HydroRTC: A Web-Based Data Transfer and Communication Library for Collaborative Data Processing and Sharing in the Hydrological Domain

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Abstract
The exponential growth in data generated by satellites, radars, sensors, and analysis and reanalysis from model outputs for the hydrological domain requires efficient real-time data management and distribution mechanisms. This paper introduces HydroRTC, a web-based data transfer and communication library designed to accelerate large-scale data sharing and analysis. Leveraging next-generation web technologies like WebSockets, WebRTC and Node.js, the library enables seamless peer-to-peer sharing, smart data transmission, and large dataset streaming. Three primary scenarios are presented as use cases, demonstrating the potential of HydroRTC as server-to-peer with intelligent data scheduling and large data streaming, peer-to-peer data sharing, and peer-to-server for data exchange. HydroRTC offers a promising solution for collaborative infrastructures in the hydrological and environmental domain, allowing real-time and high-throughput data sharing and transfer for enhancing research efficiency and collaboration capabilities.

Software Availability

Name	HydroRTC
Developers	Carlos Erazo Ramirez, Muneeb Shahid
Contact information	300 S. Riverside Dr., Iowa City, IA 52246 USA
Software required	Web Browser
Program language	JavaScript, HTML, Node.js
Data Availability	The testing data can be found in each developed case study in the library's repository.
Availability and cost	The code is open-source and free to use and can be accessed on GitHub.
Code repository	https://github.com/uihilab/HydroRTC

1. Introduction

The amount of information being generated in contemporary earth sciences exceeds the capacity for easy ingestion and digestion by researchers and data collectors. This challenge is particularly evident in hydrology, encompassing remote sensing, reanalysis data, sensor data, and various other sources. Management of this data primarily rests with governmental agencies, research institutions, and diverse organizations utilizing information systems to conduct comprehensive analyses across various metrics (Ames et al., 2012). These analyses span a wide spectrum, covering flood extents, rainfall distributions, resource allocation, humidity, temperature conditions, and other pertinent parameters crucial for informed decision-making processes (McMillan et al., 2018).

In today's landscape, managing and effectively distributing large volumes of data is crucial. Understanding how this data is used is key to leveraging new technological advancements, especially in terms of web technologies, web systems, and new implementations that improve existing systems (Zhu et al., 2013). These technological steps not only enable more efficient data management (Demir & Szczepanek, 2017) but also offer opportunities for enhancing the overall functionality and utility of these systems and how they are leveraged for data utilization and analysis (Vitolo et al., 2015). The distribution of these systems primarily relies on the effective management of servers (Fragkos et al., 2020), which play a fundamental role in advancing not just technological systems but also significantly contribute to the progression of earth sciences by handling and disseminating substantial data repositories.

1.1. Background

The conventional methods of managing, storing, and distributing data often revolve around server-based architectures, mostly growing through horizontal scaling, which involves expansion of the infrastructure with multiple servers working in parallel to manage the escalating data volumes. Data hosted on servers is accessible through various mechanisms, typically employing TCP/IP services over the internet (Balakrishnan et al., 1998). To efficiently handle diverse user needs, a semantically driven database system is usually in place. This database system allows the servers to comprehend and respond to the diverse information requirements of the users within the system. The scalability of such server systems is dependent upon factors such as the volume of users accessing the system, the level of information required, and the volume of transactions the system needs to handle (Veal & Foong, 2007).

Despite their utility, centralized systems face several challenges. They often encounter difficulties when dealing with a large number of users or accommodating a high volume of data (Nahum et al., 2002). In numerous organizations, the continuous growth in data size frequently results in server overload, leading to performance degradation or even system crashes (Liu et al., 2020). Moreover, relying on centralized servers poses a single point of failure, making them susceptible to technical issues or targeted cyberattacks, potentially resulting in system downtime and data loss. Maintaining data integrity and ensuring availability requires the implementation of complex redundancy systems and backup strategies, which, in turn, increase system complexity and operational costs. Geographical distance from a centralized server can also cause increased latency for users, resulting in slower data retrieval times (Berman & Drezner, 2007). While augmenting the number of servers can alleviate some of these issues, it comes at the expense of heightened maintenance and upgrade costs, making it a resource-intensive and expensive endeavor.

Recent technological integrations into browser and server systems have brought forth some solutions to the challenges associated with centralized systems (Kumar & Mallick, 2018). New implementations like node-based systems in cloud architectures have shown a shift in mitigating some of these issues by distributing data handling across multiple nodes (Szalay et al., 2021; Seo et al., 2019). Recognizing the challenges inherent in large-scale systems, alternative technological approaches, such as peer-to-peer connectivity paired with server technologies, offer efficient means of managing and distributing data (Conoscenti et al., 2017), and move towards data decentralization. Embracing the concept of decentralized systems allows users to interact with data in ways that align more closely with specific domain requirements.

