos of BlueGAP Champions are overlayed on the relevant maps. Upon selecting a champion, users are directed to the champion's detail page, which includes a "Brief Summary" of the champion's background, contributions, and key works. Notably, the page features a video playlist showcasing the Champion's impactful endeavors, allowing users to gain insights into their work through multimedia content.

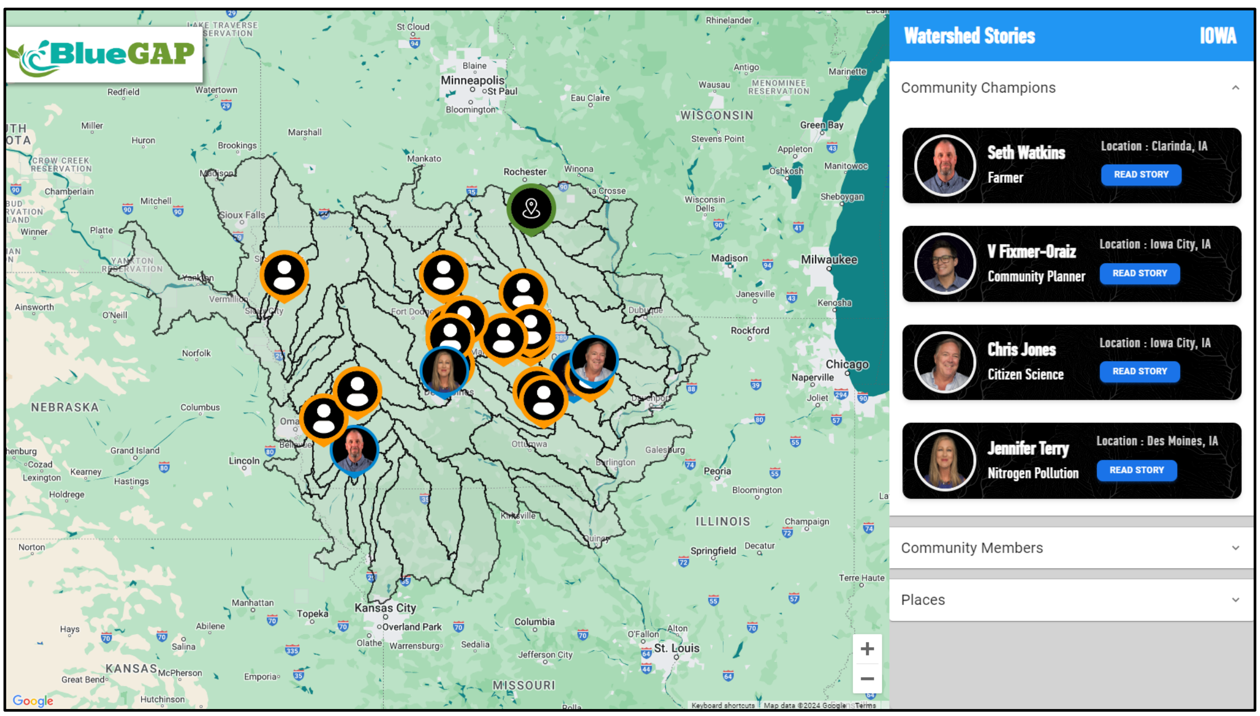


Figure 3: Interface in the "Watershed Stories" section of the BlueGAP IS

More detailed information on each Champion can be seen with the "Story Detail" feature. This feature serves as a gateway to an in-depth exploration of the champion's works, providing valuable insights and comprehensive details about their significant contributions. Users can leverage this feature to understand champion's initiatives, fostering a richer appreciation for their role in environmental conservation within the selected region.

In the video playlist feature, users are provided with two distinct options to enhance their viewing experience. First, users can directly play the video within the pop-up dialog. This allows them to gain valuable insights and information by watching the champion's work unfold through the multimedia presentation. Second, a brief description of the video provides additional context, background, or key details related to the content. This serves to enrich the user's experience and enables them to make informed decisions about engaging with the video content as shown in Figure 4. These interactive features enhance the user's ability to customize their experience, whether they prefer to immediately watch the video or first view a concise description for context and insight.

Users can initiate a dynamic interaction with the virtual AI bot, enabling them to ask questions, seek advice, or gather specific information related to the champion's expertise as shown in Figure 5. This feature provides an additional avenue for users to access valuable insights and assistance, enhancing the overall user experience within the information system. By incorporating this interactive virtual AI agent, the system aims to offer users a personalized and informative dialogue that caters to their specific queries and interests, contributing to a more engaging and user-centric platform.

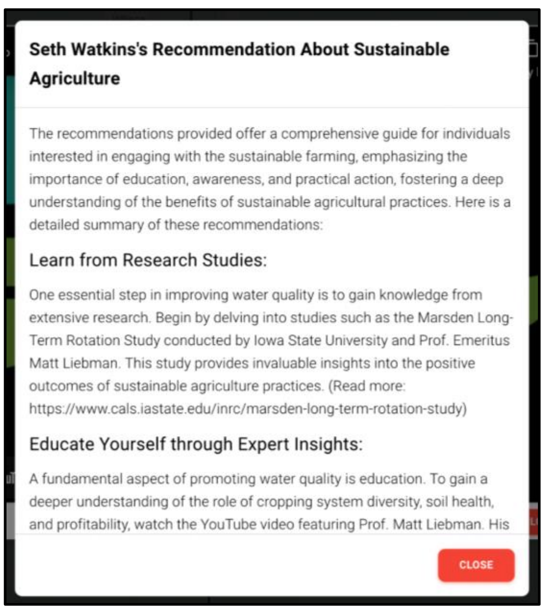


Figure 4: Brief description about the playing video about a community champion

As a final navigational option, users can explore location-specific data related to the selected champion by selecting the "Explore Data" feature. On the "Data" portal, users can access a wealth of information, charts, and datasets relevant to the specific geographical area tied to the champion. This feature enables users to delve into the intricacies of environmental data, gaining a deeper understanding of the water quality, pollution levels, or other pertinent factors specific to the champion's region. The "Explore Data" feature serves as a gateway for users to engage with comprehensive and localized information, fostering a more informed perspective on the environmental conditions and challenges in the champion's area of focus.

