Shahid, M., Sermet, Y., Mount, J., & Demir, I. (2023). Towards progressive geospatial information processing on web systems: a case study for watershed analysis in Iowa. *Earth Science Informatics*, *16*(2), 1597-1610.
https://doi.org/10.1007/s12145-023-00993-x

Towards Progressive Geospatial Information Processing on Web Systems: A Case Study for Watershed Analysis in Iowa

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Abstract

Geographic Information Systems (GIS) are available as stand-alone desktop applications as well as web platforms for vector- and raster-based geospatial data processing and visualization. While each approach offers certain advantages, limitations exist that motivate the development of hybrid systems that will increase the productivity of users for performing interactive data analytics using multidimensional gridded data. Web-based applications are platform-independent, however, require the internet to communicate with servers for data management and processing which raises issues for performance, data integrity, handling, and transfer of massive multidimensional raster data. On the other hand, stand-alone desktop applications can usually function without relying on the internet, however, they are platform-dependent, making distribution and maintenance of these systems difficult. This paper presents RasterJS, a hybrid client-side web library for geospatial data processing that is built on the Progressive Web Application (PWA) architecture to operate seamlessly in both Online and Offline modes. A packaged version of this system is also presented with the help of Web Bundles API for offline access and distribution. RasterJS entails the use of latest web technologies that are supported by modern web browsers, including Service Workers API, Cache API, IndexedDB API, Notifications API, Push API, and Web Workers API, in order to bring geospatial analytics capabilities to large-scale raster data for client-side processing. Each of these technologies acts as a component in the RasterJS to collectively provide a similar experience to users in both Online and Offline modes in terms of performing geospatial analysis activities such as flow direction calculation with hydro-conditioning, raindrop flow tracking, and watershed delineation. A large-scale case study is included in the study for watershed analysis to demonstrate the capabilities and limitations of the library. The framework further presents the potential to be utilized for other use cases that rely on raster processing, including land use, agriculture, soil erosion, transportation, and population studies.

Keywords

Georeferencing; Geospatial Analysis; Offline Maps; Progressive Web Applications; Web Workers; Web Bundles

1. Introduction

Geographic Information Systems (GIS) are widely used for environmental modeling and geospatial analysis. Since the size of raster layers keeps growing by orders of magnitude, it's difficult for applications to store, serve, and process large amounts of raster data. Traditionally, stand-alone desktop applications have been used to analyze raster data in-place as well as to access powerful workstations and high-performance computing (HPC) clusters with parallel processing capabilities (Netzel and Slopek, 2021). Such applications are costly to develop, operate, and maintain as they rely on platform-dependent software (Gkatzoflias et al., 2013). Likewise, these applications present several difficulties from the perspective of the users, including a steep learning curve and the requirement of sophisticated procedures for installation to local machines (Agliamzanov et al., 2020). Thus, such GIS applications makes geospatial analysis rather costly in terms of the time, skill, and financial resources it requires from a practical standpoint (Zhang et al., 2017). Furthermore, these, usually black-box, systems often erect barriers to the integration and sharing of geospatial data resources (Zhao et al., 2012).

As an alternative option, web-based systems enable accessibility and interoperability of geospatial resources across various domains (Zhao et al., 2012). The evolution of the web has made real-time geospatial data integration, analysis (Hu et al., 2021) and transmission easy for GIS applications, hence, functionalities like streamflow routing and surface water object tracking became feasible (Agrawal & Gupta, 2017). In comparison to desktop applications, web systems are developed according to common established standards, and thus, substantially decreasing the learning curve for the users (Xu et al., 2020). They provide rich user interfaces and intuitive design elements that minimize the need for users to go through a time-consuming learning process (Simâo et al., 2009). Such web-based systems encourage users to focus on the tasks at hand without getting overwhelmed by the system complexity, although desktop GIS applications remain more comprehensive in terms of their capabilities (Yildirim and Demir, 2021).

Web-based systems have proved their merit in many disciplines of geosciences as demonstrated by the following examples. An urban flood tool (i.e., Integrated Flood Assessment Model), that is capable of raster based flood model simulation, was merged with a WebGIS server for the analysis of flooding in coastal urban watersheds that are caused by rain and tide (Kulkarni et al., 2014). Similarly, a levee project information management system was developed (Zhang et al., 2018) based on WebGIS for flood prevention and decision management in levee projects. Furthermore, a general WebGIS framework was proposed (Nakayama et al., 2017) for the collection and management of spatial data. In the field of environmental sciences, modern web technologies, cloud and storage systems was presented (Vitolo et al., 2015; Seo et al., 2019) to address the issues in the modeling and handling multidimensional raster images. However, all of these systems rely heavily on the server-side for performing integral activities and do not utilize client-side functionalities extensively for a better user experience. Hence, the challenges of licensing and management costs of servers as well as the communication overhead between clients and the server remain unaddressed, especially considering the multidimensional nature of raster data.

Most web-based geographic information systems are traditionally developed with the client-server model (Oluwatosin, 2014). Often, client-side code focus on user interface and interaction whereas the server-side application encapsulates the geospatial data resources and functionality like preprocessing, transforming, resampling and analysis of the datasets (Sermet et al., 2020; Xu at al., 2019a). The communication between the clients and the server does not only raise performance issues but also may lead to server-side conflicts or limitations in case of concurrent access (Yang et al., 2005). Additionally, the influx of massive raster data from numerous concurrent users threatens the viability and affordability of utilizing server memory and resources for geospatial processing (Kilsedar, 2020). Unavailability of large-scale benchmark datasets (Ebert-Uphoff et al., 2017) or inconsistency in the data sources may hinder the generation of the desired response effectively and on time. These challenges can impede the progress of mission-critical operations that relies on the timely analysis of gridded geospatial data, such as creating plans for disaster response (Yildirim & Demir, 2021) and may consequently result in economic losses and population casualties (Kawasaki et al., 2012).

Web-based geospatial analytics have recently faced with the need to bring the software to raster data (Kilsedar, 2020; Xu et al., 2019b). Advancements in client-side web technologies and the evolution of web standards (e.g., optimization of JS interpreters in the browsers, ES6 features, browser-based hardware acceleration) have propelled the migration of application logic and GIS functionality from server to client-side (Kulawiak et al., 2017; Farkas, 2019). Such client-oriented and browser-based raster processing approaches showcased their values in various areas of geosciences including watershed delineation (Sit et al., 2019), water quality simulation (Walker & Chapra, 2014), well forecasting (Sit et al., 2021), marine cadastre data analysis (Kulawiak et al., 2017), immersive flood monitoring (Sermet and Demir, 2020), and the visualization of satellite imagery (Dufour, 2018). With this approach, the web application content can be updated from within the browser with minimal communication overhead. Availability of local storage APIs (Application Program Interface) in the web browsers reduces the need for clients from making unnecessary requests to the server, hence, increases the response time of the application and reducing the computational load on the server-side (Laine, 2012). Decreased centralized computational load ultimately leads towards the reduced financial cost as fewer resources will be used. Additionally, JavaScript engines in modern web browsers are optimized to handle the much greater computational load on the client-side than before (Ryza & Wall, 2010) and client-side applications are easier to manage because the team of developers does not need to switch back and forth between the client-side and server-side programming languages (Walker & Chapra, 2014).

Modern web browsers allow developers to use a certain set of technologies (e.g., Service Workers API, Cache API, IndexedDB API, Notifications API, and Push API) to make a web application progressive (Kimak & Ellman, 2015; Lee et al., 2018). Progressive Web Applications (PWA) combine certain features of web and native mobile applications to serve a single codebase on any platform in an engaging, reliable, efficient way (Pande et al., 2018), an approach that recently has gained traction for GIS. PWAs can be considered as a middle ground between native applications and web-based applications to combine both approaches and minimize the disadvantages (Tandel and Jamadar, 2018). The main characteristics of a PWA include, but are not limited to, being compatible with one-click installation on smartphones, offline usage, progressive and responsive (e.g., coherent performance regardless of device and browser), and substantially leveraging service workers in tasks such as synchronization, caching, and push notifications (Sheppard, 2017). PWAs have demonstrated their worth through case studies in disaster management and agriculture.