1.2. Related Work

Modern data sharing and processing paradigms have undergone a revolution through the use of server-client structures and signaling systems. These approaches facilitate effortless user engagement with state-of-the-art technologies across various fields. This advancement is based on TCP/IP domain manipulation and refined protocol optimization, enabling its use in diverse functionalities like video conferencing, seamless data exchange, and instant communication. These capabilities are used across a wide spectrum of domains, ranging from scientific computing in radar systems to the dynamic field of medical science and beyond. The fundamental shift towards these innovative data sharing methodologies fosters a seamless integration of multifaceted features for effective collaboration and information exchange.

In the realm of telemedicine, peer-server systems have facilitated the development of tele-home monitoring setups, enabling seamless video conferencing across multiple locations with high-bandwidth frequency, presenting an economically viable and technologically advanced approach (Jang-Jaccard et al., 2016). Additionally, in organ detection and IoT telesonography, researchers have explored the use of browser-to-browser connections integrated into WebRTC systems. This approach allows for rapid data transmission through organ detection algorithms directly, requiring minimal user input and improving response time from health practitioners (Bharath et al., 2016). Furthermore, these technologies have been instrumental in creating collaborative platforms for real-time medical teleconsultation. Leveraging single-page application concepts, these platforms enable efficient client-side data processing and sharing of medical imagery (Maglogiannis et al., 2017). Advancements in browser-based communication technologies have revolutionized e-Health services, mitigating constraints related to location and timing. These innovations have facilitated the sharing and utilization of vital signs, continuous monitoring, and intelligent communication (Sermet and Demir, 2021), offering users comprehensive healthcare solutions (Pierleoni et al., 2016).

Beyond its applications in healthcare, this technology has gained prevalence as a strong data solution. Research has explored the implementation of client and server signaling using peer-to-peer technology (Sredojev et al., 2015), as well as efficient file data scheme transfers through interface implementation without requiring additional plugins, directly leveraging HTML5 support (Quanfeng et al., 2015). Moreover, recent studies emphasize the utilization of technologies like Web-GL and WebGPU in conjunction with WebRTC, showcasing their efficacy in generating powerful visualizations, particularly in scientific data visualization on the web (Franke & Haehn, 2020; Sermet and Demir, 2022).

The use of peer-to-peer data sharing and communication schemes is prevalent in hydrology and environmental domains, especially within hydroinformatics and computer science modeling. Tailoring information sharing schemes—whether server-to-peer or peer-to-peer—requires separate handling mechanisms, enhancing comprehension of these tasks to solve particular problems in terms of data sharing, model simulations, and decision-making. Several studies address scenarios involving streaming large data for diverse analytical purposes. Distributed information services integrate atmospheric, hydrological, hydrogeological, hydraulic, and agricultural models via grid-like systems, enabling regionalized computing per peer (Galvão et al., 2009). Web-based volunteer computing explores diverse settings, from running hydrologic models directly on browsers to efficiently handling server-side applications for model execution (Agliamzanov et al., 2019). A large focus has been given to server-side workflow executions to accommodate diverse and complex model outputs and variables, creating comprehensive, data-intensive systems (Essawy et al., 2016). Systems handling big data streams rely on robust server-side hardware, often following a Model-Viewer-Controller (MVC) architecture, ensuring efficient distribution of information required for specific runtime settings and immediate manipulation for model output control (Poola et al., 2017; Bürger et al., 2012).

Nevertheless, recent advancements in browser-to-browser communication have triggered a prevalent shift in distributed systems. These systems catering to large-scale data processing and distribution can now leverage new protocols and information-sharing schemes. For instance, Zhang et al. (2022) evaluated the connection between the urban water model SWMM and on-demand flood modeling via WebRTC, facilitating collaborative peer exchanges that mitigate server-data limitations. Combining specialized systems with this technology enables progressive web applications, particularly for web-based geospatial analysis (Sit et al., 2021a), supporting decision-support systems (Shahid et al., 2023). The next generation of hydroinformatics tools aims to expand this approach, optimizing server-side computing through client-side decentralized systems (Satilmisoglu et al., 2024). With the recent advancements in artificial intelligence, large language models, and heavy data-driven models (Xiang et al., 2021; Sit et al., 2021b), the use of peer-to-peer communication can benefit the hydrological domain in aspects such as AI-driven education assistants (Sajja et al., 2023), large-scale modeling systems (Ewing et al., 2022; 2024), and web-based computing frameworks (Erazo Ramirez et al., 2022, 2023, 2024).