3.2. Data Exploration

The user has two distinct methods to select the geographical region and interact with various monitoring data on the "Data" portal:

Selecting County and Zip Code Values: Within the interface, the user can choose a scope, either "County" or "Zip Code". Following the selection of the scope, the interface provides an autocomplete search option to enter a County or Zip Code, refining the search based on user input. This dual-step process empowers users to more precisely define their geographical region of interest. The interface's responsiveness to user input ensures a seamless and efficient experience in navigating and selecting specific regions for data exploration.

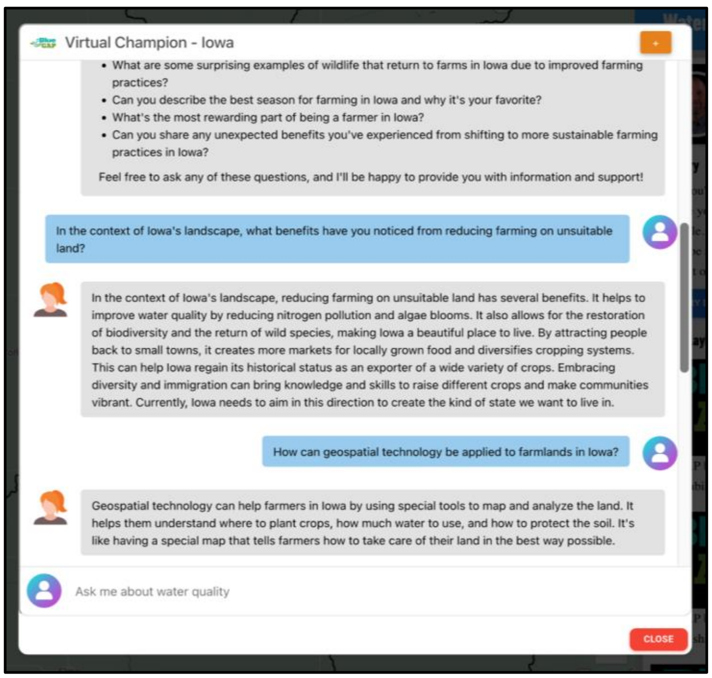


Figure 5: Virtual champion feature provided by the conversational AI system.

Visual Navigation for Each Specific Regions: In this approach, the user can visually select the desired geographical region on the map to navigate the data. The user gains the flexibility to navigate seamlessly to their preferred location, refining their selection to view data down to the level of a census tract within the selected zip code. During the visual navigation, hovering over different geographical regions on the map triggers the display of a brief data summary for the hovered region as shown on Figure 6. This summary includes a "Data Availability Score" and provides information on the number of monitoring locations and their available data from all three data sources. Data availability score is calculated based on thresholds for each region using percentiles (25%, 75%) which are determined based on number of sensors, data records, size of the region, etc.

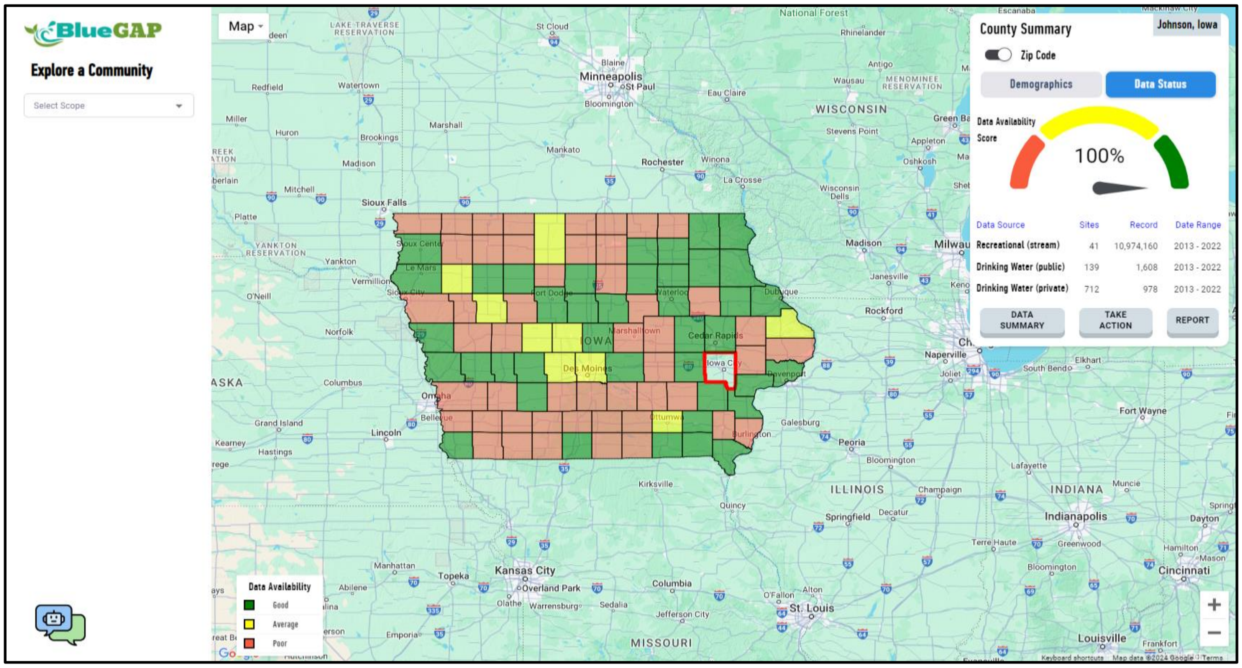


Figure 6: Information panel showing brief summary of the region of interest.