Mody et al. (2020) and Paul et al. (2019) have taken advantage of the PWA approach to address the issues pertaining to disaster response and relief with an overall focus on preparedness, response, and recovery by prioritizing factors like better connectivity of users with resources. As another application area, weather forecasting and air quality index reporting are two of the common applications in environmental science. To provide these functionalities in a single application, Maheshwari et al. (2018) have proposed a solution based on PWA concepts. Other than the dissemination of information, information collection, management, and visualization are essential processes for analyzing environmental data, which can help discover additional meaningful insights. To achieve these objectives, Mena et al. (2019) have proposed a PWA with a component-based approach for integrating geospatial data with IoT information.

In the field of agriculture, a significant portion of the professional and research activities take place in the fields, where internet connectivity is unstable. To make the information easily accessible to farmers in the field for monitoring and decision making, Nugroho et al. (2017) and Yu et al. (2019) worked on the development of information systems with the PWA approach. Regarding mitigation of droughts in agricultural areas, Opiña Jr (2020) has developed a PWA using Soil and Water Assessment Tool (SWAT) for identifying suitable locations for the development of Small Farm Reservoir. To support intelligent agriculture with information service platforms, Shi (2020) has utilized PWA technology to encourage a new way of thinking for constructing agricultural network service platforms. Literature shows the viability and the need for mobile-supported geospatial analytics tools equipped with efficient handling of composite geodata (i.e., vector and raster), powered by modern web technologies (e.g., IndexedDB) for on-site processing Park et al. (2016). Furthermore, the potential benefits of utilizing such web standards in the context of geospatial systems have not been fully explored with respect to storage, security, and offline usage (Chen, 2021).

In this paper, we present RasterJS, a web-based library developed as a PWA to provide interactive geospatial analytics functionality entirely on the client-side. It provides a framework to give users the ability to perform tasks related to hydroinformatics effectively with an intuitive user experience. As a proof-of-concept, RasterJS is released with flow direction calculation, watershed delineation, and raindrop flow tracking functions in addition to real-time raster resampling methods to adjust spatial resolution, however, it can be extended to include more functionalities that will help in geospatial analysis. This framework takes advantage of client-side web technologies to calculate and render the results of geospatial tasks efficiently. It deviates from conventional client-server architecture and delegates the data storage and processing responsibility to the client-side. Case in point, raster files are stored in the client device via IndexedDB upon their initial retrieval. This approach simplifies the complexities that occur due to frequent interactions between the clients and the server. With this framework, the users can perform their activities without relying heavily on a stable internet connection as the users can continue analytical activities within the platform even when the internet connection is unstable or absent. Furthermore, the application can be downloaded by the users in a compact file which can be used in any device that supports modern web browsers. Via this file, the application can be distributed offline using technologies like Bluetooth.

The remainder of this paper is organized as follows. Section 2 presents the methods, scope, and purpose of the RasterJS framework followed by an explanation of its architecture, components, data setup, and workflow. Section 3 discusses the potential use cases, capabilities, and useful aspects of the system. Finally, the paper concludes with a summary and future perspectives in Section 4.

2. Methods

RasterJS is a proof-of-concept web-based geospatial processing library that can function both online and offline. Providing a rich user experience using emerging web technologies and PWA concepts along with minimizing the communication with an external server are two of the main objectives of this application. It relies solely on client-side web technologies (Walker & Chapra, 2014) with JavaScript as its primary programming language. For seamless execution of tasks in both modes, APIs and libraries are utilized accordingly. RasterJS is designed to be used via browsers with three modes of use (i.e., Online, Offline, web bundle) suitable for different scenarios. As a case study, the scope/region of interest of RasterJS is limited to five counties (i.e., Linn, Jones, Johnson, Cedar, Muscatine) within the State of Iowa in the USA.

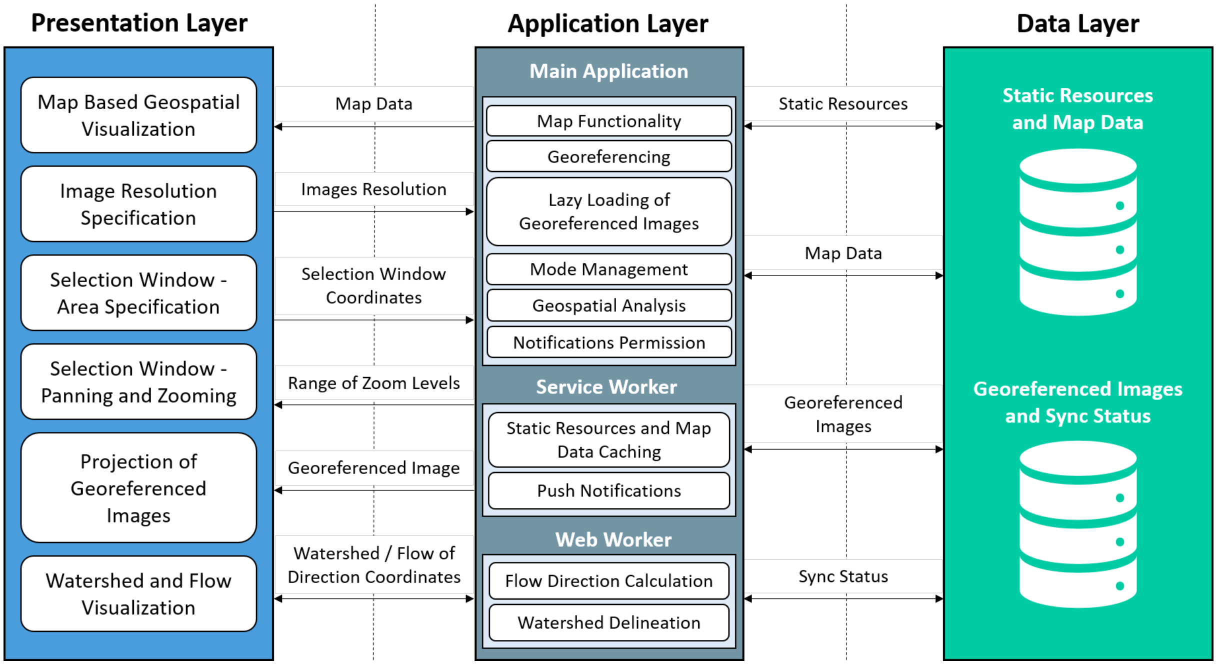


Figure 1: System architecture and three-layer modular structure

2.1. System Architecture

The architecture of RasterJS is a hybrid of 3-layer architecture (Sermet et al., 2020) and component-based architecture (Yacoub et al., 2004). RasterJS is composed of different logical and reusable components that collaborate upon a consistent workflow. Interactions between the components of RasterJS take place in the form of method invocations, broadcasting, and asynchronous invocations. This modular workflow helps RasterJS to be suitable for future upgrades and added functionality with little effort. RasterJS components are distributed into three layers (i.e., Presentation, Application, and Data) according to their functions (Figure 1). This grouping of components in three layers makes the application modular, which leads to robust, readable, and scalable implementation (Teague et al., 2021).

The presentation layer consists of the components (e.g., Google Maps API, Open Layers library) which are responsible for geospatial visualization in the form of maps. This layer is also responsible for drawing the user interface over the maps which give users the ability to interact with the system, resulting in the projection of the georeferenced image. The core logic of the application resides in the application layer that is semantically grouped under three contexts (i.e., service worker, web worker, and main application). All the processing that is independent of the sequential flow of application logic is done in the background within the service worker and web worker contexts, while the rest is handled in the main application context. Finally, the data layer consists of the components (i.e., Cache API, IndexedDB API) that deal with functionalities to retrieve and manage the data in respective client-side data stores.