With the broad landscape of data sharing solutions, there is a strong potential for leveraging web browser technologies to democratize and decentralize data in a scalable and secure manner across server and peer environments. With established standards like WebSockets and WebRTC, facilitating communication between peers and servers becomes effortless. In line with this, we have developed HydroRTC—an advanced server and peer library powered by a robust technological stack of libraries and domain-specific knowledge—to promote information democratization through real-time data sharing and multi-user collaboration. Specifically designed for the hydrological and environmental domains, this library recognizes the crucial role of communication between servers and peers, as well as among peers themselves.

The primary objective of this project is to provide a collaborative platform that promotes data sharing, encourages user collaboration, facilitates efficient data analysis, and establishes a resilient peer-to-peer communication infrastructure, removing different barriers to accessing and utilizing large-scale data. This work adheres to the best practices in modular software ontology, encompassing a diverse range of functionalities for managing various data types within the library. Our approach promotes easy integration of new functions from the user community, amplified by comprehensive case studies that broaden the vision of our approach.

The subsequent sections of the paper are organized as follows: Section 2 details the methodology employed in the library's development, encompassing system architecture, functionalities, approaches to diverse data types, and potential use cases. Section 3 delves into results and discussions arising from implemented functionalities within case studies, highlighting the library's potential applications. Finally, Section 4 outlines observed limitations, proposes future work directions, and concludes the development discourse.

2. Methodology

2.1. HydroRTC Architecture

HydroRTC is a library built on top of Node.js, Socket.IO, and Peer.js to create full server-to-peer, peer-to-peer, and peer-to-server interactions. Node.js is a JavaScript runtime environment similar to in-browser engines that allow building server-side applications using JavaScript language supporting different versions of language—i.e., ES6 module support—providing an event-driven, non-blocking architecture that works properly for real-time applications that require server-side interactions for a client (OpenJS, 2023). It is extensible and comprehensive enough that it can be deployed as server handling using different types of libraries, with many of the functionalities described below leveraging this key feature of the runtime. Socket.IO is a library that enables protocol sharing and transport through the use of WebSockets (W3C, 2023a) to transfer information between a client and server and is used for building applications that require instant interactions and updates between a server and client(s) in a bidirectional manner (Socket.IO, 2023).

Peer.js is a library built on top of WebRTC (W3C, 2023b) to create peer-to-peer data streaming. Through the use of in-browser support for WebRTC, Peer.js creates direct communication between peers without the need of intermediary servers (Peer.JS, 2023), only a signaling server that can be either provided by the user or the library developer's existing solutions, which is not recommended for production. A signaling server is a server that allows peer-to-peer communication so that two or more peers can establish a connection through a protocol handshake. For the development of the library, we have used the signaling server from the original Peer.js stack that allows the connection between peers, simplifying the process of defining a server. This can be changed depending on the requirements of the users, and future deployments of the library will allow user-tailored servers and protocols.

In terms of storage, the HydroRTC system was designed with consideration for the connections between a server that holds the information required by the user, data stored locally by the user that other users may want to share, and data from the user intended for the server. To achieve this, IndexedDB was utilized in the client-side implementation to establish a strong and reliable method for storing and exchanging data with the server. The library allows users to create web applications interfacing through API calls the implemented methods within the client-side, while the server listens and interacts with and manages other requirements. This deployment can occur either on a local machine functioning as both server and client or on dedicated machines accessing the server side and communicating through HTTPS protocol requests to the client.

2.2. System Functionalities

The HydroRTC library was developed in consideration of the prevalence of scalable server systems that store large amounts of data and the necessary connectivity between peers. This framework aims to reduce some of the server requirements to enable robust real-time data sharing and collaboration. To achieve this goal, two interconnected approaches were used: a server-side implementation responsible for providing an environment that facilitates peer connections, stores peer information, and enables easy interaction for data sharing and tasks among connected peers. It manages file requests for specific data types, serves HTML files, and responds to various events and requests between clients. On the client side, the implemented class connects to the server using several event listeners and handlers that directly interact with user inputs. These inputs vary depending on the selected communication and sharing scheme, such as direct peer-to-peer interaction, server-to-peer, and peer-to-server data connections for sharing. The architecture of both implementations can be found in Figure 1.