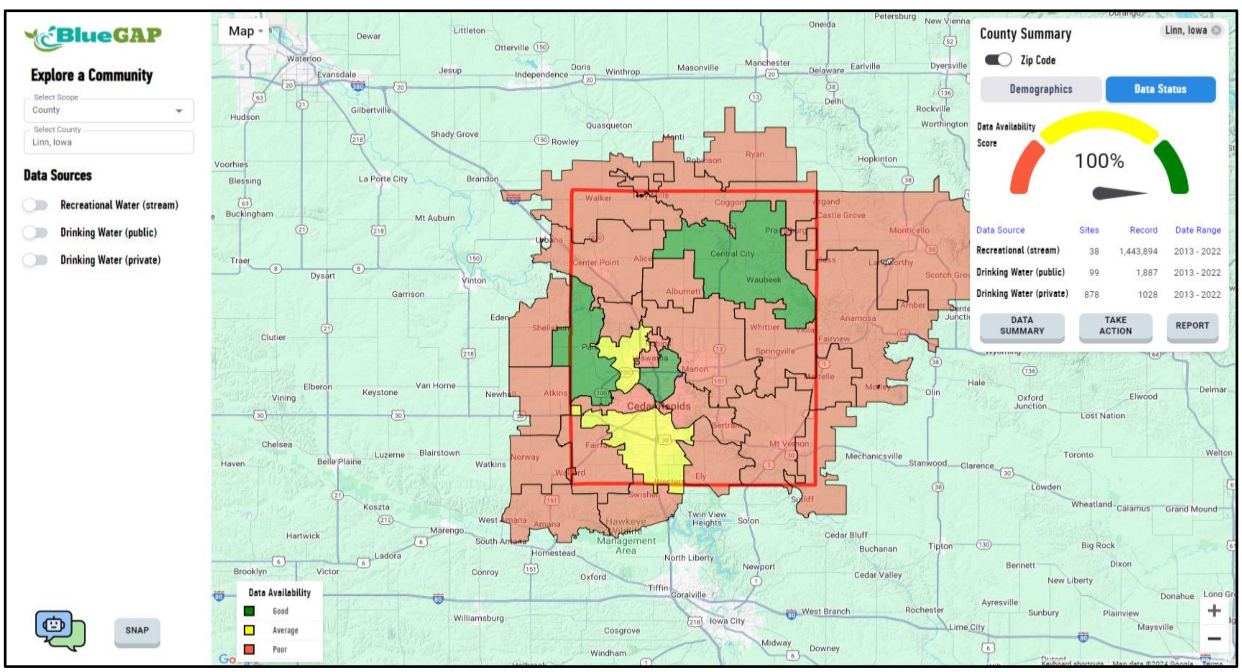
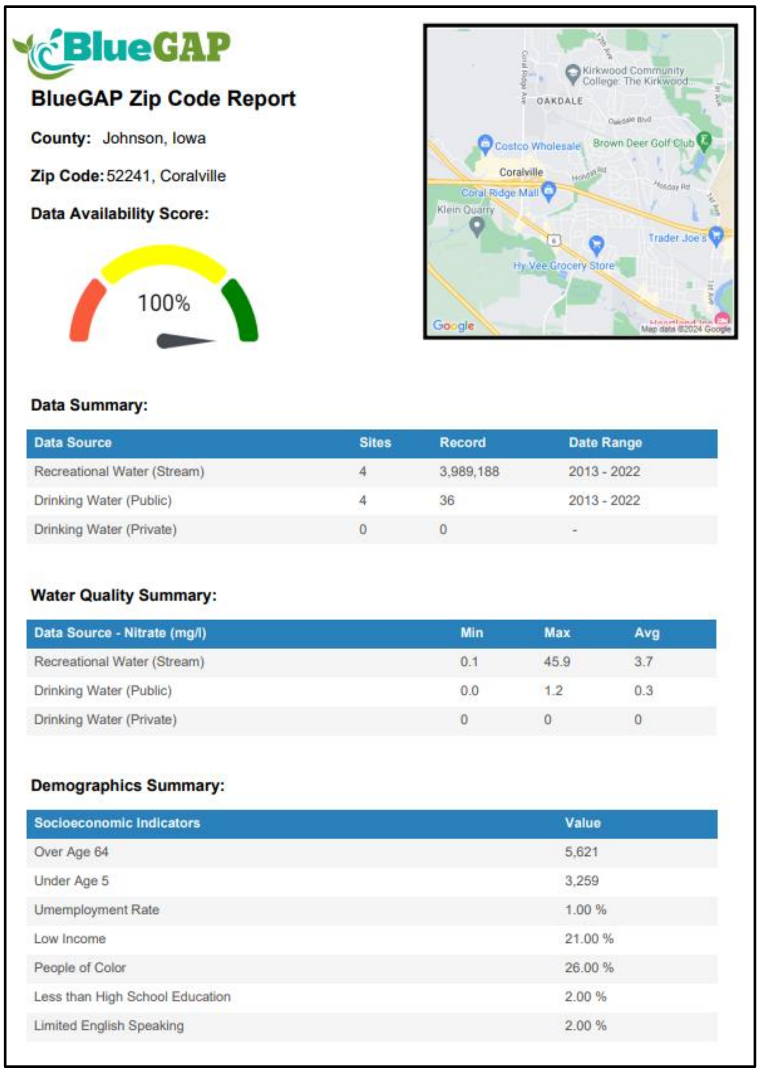


Figure 7: County view and information panel showing zip codes inside the selected county.

The legend panel contains color descriptions corresponding to different "Data Availability Scores," aiding users in understanding the significance of the displayed information based on the selected geographical regions. This visual navigation feature enhances user engagement by providing an intuitive and interactive experience. Users can explore and analyze data at varying levels of granularity, guided by visual cues and informative summaries displayed directly on the map interface. When the user selects a specific region, the platform provides an immersive experience by presenting all the sub-regions contained within the clicked region as shown on Figure 7. The behavior varies based on the selected scope:

County Selection: The platform zooms inside the selected county, revealing all the zip codes within its boundary. Users can view the Demographics and Data Status information in the summary window. They are presented with a comprehensive view of the zip codes, allowing them to explore and interact with individual areas.