2.2. Integration of JavaScript APIs

RasterJS utilizes several contemporary JavaScript APIs to support Online and Offline modes as listed in Table A1 in the appendix. The JavaScript API details, and implementation is detailed below.

Fetch API: Fetch API is used by client-side applications for fetching resources from external servers. This requires an internet connection, hence, it can only be used in Online mode (Pande et al., 2018). RasterJS uses this API in the service worker context by retrieving resources from external repositories only when the requested resource is not available in internal components (Cache, IndexedDB).

Service Workers API: The service worker is a JavaScript API that runs in the background and sits between the client-side applications and external components. Whenever the request is made by the client to fetch resources from the external component it is intercepted by the service worker (Pande et al., 2018). RasterJS registers the service worker in the browser when it is loaded for the very first time in the Online mode. When the service worker is registered, it is then invoked by the browser by broadcasting events (e.g., install, activate, fetch, notification close, notification click, and push). In RasterJS, handler functions for each of these events are defined. The goal of these handler functions is to enable RasterJS to perform analytical activities in Offline mode and Online mode.

Cache API: RasterJS benefits from Cache API to cache the requested static resources in the browser. Cache API is used in the service worker context to cache CSS (Cascading Style Sheets) files, JavaScript files, HTML (Hypertext Markup Language) files, application images, and OpenStreetMap raster tiles. All of these resources are cached during the install event of the service worker which is triggered when it is registered in the browser. Cached resources are retrieved by the Cache API when the fetch event of the service worker gets triggered by the browser (Behl & Raj, 2018). Since the resources are stored locally in the browser the storage capacity for caching is limited. Due to this limitation, it is not recommended to cache every resource in the browser. Considering this recommendation, georeferenced images are downloaded in indexedDB for Offline mode (Al-Shaikh & Sleit, 2017).

IndexedDB API: IndexedDB is a client-side Object-Oriented Database in which any structured data including files/blobs can be stored. IndexedDB API is used to communicate with IndexedDB to perform data-related functionalities (Al-Shaikh & Sleit, 2017). With the help of this API, RasterJS creates an IndexedDB to store georeferenced images in the form of blobs for Offline mode and lazy loading. IndexedDB API is used in the main application context when the request for the georeferenced image is made. In this case, the application first looks for that image in IndexedDB. If the image is found then it is retrieved from IndexedDB otherwise, it fetches the image from the external component and stores the image. IndexedDB is capable of storing a great number of files of considerable size and that is why RasterJS uses it for storing georeferenced images (Al-Shaikh & Sleit, 2017; Kimak & Ellman, 2015). Nevertheless, storage capacity for IndexedDB is still limited as it stores data on the client-side. The storage capacity depends on the available disk space on the client-side. Browsers allocate a certain percentage of disk space to IndexedDB and this percentage is browser-specific (Naseem & Majeed, 2013) changing between 5 GB to entire available space on the harddisk.

Notifications API: The purpose of the Notification API is to display the notifications to the end-user. These notifications are related to updates made in the RasterJS application resources. According to the response given by the user to these notifications, the application will update its resources that were stored on the client-side (Cache, IndexedDB). Notifications will only be displayed when the user has given application permission to do so and the application asks for permission when it is loaded in the browser for the very first time. For this purpose, the RasterJS uses this API in the application context and for the rest of the lifecycle of the application, it is used in the registered service worker context (MDN Web Docs, 2021).

Push API: Push API is used to alert the user when the application is closed. It takes advantage of the browser's push messaging system to receive notifications from the server outside the context of the web page or application. RasterJS uses this API for the same reasons. RasterJS uses it in the main application context to subscribe to push messaging service on the client-side and to send that subscription information to the server. In the Service Worker context, RasterJS listens for the push event and handles the received messages and notifications to display them to the user via Notifications API (Beverloo & Thomson, 2021).

Web Workers API: Web Workers API helps in improving the performance of client-side data processing for web applications. Browsers have a single thread that is used for executing JavaScript code and as well as for rendering the user interface. If JavaScript code takes a long time to execute then the user interface gets blocked until that code is executed. To solve this problem, the Web Workers API enables web content to run JavaScript code in background threads without blocking the user interface. JavaScript is a single-threaded language and without web workers, it cannot perform multiple tasks simultaneously. RasterJS uses this API to perform geospatial analysis calculations. It uses web workers for the calculation of the flow direction, raindrop tracking and another for watershed delineation. Web Workers API is used to provide rich user-experience and native applications like performance as these calculations cannot be done in real-time (Wang et al., 2018).

Web Bundles API: Web Bundles is the technology that packages entire website in a single file. This file can be shared like any other file and a whole website can be accessed by opening this file in the browser. Web Bundles is a CBOR file with a .wbn extension in which all of the resources which are necessary for the website to perform its functionalities are bundled. Since the purpose of using this technology was to make the RasterJS application accessible and portable in Offline mode, only those resources are bundled that are essential for the application to function in this mode. To keep the size of the bundled file suitable for distribution, large georeferenced images were not bundled in it. Currently, web bundles are only supported in the Chrome browser and it is an experimental technology that is a part of the web packaging proposal (Yasskin, 2021).

2.3. Geospatial Libraries and Functionality

2.3.1. Mapping Libraries

Google Maps API and OpenLayers JavaScript library are used as map engines to render and interact with maps, drawing a selection window over maps, calculating coordinates of the selected area of interest, projecting georeferenced images, and displaying watersheds. Google Maps API is used in Online mode whereas OpenLayers JavaScript library powers the map in Offline mode. In the Online mode, all the functionalities and data related to maps are managed and provided by Google Maps API. In the Offline Mode, RasterJS provides static map tiles, the extent of these tiles, and a range of zoom levels supported for these tiles to the OpenLayers library. OpenLayers library then renders these tiles according to the specified parameters (Faienza, 2019). If all of the map tiles and georeferenced images are stored on the client-side, then the user of RasterJS can perform geospatial analysis in the Offline mode with only restrictions for specified zoom levels and extent, in comparison to Online mode.

When the application is loaded in the browser it creates a map instance. In this instance, it specifies map specific properties which include map type, starting zoom level, control options, features, and map center coordinates. Map tiles location and range of zoom levels are two extra properties that are set in Offline mode. Since the scope of this application was limited to five counties of Iowa so the value of these properties is set accordingly. To draw the selection window for selecting an area of interest, the application computes the offset with the help of the area of selection window, map center, and direction (North, East, South, and West) parameters. Then it extracts longitude and latitude coordinates from these offsets of each direction and draws a selection window accordingly in the previously created map instance. The selection window can be moved around by the user to select an area of interest. For the projection of the georeferenced image, the application gets longitude and latitude coordinates for each direction from the selection window and retrieves the image respectively. This image is then projected over the selected area in the map's instance. After georeferencing, upon request, the watershed delineation or raindrop flow for the requested location is determined and displayed using flow direction.

2.3.2. Geospatial Algorithms

Georeferencing is the fundamental feature of this application which lays the foundation for the analysis of the georeferenced image. The three important features that can be determined by the analysis of the georeferenced image are the flow directions, watershed boundaries, and rainwater drainage path.

Georeferencing: For georeferencing (Eugenio & Marques, 2003), first, RasterJS gets the bounds of the area of interest in geographic (longitude and latitude) coordinates. These coordinates are then transformed from coordinate pairs (EPSG:4326) to projected coordinates in the Pseudo-Mercator coordinate system

(EPSG:3857). After the bounding coordinates are transformed to Pseudo-Mercator coordinates, the tile server responds with image tiles at the requested zoom level that also cover the requested bounds. RasterJS then fetches these images either from IndexedDB (offline mode) or from the server (online mode). All of these rasters are mosaicked to form a single image according to previously calculated dimensions. The merged raster is then cropped from the starting point. The width of the final cropped raster is determined according to the selected area and resolution. The cropped raster is then sent for display over the map.