Both implementations rely on each other to create a comprehensive system that enables connections across multiple peers. They are both based on the Node.js development scheme and share commonalities in terms of event listeners, event handlers, and data sharing schemes. Upon initialization within an HTML structure, the library loads all the necessary packages required for operation (further descriptions will be provided in the paper). After initialization, the server establishes a connection with the client and, through various implemented methods, serves the necessary data for effective sharing.

Server-Side Component: The server is built on Node.js, creating a scalable and efficient server-side application using a robust backend. The core functionality of the library relies on

WebSocket connections achieved through Socket.IO, facilitating bidirectional communication between the server and client(s). This enables fast data transmission, real-time updates, and interactions with efficient, low-latency communication. Upon deployment, the server listens for user-triggered events via a defined event message passing interface, using pre-defined JavaScript objects corresponding to various messaging types, either containing or missing associated data from the client. The implementation includes event definitions establishing triggers between the client and server, as outlined in Table 1. These event emitters are accessible on the client side and activate upon user registration. Initially, the HTML serving the library remains on standby, awaiting instructions. User information data is stored server-side and emitted back to the client component, confirming the established connection between both ends. This connection also initiates WebRTC setup for the user using Peer.js within the client component, enabling user broadcasting within the system, checking existing connections on the server, and facilitating user awareness of others connected to the server or session.

Table 1. Event triggers for the server and client implementations.

Events	**Description**
Join, connection & disconnect	On connection/disconnection to the server. Triggers all the event listeners on the socket.
Validate-Username	Validating if a user is not already registered in the server.
Stream-Data	Creates a stream data listener for a server-peer response.
Peers-list	Returns all the list of peers connected to the server.
Peer-id	Returns a specific id given to a user for p2p connection.
Request-peer	Initializer for p2p connection.
Start & Update smart-data-sharing	Smart data transfer based on the user needs.
Peer-to-server	Upload data to a server from a given peer.
Get-task & task-result	Distributed computing listener for tasks.
Netcdf-reader, hdf5-reader, tiff-reader, gribb-reader	Specific data type readers with handlers in the server.

The server implementation has been tailored to handle various types of data commonly found in the hydrological domain. Specifically, it can manage large data sizes, including numerous files or file sizes reaching the scale of tens of gigabytes. This data covers sensor observations, satellite imagery, scientific packaging formats for specific earth observation variables, GIS input/output data, or model analysis/reanalysis outputs from research institutions. Data streaming is achieved by utilizing existing libraries and tools within the Node.js environment. Specifically, it creates array buffer binary streams divided into chunks that can be sent to the client—or from the client's local storage to the server—and saved according to the client's requirements. Moreover, the packages are compressed to ensure secure and efficient streaming. On the client side, the user can decide whether to retain this information in the local web environment or save it to their storage.

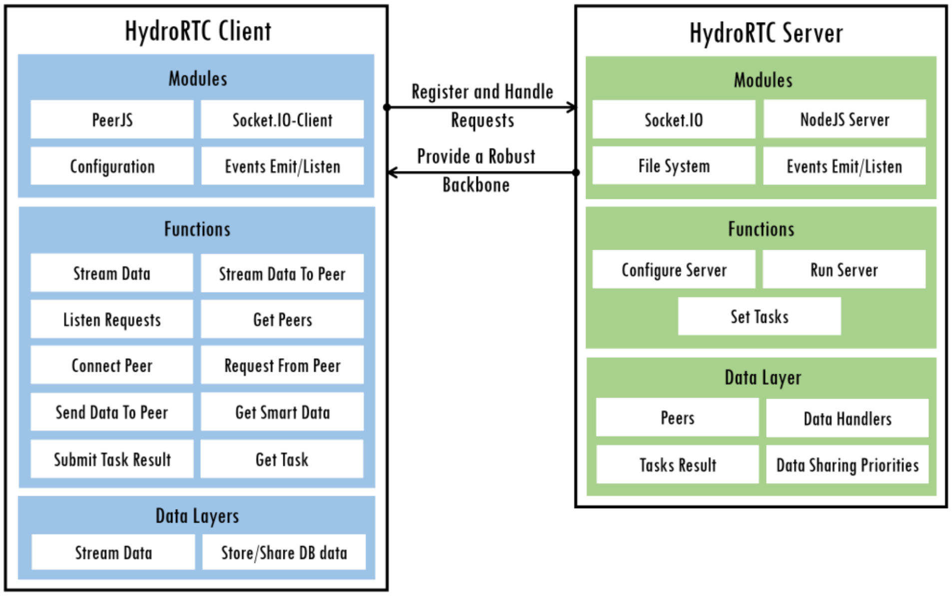

Figure 1. Server-side architecture. The different functionalities are meant to establish direct connection with the client component.