BlueGAP

BlueGAP Zip Code Report

County: Johnson, Iowa

Zip Code: 52241, Coralville

Data Availability Score:

100%

Data Summary:

Data Source	Sites	Record	Date Range
Recreational Water (Stream)	4	3,989,188	2013 - 2022
Drinking Water (Public)	4	36	2013 - 2022
Drinking Water (Private)	0	0	-

Water Quality Summary:

Data Source - Nitrate (mg/l)	Min	Max	Avg
Recreational Water (Stream)	0.1	45.9	3.7
Drinking Water (Public)	0.0	1.2	0.3
Drinking Water (Private)	0	0	0

Demographics Summary:

Socioeconomic Indicators	Value
Over Age 64	5,621
Under Age 5	3,259
Umemployment Rate	1.00 %
Low Income	21.00 %
People of Color	26.00 %
Less than High School Education	2.00 %
Limited English Speaking	2.00 %

Figure 8: PDF report example for the zip code selected by the user showing data availability, water quality and demographics summary.

<u>Zip Code Selection:</u> The platform navigates to the selected zip code, showcasing all the census tracts within its boundary. Users can view the Demographics, Data Status and Water Quality information in the summary window. They can navigate and analyze data at a more granular level by exploring the census tracts within the chosen zip code.

The interface enhances user control by offering a convenient toggle feature. Users have the option to hide or show sub-regions based on their preferences. Toggle functionality allows users to streamline their view, focusing on specific sub-regions of interest while maintaining a clean and user-friendly interface. This approach allows users to navigate through hierarchical geographical layers, gaining insights into data availability at varying levels of granularity, and customize their view for a more tailored and efficient experience.

Snapshot State: The "Snapshot State" feature in the system allows users to share their current application state with others through a unique link. The interface incorporates a "Snap" button, which copies the link to the user's clipboard. This link can then be shared with other users. The primary purpose of this feature is to streamline sharing with other users by directly accessing the shared state without manually repeating the visual browsing steps. When recipients access the shared URL, they are immediately directed to the exact state captured by the user who initiated the snapshot.

Figure 9: Data Summary interface with 3-yr and 10-yr charts and simple statistics of these data.

3.3. Report Generation

Users can generate and download an extensive report for the selected "County" or "Zip Code" region using an integrated function of the system. A PDF report is produced with important information such as the water quality summary, data availability score, demographics, and general information about the chosen area. A static map image of the selected area is also included in the PDF. Users can download and share the PDF to store and retrieve specific data related to a certain area. This feature makes the user's experience more convenient and makes it possible to save important data for later use. A sample of the PDF is shown in Figure 8.

Data Summary Details: The "Data Summary" feature provides comprehensive reports for the selected region. This report presents data summaries for both a 3-year and a 10-year period, encompassing information from all three distinct data sources. The report can be used to assess the environmental data trends over these specified timeframes (Figure 9). Users can toggle between these periods to gain insights into both short-term and long-term trends. The report utilizes graphical representations to enhance data visualization. A bar chart is included to present trends, fluctuations, and patterns in an easily interpretable format. The interface is designed for user convenience, allowing for smooth navigation and exploration of the data report.

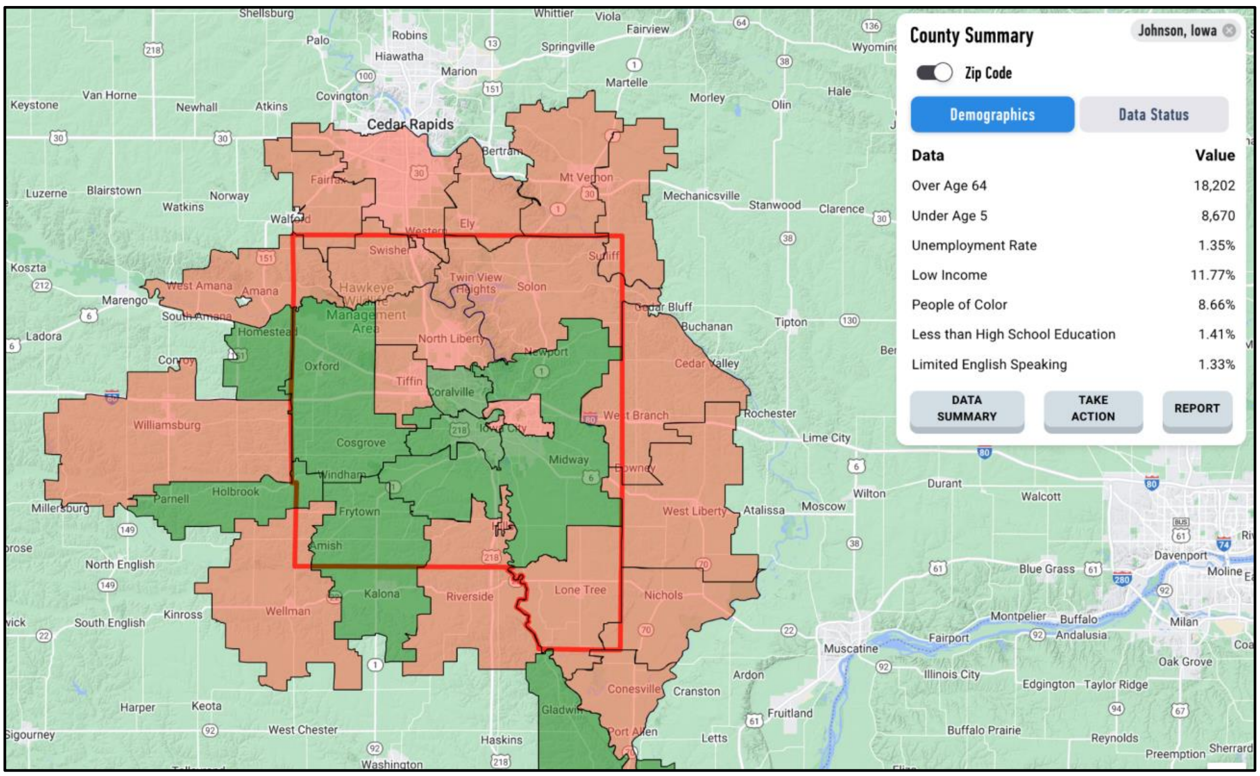


Figure 10: Demographics data summary for the selected zip code or census block

Demographics and Water Quality: The "Demographics" tab offers a comprehensive view of the selected region's demographic data (Ebi, 2019). Key indicators, including the low-income rate, Age distribution, English-speaking rate, race, and other relevant demographic metrics, are presented as shown on Figure 10. Users can gain valuable insights into the social and economic characteristics of the region, contributing to a nuanced understanding of its population dynamics.