***Flow Direction Calculation*:** Flow direction is a watershed characteristic that needs to be determined before watershed delineation. It is determined in a step-by-step process (Zhang et al., 2017). First, the georeferenced image is conditioned by using the Priority Flood algorithm. This algorithm fills depressions that are surrounded by higher terrains and have no outlet to lower areas (Barnes et al., 2014) After this preprocessing step, the D8 algorithm (Tarboton, 1997) is employed for calculating flow direction for non-flat areas only as it is difficult to use it for flat areas (Zhang et al., 2017). Flat areas need to be resolved first before determining their flow direction. For this purpose, flat areas are identified, and then they are divided into two categories according to their adjacency. Some flat areas are adjacent to higher terrains and some are adjacent to lower terrains. After this categorization, gradients away from higher terrain and gradients towards lower terrain are constructed respectively. Using these gradients final flow direction is calculated again using D8 (Barnes et al., 2014). RasterJS makes this flow direction data available for download for future reference.

Watershed Delineation: Watershed delineation is a procedure for identifying and marking a boundary of an area in which any rainfall will flow towards the same outlet. Watershed visualizations assist stakeholders in characterization and analysis, which leads to the identification of surface water features. The analysis is done for the planning and implementation of actions to protect from the harmful effects related to water quality and quantity (Sit et al., 2019). RasterJS first determines the flow directions of the georeferenced image and supplies that as an input to the watershed delineation process resulting in the visualization of the watershed.

Raindrop Flow Tracker: Raindrop flow tracker is a tool that allows users to select a point location on the map and assesses the route a raindrop would follow through the rivers and creeks if it were to fall at that point of interest (Shea et al., 2021). Similar to watershed delineation, flow directions that results from the georeferenced image are used as the basis in assessment of the raindrop flow path. The ability to identify the drainage pathways in the river network and to localize rain movement can help communities to evaluate the areas that are subject to increased risk of being affected by heavy rainfalls. In addition to map visualization, the tool may also be utilized with quantitative parameters, such as travel time and distance the rain movement would take until reaching to the outlet of selected geographical region.

2.4. System Workflow

This section describes the interaction between components and low-level implementation details of Online and Offline mapping services (Figure 2). Each component in the RasterJS plays an important role in ensuring that the application works seamlessly in both Online and Offline modes. To achieve this objective, these components interact with each other to carry out certain tasks. The sequence of these interactions is designed to ensure a uniform transition from one mode to another in case of an unstable internet connection. These interactions are for the transfer of knowledge between the components. In addition to the Offline and Online modes, Web Bundle Mode is introduced as a way for Offline distribution of the application.

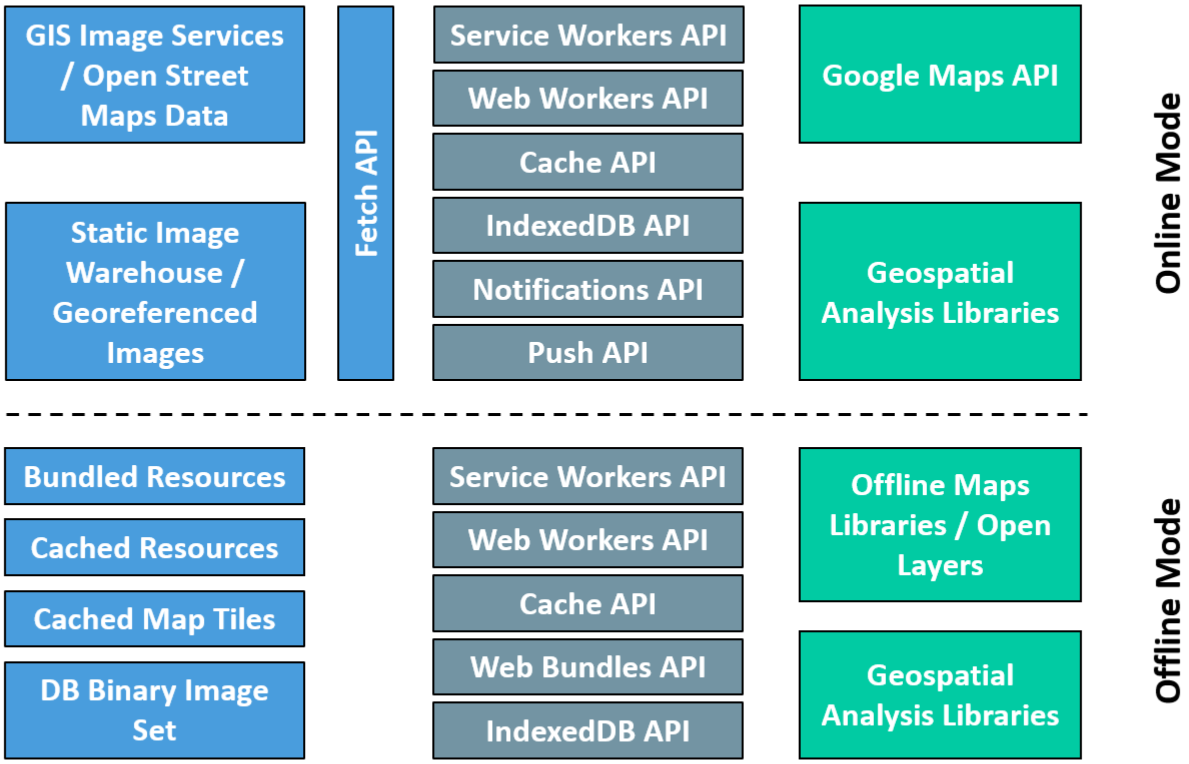


Figure 2: Component-based architecture diagram

2.4.1. Online Mode

When the RasterJS is first loaded in the browser, it asks the user for permission of notifications through Notifications API, registers service worker, caches static assets and OpenStreetMap data with the help of Service Workers API and Cache API, and subscribes user for notifications through Push API (if permission was granted). Then, it sets map specific properties to initializes Google Maps accordingly and renders with RasterJS's user interface. To request a georeferenced image, the user then selects elevation resolution, area dimension, elevation dataset, and navigates to the area of interest. Upon receiving the request, the application calculates georeferencing to get the constituent georeferenced images according to user-selected parameters. If available in indexedDB cache, it gets the georeferenced images from cache via indexedDB API otherwise it fetches images from the server using Fetch API and stores them in indexedDB for future access. After retrieving the images, it merges the images into one georeferenced image according to indexes and requests Google Maps API to georeference this image over the map. Finally, it renders the updated map. The user can view the georeferenced image on the selected area of interest. After georeferencing, RasterJS then invokes a web worker for determining the flow direction of the georeferenced image. To calculate and visualize a watershed, the user needs to click on any location inside the georeferenced image then RasterJS invokes the web worker for the watershed delineation for the requested location, and when boundaries are calculated it displays the watershed over the georeferenced image. A similar procedure needs to be followed for visualizing raindrop flow tracker after selecting the raindrop flow option.

Notifications are configured to make updates in the client-side cache and storage whenever there is a data update on the server-side. Notification is sent from the server whenever there is an update on the server-side. When the notification is received on the client-side, the push event is triggered via Push API. Push event is handled by the Service Worker API and it displays the notification to the user by using Notifications API (Behl & Raj, 2018) If the user response is affirmative then Service Worker API clears the cache, recaches the data.

2.4.2. Offline Mode

Similar to Online mode, in Offline mode, the application first sets map specific properties. Extent, range of zoom levels, and location of map tiles are extra properties that are set in Offline mode only. All of these properties are then fed to the OpenLayers library. This library gets the map tiles from the cache with the help of Cache API which is used in the service worker context. OpenLayers library then constructs the map according to given properties and returns the map to the application. The application then renders the map along with the user interface for interaction. To request a georeferenced image, the user then selects elevation resolution, area dimension, elevation dataset, and navigates to the area of interest. Upon receiving the request, the application does calculations for georeferencing according to user-selected parameters. If available in IndexedDB, it gets the georeferenced images from cache via IndexedDB API otherwise it displays an image not found error to the user. After retrieving the images, it merges the images into one georeferenced image according to indexes and sends this image to Open Layers Library. Open Layers Library georeferences the given image over the map and sends it back to the application. The application renders the updated map, and the user can view the georeferenced image on the selected area of interest. Regarding geospatial analysis, a similar workflow is followed in Offline mode as in Online mode.