The “Water Quality” tab provides a summary of water quality for a selected zip code. This section provides detailed data about the analytes present in the chosen zip code region. By default, the table displays data for nitrates. However, users can make an “Advanced Selection” of analytes based on the chosen data source. Users can exercise control over the analytes displayed in the table, tailoring their view to specific data sources and preferences as shown on Figure 11.

These additional data sections enhance the platform's capability to provide a holistic perspective on the selected region. Users can navigate between demographics and water quality data to better understand the societal and environmental characteristics of their area of interest. The platform's user-friendly design allows users to customize their data exploration experience based on their specific needs and preferences.

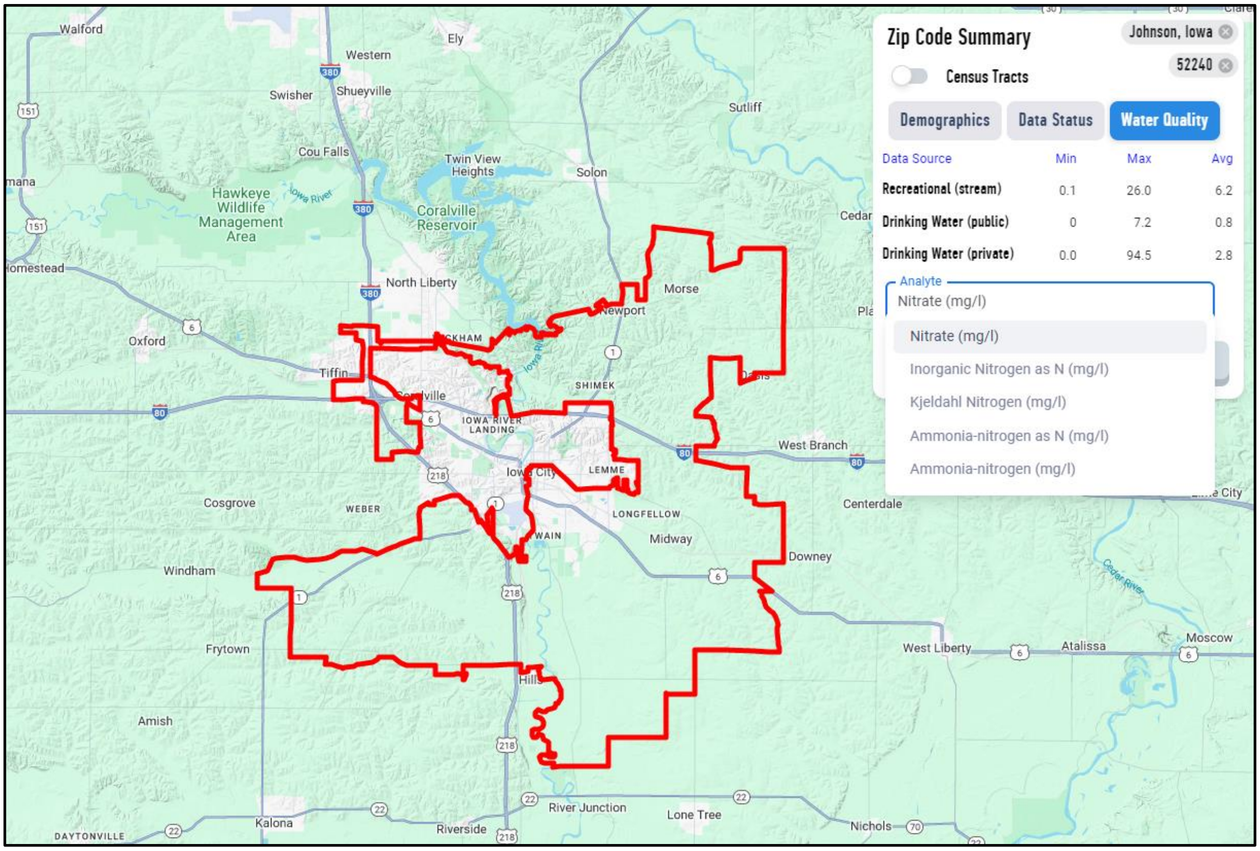


Figure 11: Advanced selection feature for analytes or data sources.

Water Quality Monitoring: Using a standardized query interface, the BlueGAP IS has the capacity to retrieve real-time sensor data from other sites. Different colored markers are used to dynamically acquire and show sensors that fall inside the specified context geometry on the map. These marks indicate sensor units that store data on water quality, making it possible for users to see the distribution and placement of these sensors graphically as shown on Figure 12.

Every site on the map denotes a monitoring location (water quality sensor or sample location) and offers crucial information. Users can examine details like the sensor's location, the organization or group in charge of deploying and maintaining it, and other pertinent metadata. The particular information displayed on the interface could differ according to the data source selected and include things like facility name, agency, site, river, city, address, construction method, well usage, owner and so on. This approach provides an intuitive and educational user interface, allowing users to interact with sensor data to learn about the quality of the water in various places.

Observation Details: The platform offers features to filter and visualize sensor observations over a variable timespan. As the nature and resolution of data varies among providers, an automatic approach has been taken to query the available parameters as well as the time range that data is available for the parameter and unit. This preprocessed and cached sensor-specific metadata allows the user to navigate through multivariate and nonuniform sets of information. Hence, as soon as the user activates the observation view, the list of available variables, their time ranges, as well as the resolution of data supported is auto filled, followed by the display of observations for one of the available parameters, selected randomly. An interactive, zoomable, and detailed chart view, accompanied with a smaller view to navigate through multi-year data, is created (Figure 13). The user can also view tabular data if the observations are sparse. The user can also interact with the data expert, which is an AI agent that can give conversational information about the selected sensor and its data (Figure 15).