2.4.3. Web Bundle Mode

This mode allows users to download the RasterJS as a stand-alone application on demand. All the resources that are needed for the application to work in Offline mode are packaged in a single file. The size of the packaged file is around 300 MB for the five counties, therefore, it is practical to store the file in any device. This file can be distributed to other devices using any Offline data transfer technology (i.e., Bluetooth). To use the application, the user simply needs to run the bundle via a web browser, which then grants access to all the functionalities that are available in the Offline mode. As of 2021, Web Bundles are supported in Google Chrome as an experimental proposed feature (Utsunomiya and Baheux, 2019).

3. Results and Discussions

A case study is defined to demonstrate the capability offered by RasterJS as well as its flexibility to function with different data resources and circumstances. The use case serves as a proof of concept with selected geospatial analytics tools for showcasing its utility in research and operational capacities and does not intend to be a comprehensive web GIS. As the case study location, a 5-county extent within the State of Iowa was selected, encompassing an area of 2,956 mi^2 (i.e., 7,656 km^2). The region of interest was defined by ranges of latitude (41.30, 42.33) and longitude (-92.31, -90.23).

3.1. Case Study Design

RasterJS relies on several raw data resources to function. Georeferenced images and map tiles are needed to fulfill all the requirements of the application. Georeferenced images are needed for georeferencing functionality whereas Map tiles are needed for managing maps in Offline mode. The original georeferenced images or digital elevation model (DEM) data was obtained from the Iowa Department of Natural Resources as a series of 142 arbitrary sections. These data were created from the Iowa LiDAR Mapping Project (UNI, 2021). The DEM sections were provided as 1-meter ESRI GRIDs projected into the UTM Zone 15N coordinate system (EPSG:26915) with floating-point elevations in meters. Although the data represents mostly bare-earth elevations, some built features are seen in the data (e.g., buildings and bridges). Altogether, the file size for the entire dataset is about 570 GB. For this project, we determined that a subset of the entire DEM encompassing the selected case study area.

The DEMs were mosaicked into one large DEM for all of Iowa although the elevation values were converted into US feet as integers (i.e., integerized). All the other coordinate parameters were maintained. The DEM was clipped to this extent and converted to GeoTIFF. At this stage, the clipped DEM was a 1-band 16-bit unsigned value GeoTIFF. An advantage of this format is that it is easily read by GIS and other imaging systems. Although this format is versatile, we decided that the portable network graphics (PNG) was better suited for a web project due to its lossless compression and smaller file size (Sit et al., 2019). We developed a method (Eq. 1) to encode the elevation in the Red and Green bands of the PNG so that the entire range of elevations can be stored within those two bands and still be easily readable from a webpage canvas. This method is as follows:

$$\text{Integerized elevation (ft)} = \text{R-band value} \times 256 + \text{G-band value} \qquad \text{Eq. 1}$$

$$\text{R-band} = \text{quotient, G-band} = \text{remainder, B-band} = 0$$

Using this method, we produced a 24-bit, 3-channel RGB with the elevation stored in the R and G bands. As we are working in a web-based mapping application, we reprojected the raster to the Spherical Mercator projection (EPSG:3857) to display more easily in a web format. We then created a tiling schema to create tile caches at a variety of scales (Table 1). Tiles were structured in terms of zoom level, row, and column so the cached images can be selected based on the bounding box of the view. Using this tiling schema, over 13,000 image tiles were created for the selected region of interest consisting of five Iowa counties.

Table 1: Cell resolution (meter) of tiles and resampling with respect to scale.

Scale	Resolution	Resampling
1:188,976	50m	Yes
1:94,488	25m	Yes
1:37,795	10m	Yes
1:18,897	5m	Yes
1:3,779	1m	No

Extraction of map tiles for Offline mode: RasterJS provides map functions Offline due to its client-side tile caching mechanism. However, in the Offline mode, storage capacity is limited with the hard disk size and browser specification, which encourages restricting the cached tiles to a certain area and zoom levels. Thus, in the case study tiles were selected for 5 counties as part of the case study along with their vicinities for three different zoom levels (i.e., 10, 11, 12). All of these tiles were downloaded from OpenStreetMap data (Singh et al., 2013) with the help of the JTileDownloader application. Retrieved tiles were categorized into folders identified by the corresponding zoom level (OSM, 2021).

3.2. System Evaluation

RasterJS's unique architecture and methodology distinguishes itself from existing geospatial web applications by combining the advantages of both desktop and web-based geoprocessing capabilities regarding performance, accessibility, and convenience. Its functionalities are available in Offline mode and can be used in any browser-equipped device (e.g., mobile, desktop, and tablet). To make the geospatial analysis feature available in Offline mode and to improve the response time of the application, a lazy loading strategy has been adopted. Requested georeferenced images will be cached in indexedDB once received. The application caches map tiles so that the user can navigate the map in Offline mode. In the case study, if all the data (e.g., georeferenced images, map tiles, other static resources) is downloaded on the client-side, then it takes a total space of 3,286 MB, out of which a large chunk of size (i.e., ~3,274 MB) is occupied by IndexedDB where georeferenced images are stored. Other than that, static resources along with the map tiles take 11.9 MB of space in the cache, and Service Workers take only 33.3 KB of space.

Push notifications make the application more engaging as the user is informed about the updates made to the resources of the application and the user then opens the application to incorporate those updates on the client-side. Since the library is designed as a PWA, mobile users can use this application with a native-like experience. It is readily available from the browser and users can add it to the home screen. This saves the storage space in mobile devices as native applications are larger in size than PWA. However, there are some limitations in iOS devices regarding native-like experience as such devices do not support Push notifications and web manifest files.

The system does not require external software framework knowledge to maintain as it relies on vanilla JavaScript and default JS Web APIs. From a user standpoint, the user interface is responsive and intuitive to enable associates of any technical proficiency level to use the system to its full potential without requiring training and previous expertise. The interface shown in the following figures summarizes the map view and user control panel (Figure 3, Figure 4a-d, Figure 5). The user can navigate on the map with the help of panning and zooming. The control panel gives the user the ability to select the values for resolution, area, and elevation for georeferencing. Based on the selected values for these parameters, the selection window appears on the interface which can be moved around for the selection of the area of interest. The georeferenced image will be placed inside this selected area with the watershed boundary or raindrop flow overlaid on top. In Online mode, Google Maps view is displayed whereas in Offline mode OpenStreetMaps tiles are used to construct the map with a reduced extent and restricted zoom levels.

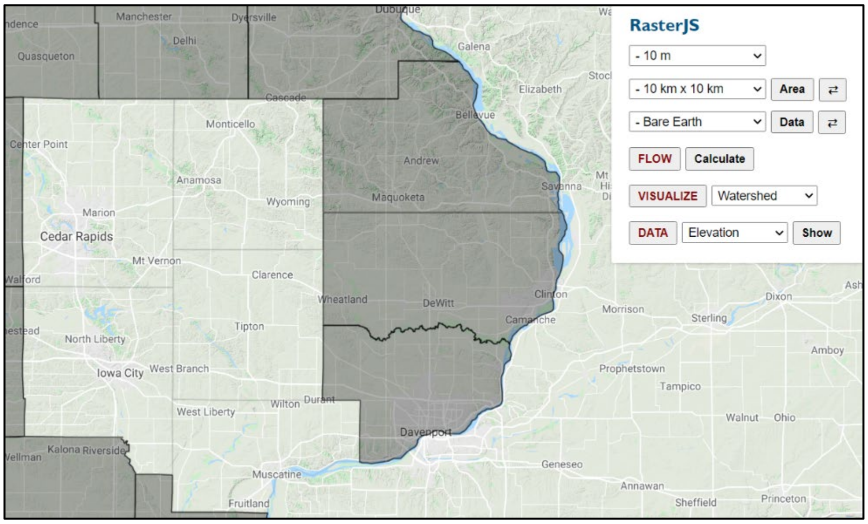
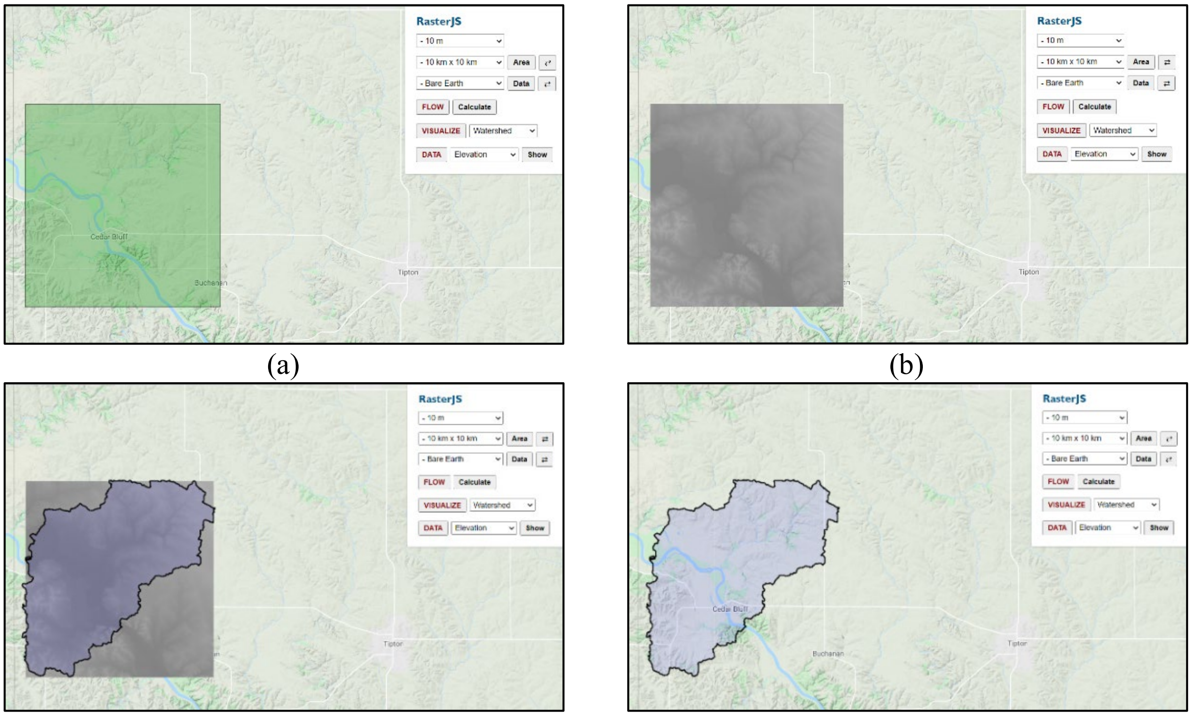


Figure 3: Default view in Online mode



(a)

(b)

(c)

(d)

Figure 4. (a) Selection Window, (b) Projected georeferenced image, (c) Watershed in the georeferenced image, (d) Watershed in the map context

RasterJS provides a cost-effective solution as traditional GIS systems rely on powerful servers and workstations, which may be costly to acquire and maintain for educational and non-profit institutions. The presented approach reduces the dependability on the server-side, hence reducing the licensing costs. Students can use the system via everyday computers as RasterJS leverages the advanced features of web technologies to function on browsers. RasterJS makes real-time data analysis and tracking possible by collecting and integrating data from remote servers on the client-side as needed. It minimizes the requests between client and server, hence displaying results to the user in real-time without any lag that occurs due to communication overhead. Furthermore, the RasterJS can be packaged in a single stand-alone application along with its resources and dependencies. This file can be distributed via Bluetooth, Wi-Fi Direct, AirDrop, and USB without requiring an internet connection. This functionality is essential for ensuring and increasing the productivity of the users who work in non-conventional settings (e.g., outdoors). Specifically, stakeholders, researchers, and staff can utilize RasterJS for in-situ geospatial analysis and reference while performing duties on the field with limited or missing signal for internet connectivity.

Figure 5: Raindrop flow tracker in the georeferenced image

4. Conclusions

This paper presents RasterJS, a web-based geospatial processing library that is built using client-side web technologies and concepts of Progressive Web Application. It provides a framework to perform geospatial analytical activities in real-time and with an engaging user experience. It transfers data storage, management and processing responsibility to the web-client as opposed to the conventional server-based architecture. RasterJS proposes to solve the problems that occur with web GIS such as the high cost of development and maintenance, performance issues, and inconsistency of data in case of concurrent access. The use of modern web technologies like Service Workers API, Fetch API, Cache API, IndexedDB API, Notifications API, Push API, and Web Workers API gives RasterJS the capability to function like both web and native applications. It provides three modes to suit different use cases: Online, Offline, and Web Bundle modes. Online and Offline modes offer similar functionality while allowing the user to coherently switch between them in case of an unstable connection. Other than these two modes, a bundled version of this application can also be created for offline access and distribution.

The architecture of RasterJS is inspired by 3-layer architecture and component-based architecture. RasterJS consists of components that are distributed in 3-layers with respect to their functionality and these components collaborate to achieve a common objective. To perform map-related tasks, RasterJS is dependent on Google Maps API in Online mode and OpenLayers library in Offline mode. Capabilities of the library is demonstrated with a watershed analysis case study for five counties (Linn, Jones, Johnson, Cedar, Muscatine) in the State of Iowa, USA. Three geospatial analysis functions are demonstrated in the system for flow direction calculation from elevation data with hydro-conditioning, raindrop flow tracking, and watershed delineation. RasterJS gives the user the ability to interact with the system in an intuitive and interoperable manner to visualize and analyze georeferenced images for the area of interest.

The vision behind the proposed framework can lead to research institutions providing training to their students without having to worry about setting up expensive systems. On-site workers in remote areas where internet connection is limited can access GIS functionality in a productive manner. They can save the results of their tasks in a packaged file and share it with their peers. The RasterJS makes it easier to ensure data integrity as all the major responsibilities related to data processing and its storage are transferred to the client-side. This methodology also reduces the complexities that arise due to frequent round trips between client and server, which consequently makes real-time data analysis and tracking feasible. Additionally, push notifications and an easy-to-use interface makes the application more engaging and gives a seamless user experience.

The RasterJS will be updated as new web libraries and technologies emerge and existing ones improve. Open-source JavaScript libraries that provide hydrological and GIS-related functions can be readily integrated in the framework to enrich its features and use cases (Ramirez et al., 2022). Web Assembly is a technology that can be incorporated to improve the performance of the system. The development of the RasterJS has opened the door for exploring peer to peer geospatial data distribution using WebRTC. For advanced data visualization approaches, technologies like WebGL can play an important role. WebCL is another technology that can be used for improving the performance of the application especially when the scope of the application will be extended beyond Iowa case study which would require the processing of a large number of images for georeferencing. Other than hydrological analysis, the application can be extended to other areas (e.g., urban planning, transportation, population studies, agriculture) by introducing more analytical abilities (Sermet et al., 2018). Furthermore, several other raster data formats (e.g., GeoPackage, ArcGrid, ImageMosaic) can be supported to encompass a wide array of use cases (Kilsedar, 2020). In summary, the overarching vision of this research is the modernization of GIS services by leveraging and adopting progressive approaches in web development to democratize computational solutions for spatiotemporal data to assist the stakeholders of environmental sciences.

Author Contributions

Muneeb Shahid: Conceptualization, Software, Writing - original draft, Methodology, Visualization, Investigation, Validation, Data curation. **Yusuf Sermet**: Writing - original draft, Investigation, Validation. **Jerry Mount**: Data curation, Writing – review & editing, Resources. **Ibrahim Demir**: Conceptualization, Writing – review & editing, Supervision, Project administration, Resources, Investigation, Methodology, Validation.