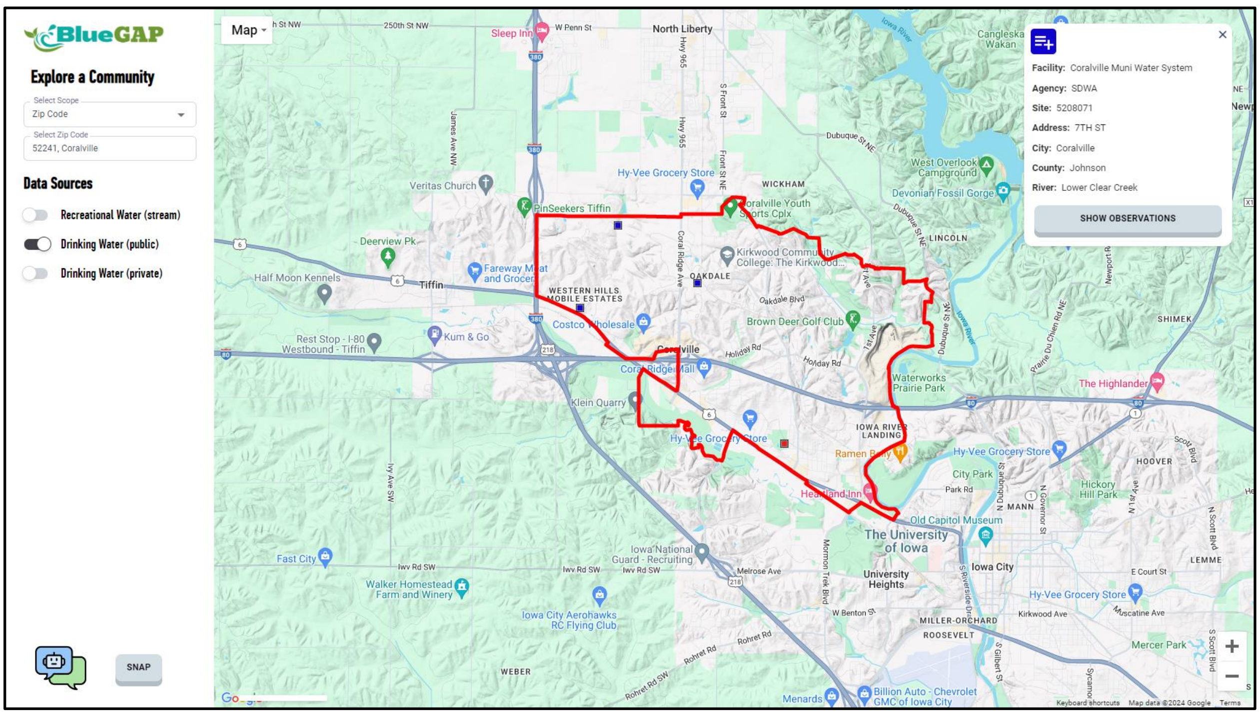


Figure 12: Water quality monitoring stations from various agencies and organizations.

3.4. Action Planner

BlueGAP IS provides an advanced decision support tool designed specifically to assist communities in addressing water quality challenges (Figure 14). The Action Planner utilizes Tampa Bay Comprehensive Conservation and Management Plan (TBEP, 2017) as a knowledge source as a generalized structure on water quality issues and solutions. This feature-rich platform allows users to select a particular problem domain from an extensive list of common water quality issues and explore a variety of alternative solutions and best practices generated by expert input. Once users choose a specific problem domain, they have the opportunity to articulate their current water quality issues in greater detail. This articulation triggers the presentation of a tailored solution designed to meet their specific needs.

The main panel within BlueGAP IS offers a comprehensive overview of the selected solution, ensuring that users gain a clear understanding of the proposed strategies and measures. For those seeking a more in-depth approach, the platform includes a generative AI capability, which generates a detailed, step-by-step plan using Tampa Bay Comprehensive Conservation and Management Plan (TBEP, 2017). The information extracted for Action Planner is also generalized to provide region independent suggestions. This comprehensive plan acts as a strategic roadmap, guiding users through each phase necessary for the successful implementation of the chosen solution, thereby addressing their unique water quality challenges effectively.

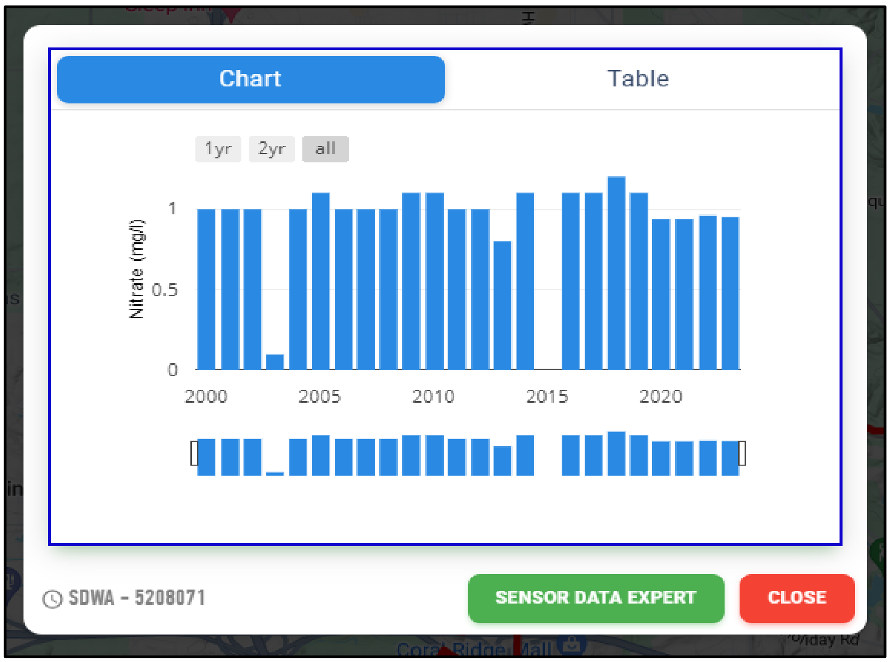


Figure 13: Sensor data observation summary interface provided as a chart or table.