Funding

This project was funded by the National Oceanic & Atmospheric Administration (NOAA) via a cooperative agreement with The University of Alabama (NA22NWS4320003) awarded to the Cooperative Institute for Research to Operations in Hydrology (CIROH).

Data Availability Statement

The data and codes that support the findings of this study are available on GitHub (https://github.com/uihilab/RasterJS).

Conflicts of Interest

The authors declare no conflict of interest.

References

Agliamzanov, R., Sit, M., & Demir, I. (2020). Hydrology@ Home: a distributed volunteer computing framework for hydrological research and applications. *Journal of Hydroinformatics*, *22*(2), 235-248.

Agrawal, S., & Gupta, R. D. (2017). Web GIS and its architecture: a review. *Arabian Journal of Geosciences*, *10*(23), 1-13.

Al-Shaikh, A. & Sleit, A. (2017, May). Evaluating IndexedDB performance on web browsers. In *2017 8th International Conference on Information Technology (ICIT)* (pp. 488-494). IEEE.

Barnes, R., Lehman, C., & Mulla, D. (2014). Priority-flood: An optimal depression-filling and watershed-labeling algorithm for digital elevation models. *Computers & Geosciences*, *62*, 117-127.

Behl, K., & Raj, G. (2018, June). Architectural pattern of progressive web and background synchronization. In *2018 International Conference on Advances in Computing and Communication Engineering (ICACCE)* (pp. 366-371). IEEE.

Bermejo-Solera, M. and Otero, J. (2008). Simple and highly accurate formulas for the computation of Transverse Mercator coordinates from longitude and isometric latitude. *Journal of Geodesy*, 83(1), pp.1–12.

Beverloo, P., Thomson, M. (2021, November 3). *Push API – W3C Working Draft*. World Wide Web Consortium (W3C). https://www.w3.org/TR/push-api/

Bildirici, I. O., & Ulugtekin, N. N. (2010, November). Web mapping with Google Maps Mashups: overlaying geodata. In *A Special Joint Symposium of ISPRS Technical Commission IV & AutoCarto in Conjunction with ASPRS/CaGIS* (pp. 15-19).

Dufour, D. J. (2018, December). Capabilities and Limitations of Client-Side Raster Processing. In *AGU Fall Meeting Abstracts* (Vol. 2018, pp. IN41D-0857).

Ebert-Uphoff, I., Thompson, D. R., Demir, I., Gel, Y. R., Karpatne, A., Guereque, M., ... & Smyth, P. (2017, September). A vision for the development of benchmarks to bridge geoscience and data science. In 17th International Workshop on Climate Informatics.

Eugenio, F. and Marques, F. (2003). Automatic satellite image georeferencing using a contour-matching approach. *IEEE Transactions on Geoscience and Remote Sensing*, 41(12), pp.2869–2880.

Faienza, Antonio. (2019). Build an open-source web platform based on OpenLayers, Express and NoSQL DB. 10.13140/RG.2.2.11866.29120.

Farkas, G. (2017). Applicability of open-source web mapping libraries for building massive Web GIS clients. *Journal of Geographical Systems*, 19(3), pp.273–295.

Farkas, G. (2019). Possibilities of using raster data in client-side web maps. *Transactions in GIS*, 24(1), pp.72–84.

Favretto, A. (2014). Coordinate questions in the web environment. *Cartographica: The International Journal for Geographic Information and Geovisualization*, *49*(3), 164-174

Gkatzoflias, D., Mellios, G. and Samaras, Z. (2013). Development of a web GIS application for emissions inventory spatial allocation based on open source software tools. *Computers & Geosciences*, 52, pp.21–33.

Hu, A., & Demir, I. (2021). Real-Time Flood Mapping on Client-Side Web Systems Using HAND Model. Hydrology, 8(2), 65.

Kawasaki, A., Berman, M. L., & Guan, W. (2012). The growing role of web-based geospatial technology in disaster response and support. *Disasters*, *37*(2), 201–221.

Kilsedar, C. E. (2020). Using free and open source software for multidimensional visualization and processing of big open urban geospatial data on the web.

Kimak, S., & Ellman, J. (2015, December). The role of HTML5 IndexedDB, the past, present and future. In *2015 10th International Conference for Internet Technology and Secured Transactions (ICITST)* (pp. 379-383). IEEE.

Kulawiak, M., Dawidowicz, A. and Pacholczyk, M.E. (2019). Analysis of server-side and client-side Web-GIS data processing methods on the example of JTS and JSTS using open data from OSM and geoportal. *Computers & Geosciences*, 129, pp.26–37.

Kulkarni, A. T., Mohanty, J., Eldho, T. I., Rao, E. P., & Mohan, B. K. (2014). A web GIS based integrated flood assessment modeling tool for coastal urban watersheds. *Computers & Geosciences*, *64*, 7–14. https://doi.org/10.1016/j.cageo.2013.11.002

Laine, M. (2012). Client-side storage in web applications. *Aalto University*.

Lee, J., Kim, H., Park, J., Shin, I., & Son, S. (2018, October). Pride and prejudice in progressive web apps: Abusing native app-like features in web applications. In *Proceedings of the 2018 ACM SIGSAC Conference on Computer and Communications Security* (pp. 1731-1746).

Maheshwari, J., Kavishwar, R., Panggam, O., & Deoda, K. (n.d.). Meridian : Multi-featured Android app serving an Offline first Progressive Web application. *International Journal of Innovations in Engineering and Technology*. https://doi.org/10.21172/ijiet.101.13

MDN Web Docs. (2021, September 14). *Notifications API*. Mozilla. https://developer.mozilla.org/en-US/docs/Web/API/Notifications_API

Mena, M., Corral, A., Iribarne, L., & Criado, J. (2019). A Progressive Web Application Based on Microservices Combining Geospatial Data and the Internet of Things. *IEEE Access*, *7*, 104577–104590. https://doi.org/10.1109/access.2019.2932196

Mody, V., Mody, V., & Parekh, S. (2020). Distress – An Application for Emergency Response and Disaster Management. *2020 International Conference on Smart Electronics and Communication (ICOSEC)*. https://doi.org/10.1109/icosec49089.2020.9215288

Nakayama, Y., Nakamura, K., Saito, H., & Fukumoto, R. (2017). A Web GIS Framework for Participatory Sensing Service: An Open Source-Based Implementation. *Geosciences*, *7*(2), 22. https://doi.org/10.3390/geosciences7020022

Naseem, S. Z., & Majeed, F. (2013, September). Extending HTML5 local storage to save more data; efficiently and in more structured way. In *Eighth International Conference on Digital Information Management (ICDIM 2013)* (pp. 337-340). IEEE.

Nugroho, L. E., Pratama, A. G. H., Mustika, I. W., & Ferdiana, R. (2017). Development of monitoring system for smart farming using Progressive Web App. *2017 9th International Conference on Information Technology and Electrical Engineering (ICITEE)*. https://doi.org/10.1109/iciteed.2017.8250513

Oluwatosin, H.S. (2014). Client-Server Model. *IOSR Journal of Computer Engineering*, 16(1), pp.57–71.

Opiña Jr, P. V. (2020). Progressive Web Application for Suitability Mapping of Small Farm Reservoir in Isabela using Soil and Water Assessment Tool. *International Journal of Advanced Trends in Computer Science and Engineering*, *9*(3), 3188–3190.

Open Street Map (OSM) (2020, December 27). *JTileDownloader - OpenStreetMap Wiki*. https://wiki.openstreetmap.org/wiki/JTileDownloader

Pande, N., Somani, A., Prasad Samal, S. and Kakkirala, V. (2018). *Enhanced Web Application and Browsing Performance through Service-Worker Infusion Framework*. IEEE Xplore.

Park, H., Kim, K., & Lee, K. (2016, July). Geo-data visualization on online and offline mode of mobile web using HTML5. In *2016 4th International Workshop on Earth Observation and Remote Sensing Applications (EORSA)* (pp. 237-240). IEEE.

Paul, U., Nekrasov, M., & Belding, E. (2019). EmerGence. *Proceedings of the 20th International Workshop on Mobile Computing Systems and Applications*. https://doi.org/10.1145/3301293.3309557

Ramirez, C. E., Sermet, Y., Molkenthin, F., & Demir, I. (2022). HydroLang: An open-source web-based programming framework for hydrological sciences. *Environmental Modelling & Software*, *157*, 105525.

Rêgo, F., Portela, F. and Santos, M.F. (2019). Towards PWA in Healthcare. *Procedia Computer Science*, 160, pp.678–683.

Ryza, S., & Wall, T. (2010). *MRJS: A JavaScript MapReduce Framework for Web Browsers*. http://128.148.32.110/courses/csci2950-u/f11/papers/mrjs.pdf

Seo, B. C., Keem, M., Hammond, R., Demir, I., & Krajewski, W. F. (2019). A pilot infrastructure for searching rainfall metadata and generating rainfall product using the big data of NEXRAD. Environmental modelling & software, 117, 69-75.

Sermet, M. Y., Demir, I., & Kucuksari, S. (2018, September). Overhead power line sag monitoring through augmented reality. In *2018 North American Power Symposium (NAPS)* (pp. 1-5). IEEE.

Sermet, Y., Demir, I. and Muste, M. (2020). A serious gaming framework for decision support on hydrological hazards. *Science of The Total Environment*, 728, p.138895.

Sermet, Y., & Demir, I. (2020). Virtual and augmented reality applications for environmental science education and training. In New Perspectives on Virtual and Augmented Reality (pp. 261-275). Routledge.

Shea, B., Johannes, A., Giannini, K., & Skopec, M. (2021, November 17). Iowa's Changing Land Use. *Iowa Pressbooks*, *Iowa 8th Grade Science Bundles*.

Sheppard, D. (2017). *Beginning Progressive Web App Development: Creating a Native App Experience on the Web*; Springer: Berlin/Heidelberg, Germany.

Shi, K. (2020). Design of Network Information Service Platform for Intelligent Agricultural Industry Chain. *2020 International Conference on Communications, Information System and Computer Engineering (CISCE)*. https://doi.org/10.1109/cisce50729.2020.00087

Simão, A., Densham, P. J., & Muki) Haklay, M. (2009). Web-based GIS for collaborative planning and public participation: An application to the strategic planning of wind farm sites. Journal of Environmental Management, 90(6), 2027–2040.

Singh Sehra, S., Ludhiana, I., Singh, Hardeep, I. and Rai, S. (2013). Assessment of OpenStreetMap Data - A Review. *International Journal of Computer Applications*, 76(16), pp.975–8887.

Sit, M., Langel, R. J., Thompson, D., Cwiertny, D. M., & Demir, I. (2021). Web-based data analytics framework for well forecasting and groundwater quality. Science of The Total Environment, 761, 144121.

Sit, M., Sermet, Y., & Demir, I. (2019). Optimized watershed delineation library for server-side and client-side web applications. *Open Geospatial Data, Software and Standards*, *4*(1), 1-10.

Swain, N.R., Christensen, S.D., Snow, A.D., Dolder, H., Espinoza-Dávalos, G., Goharian, E., Jones, N.L., Nelson, E.J., Ames, D.P. and Burian, S.J. (2016). A new open source platform for lowering the barrier for environmental web app development. *Environmental Modelling & Software*, 85, pp.11–26.

Swain, N.R., Latu, K., Christensen, S.D., Jones, N.L., Nelson, E.J., Ames, D.P. and Williams, G.P. (2015). A review of open source software solutions for developing water resources web applications. *Environmental Modelling & Software*, 67, pp.108–117.

Tandel, S., & Jamadar, A. (2018). Impact of progressive web apps on web app development. *International Journal of Innovative Research in Science, Engineering and Technology*, *7*(9), 9439-9444.

Tarboton, D. G. (1997). A new method for the determination of flow directions and upslope areas in grid digital elevation models. *Water resources research*, *33*(2), 309-319.

Teague, A., Sermet, Y., Demir, I., & Muste, M. (2021). A collaborative serious game for water resources planning and hazard mitigation. *International Journal of Disaster Risk Reduction*, *53*, 101977.

University of Northern Iowa (UNI) (2021, November 16). *Iowa LiDAR Mapping Project*. https://www.geotree.uni.edu/en/extension/iowa-lidar-mapping-project/

Utsunomiya, Y., Baheux, K. (2019, November 11). *Get started with Web Bundles*. Google Developers. https://web.dev/web-bundles/

Vitolo, C., Elkhatib, Y., Reusser, D., Macleod, C.J.A. and Buytaert, W. (2015). Web technologies for environmental Big Data. *Environmental Modelling & Software*, 63, pp.185–198.

Walker, J.D. and Chapra, S.C. (2014). A client-side web application for interactive environmental simulation modeling. *Environmental Modelling & Software*, 55, pp.49–60.

Wang, Z., Deng, H., Hu, L., & Zhu, X. (2018, October). HTML5 Web Worker Transparent Offloading Method for Web Applications. In *2018 IEEE 18th International Conference on Communication Technology (ICCT)* (pp. 1319-1323). IEEE.

Xu, H., Demir, I., Koylu, C., & Muste, M. (2019a). A web-based geovisual analytics platform for identifying potential contributors to culvert sedimentation. Science of the Total Environment, 692, 806-817.

Xu, H., Muste, M., & Demir, I. (2019b). Web-based geospatial platform for the analysis and forecasting of sedimentation at culverts. Journal of Hydroinformatics, 21(6), 1064-1081.

Xu, H., Windsor, M., Muste, M. and Demir, I. (2020). A web-based decision support system for collaborative mitigation of multiple water-related hazards using serious gaming. *Journal of Environmental Management*, 255, p.109887.

Yacoub, S., Cukic, B. and Ammar, H.H. (2004). A scenario-based reliability analysis approach for component-based software. *IEEE Transactions on Reliability*, 53(4), pp.465–480.

Yang, C., Wong, D.W., Yang, R., Kafatos, M. and Li, Q. (2005). Performance-improving techniques in web-based GIS. *International Journal of Geographical Information Science*, 19(3), pp.319–342.

Yasskin, J. (2021, April 13). *Web Bundles*. Google. https://wicg.github.io/webpackage/draft-yasskin-wpack-bundled-exchanges.html.

Yildirim, E., & Demir, I. (2021). An Integrated Flood Risk Assessment and Mitigation Framework: A Case Study for Middle Cedar River Basin, Iowa, US. International Journal of Disaster Risk Reduction, 56, 102113.

Zhang, B., Ye, Y., Shen, X., Mei, G., & Wang, H. (2018). Design and implementation of levee project information management system based on WebGIS. *Royal Society Open Science*, *5*(7), 180625.

Zhang, H., Yao, Z., Yang, Q., Li, S., Baartman, J.E.M., Gai, L., Yao, M., Yang, X., Ritsema, C.J. and Geissen, V. (2017). An integrated algorithm to evaluate flow direction and flow accumulation in flat regions of hydrologically corrected DEMs. CATENA, 151, pp.174–181.

Zhao, P., Foerster, T. and Yue, P. (2012). The Geoprocessing Web. *Computers & Geosciences*, 47, pp.3–12.

Appendix

Table A1: Modern browser support for JavaScript APIs utilized in RasterJS.

	Chrome	**Firefox**	**Edge**	**Opera**	**Safari**
Service Workers API	>= 45	>= 44	>= 17	>= 32	>= 11.1
Cache API	>= 43	>= 39	>= 18	>= 30	>= 11
Indexed DB API 2.0	>= 58	>= 51	>= 79	>= 45	>= 10.1
Notifications Permission API	>= 43	>= 46	>= 79	>= 30	Not Supported
Push API	>= 50	>= 44	>= 17	>= 42	Not Supported