Beyond its functional capabilities, BlueGAP IS transforms the user experience into an engaging, user-centric journey. The platform seamlessly guides users from the initial stage of problem identification through to the resolution stage, offering continuous support and clear direction. This holistic approach ensures that communities are not merely interacting with a tool but are embarking on a guided process designed to bring about tangible improvements in their water quality management practices. Such a progression underscores the platform's commitment to fostering sustainable water resource management and enhancing community resilience against water quality issues.

3.5. Conversational AI Agents

BlueGAP IS provides access to several unique water quality AI agents. The AI agent system offers various functionalities tailored to different user requirements, making the system a powerful tool for water quality management. Users can interact with the system using natural language queries, which the agents interpret to perform data retrieval and analysis, presenting information in an understandable format. Geocoding capabilities allow the system to process location-based queries, providing localized water quality data. The agents can also adjust their responses based on user preferences, offering more detailed or concise answers as needed, and perform sentiment analysis to enhance user satisfaction. Additionally, the system supports multilingual interactions, leveraging the capabilities of Large Language Models to process and respond to queries in multiple languages, increasing its accessibility. This combination of functionalities empowers a wide range of users, from academics to amateur analysts, to make informed decisions about water quality through an intuitive and adaptable interface.

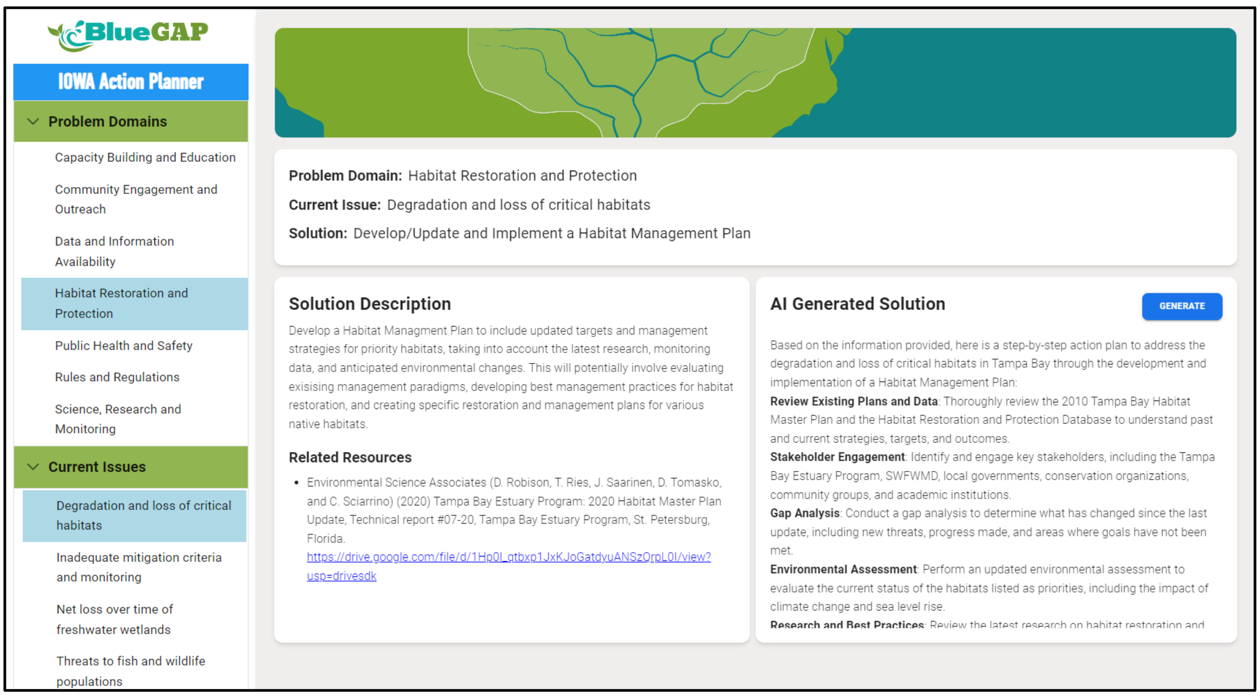


Figure 14: Action planner interface for the Iowa region with options to select problem domain, issues and alternative solutions.

The engagement with the Data Expert AI agent (Figure 15) is instrumental in enhancing user comprehension by offering an intuitive, dialogue-based exploration of complex data sets. The conversational interface enables users to navigate through the vast amount of information seamlessly, ensuring that they can make more informed and data-driven decisions. This improved understanding of environmental data sources empowers users to address water quality challenges more holistically and strategically.

Furthermore, the Data Expert AI agent contributes to creating a user-centric experience by adapting to the needs and queries of individual users. This personalized interaction fosters a sense of confidence and clarity among users, encouraging them to leverage the full potential of the platform's data analytics capabilities. Ultimately, the involvement with the conversational AI agent supports the platform's overarching goal of facilitating effective and sustainable water quality management practices by ensuring that users are well-informed and equipped to act on precise and contextually relevant data.

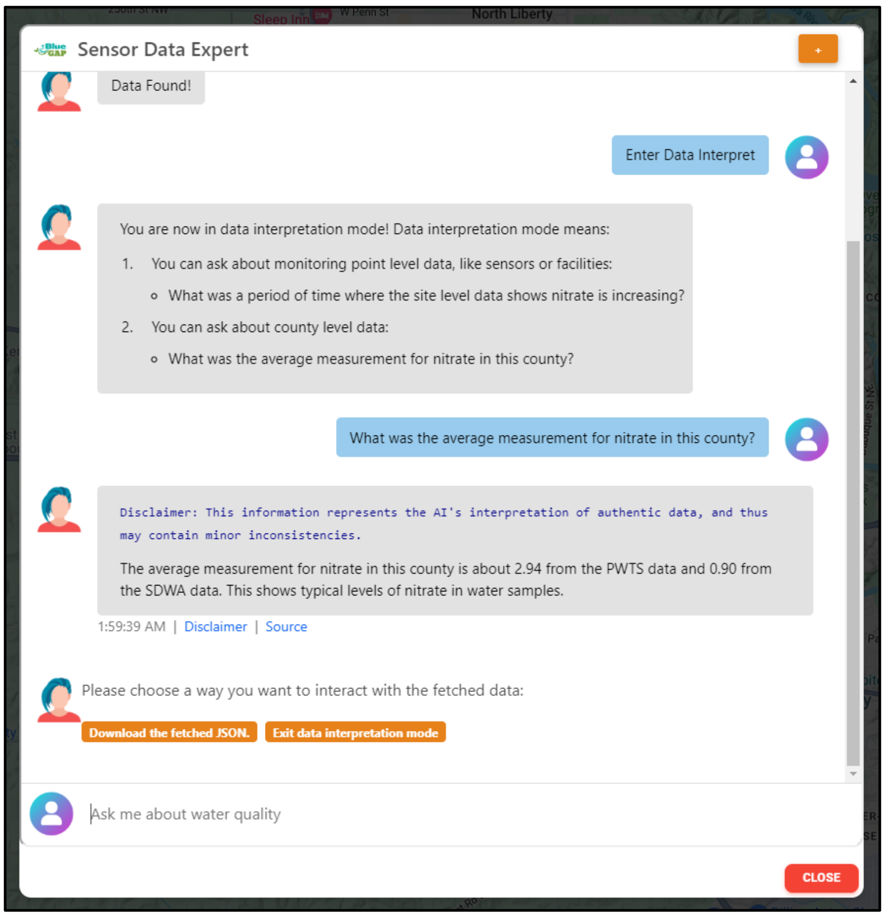


Figure 15: AI-assisted Data Expert interface with conversational interaction capabilities with sensor data.

4. Discussions

The prototype BlueGAP IS was test-driven at several public events, including at Stetson University, College of Lawand the College of Engineering at the University of Iowa. Several key lessons emerged from these interactions. Feedback from diverse user groups underscored the importance of designing an intuitive and user-friendly interface. Features like the AI agents and interactive maps were particularly well-received, highlighting the value of making complex data accessible and engaging. The system's ability to handle various data sources and types proved essential for communicating water quality conditions to communities. Ensuring the architecture could accommodate new data sources and integrate additional functionalities without significant rework was considered a design success. Providing thorough documentation and video tutorials also enhanced user adoption and satisfaction. These resources were crucial in helping users understand and leverage the system's capabilities effectively. Conducting multiple demonstrations and actively seeking user feedback were instrumental in refining the system. This iterative approach allowed for timely identification and addressing of issues, ensuring the system met user needs.

However, the system does have some limitations and areas for improvement. Integrating data from diverse sources with varying formats and standards poses challenges. Ensuring consistency and compatibility requires significant preprocessing and standardization efforts. While the system is designed to be scalable, managing large volumes of high-dimensional spatiotemporal data can strain resources. Continuous optimization and scaling strategies are necessary to maintain performance. The system's effectiveness is contingent on the availability and quality of data from external sources. Gaps or inconsistencies in data can impact the accuracy and reliability of analyses. Despite efforts to create an intuitive interface, the underlying technical complexity may pose challenges for users with limited technical expertise. Ongoing support and training resources are essential to mitigate this issue. Continuous data updates, system maintenance, and user support require substantial resources. Ensuring sustainable funding and resource allocation is critical for the system's long-term viability.

Additionally, the three study areas represent very different scenarios of data quantity and quality. The IS team had several discussions on how to display the data using a similar framework applied to all locations and several explicit design choices were made to accommodate these differences. Identifying and recruiting "champions" was another challenge, both in representation and the information provided by each. In some cases, champions may have provided conflicting suggestions or recommendations on the ideal course of action for addressing water quality issues. The IS team had many discussions on how to handle these differences and if/how they might be used as recommended actions. The action planner was based largely on a single planning document for the Tampa Bay region. No similar documents were available for the other locations and the specificity of information for Iowa and USVI was compromised as a result. Lack of sufficient material to train AI/LLMs is a considerable challenge for creating these types of tools.

5. Conclusion

The BlueGAP IS provides an advanced cyberinfrastructure that enhances the analysis of water quality data in the context of demographic insights. By integrating an array of data sources, including USGS, EPA, and various state and regional agencies, the system empowers users with a robust platform for monitoring nitrogen-related analytes across key regions such as Iowa, Tampa Bay, and the U.S. Virgin Islands. The integration of AI agents and the inclusion of champion narratives play pivotal roles in fostering community engagement by offering an educational framework and facilitating informed decision-making. Underpinned by modern web technologies, BlueGAP IS is designed to be a highly scalable and resilient platform, adept at handling high-dimensional spatiotemporal data.

The system's success has been demonstrated through positive feedback gathered from various showcase events, yet recognizing and addressing areas for improvement is vital for its continued evolution. Future development will focus on incorporating user-requested functionalities and refining the interface through agile development practices, ensuring that the platform adapts dynamically to meet evolving user needs. Actively soliciting and integrating user feedback via usability surveys and feedback forms will enable the system to satisfy user preferences and expectations.

BlueGAP IS is scalable nationwide and portable to other regions. Expanding the platform's reach will involve fine-tuning data integration processes to incorporate additional regional and local data sources, ensuring that users nationwide can benefit from the system's capabilities. By taking a forward-looking approach that embraces technological advancements and prioritizes user feedback, BlueGAP IS aspires to remain a dynamic and responsive tool. BlueGAP IS will continue to serve its current users and reach new communities, fostering a broader impact on environmental stewardship and public health.

Acknowledgements

This project was funded by the National Science Foundation (#2230710).

Disclaimer

During the preparation of this work, the authors used ChatGPT in order to improve the flow of the text, correct any potential grammatical errors, and improve the writing. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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