Client-Side Component: The client-side component was developed using Web sockets via Socket.IO for seamless message passing, connection establishment, and interoperability between the server and client. The component heavily relies on Peer.js' WebRTC connections to establish communication channels among different clients. The library works through event triggers, facilitating a flexible framework for users to create specific data channels and various passing mechanisms, such as chat interfaces and handling binary data. Further explanation of these functionalities will be provided in the description of case studies. Additionally, an IndexedDB interface serves as client-side storage for data sourced from the server, other peers, the user's local machine, or outputs from specific simulations or direct browser-based work. This data can subsequently be saved on the server or shared with other peers.

When a user connects, the component creates a unique identifier that is used to create peer-to-peer connections with other users. This information is saved in the server component. The interactions between peers are directly managed within the client component, where the connection between receiver and requestor peers is handled according to each role. Once the connection has been requested, the server checks for the user identifier and looks to see if there is no other connection already established with other peers. If this is the case, then the server signals back to the client that a connection can be correctly made, and the WebRTC handling mechanism that creates the different connections is triggered. This is a communication channel that allows for either message passing, data transfers using Node.js functions, or media transfers through the user's media outlets.

File viewers and interpreters are being used from the server side, meaning that once a file has been emitted either from the server to the client or from a peer-to-peer channel, the implemented handlers for specific files are used to create a viewport for the user receiving the data. Given the nature of the UI and blocking paradigm from a security and implementation perspective, only small subsets of the information found within each file are given to users, but this information can be further explored on the user's local machine.

2.3. Data Formats and Support

Scientific formats considered throughout the components' development include but are not limited to the scientific compression formats (i.e., HDF.v5, netCDF.v3 and v4, GRIBB), GIS files (i.e., shapefiles, raster files, TIFF and GeoTIFF), images (i.e., JPEG, PNG), and general formats (i.e., CSV, JSON, GeoJSON, tabular, XML) with an explanation for each in the following paragraphs.

TIFF and GeoTIFF formats are widely used raster image formats supporting geospatial information, commonly employed in scientific and geographical applications (Ritter & Ruth, 1997). HDF5 is a versatile file format used extensively in environmental and hydrological domains for managing complex data (Folk et al., 2011). NetCDF files are hierarchical data formats ideal for multidimensional scientific data, particularly atmospheric, oceanographic, and geospatial data (Rew & Davis, 1990). GRIB, or gridded binary, is commonly used for weather forecasting and climate model outputs (NCEP, 2023). Shapefiles are popular geospatial vector data formats used in GIS software for mapping and spatial analysis. JPEG is a widely used image format suitable for photography and web-based graphics, renowned for its compression capabilities. PNG, or Portable Network Graphics format, offers lossless compression and transparency support, commonly utilized in web graphics.

CSV, or comma-separated values, represent tabular data formats used for storing and exchanging structured data. JSON and GeoJSON, lightweight data interchange formats, are utilized in web-based applications. The 'geo' in GeoJSON denotes a special type of JSON that contains geospatial features like points, lines, and polygons. Tabular data is a general term denoting data organized in rows and columns, while XML, or Extensible Markup Language, is a versatile format commonly used in web services and configuration files for storing and transporting data.

These data formats can expand in the future to accommodate emerging formats and innovations in information technology with community support. All these data formats have challenges that stem from traditional methods of handling this type of information. Large data streams from a comprehensive GIS system pose obstacles for clients. Additionally, specialized software is required to properly compute these formats for further analysis.

The data handled within the HydroRTC client and server implementations originates from various sources. These include information and outputs generated by diverse models employed in the atmospheric, hydrological, and environmental sciences. Radar data used in GIS systems typically derives from radar installations distributed across geographical regions, capturing real-time or historical information on precipitation, weather patterns, and other spatially sensitive meteorological data. These radar datasets, crucial for weather forecasting and analysis, are often made available through meteorological agencies or institutions specializing in climate studies.

Furthermore, the data generated from models in the atmospheric, hydrological, and environmental sciences comprises a diverse range of information. From statistically derived models, which rely on historical data and patterns to predict future trends, to physically driven models that simulate complex environmental processes. These may include numerical weather prediction models, climate models, hydrological models, and environmental impact assessment tools. The latter generates data utilized for research, predictions, scenario simulations, and policy decision-making. The accessibility of this information varies depending on location and the type of information required. It can be sourced from locally developed or institution-specific models, publicly available repositories, or served systems provided by research institutions, governmental bodies, or international organizations. Institutions dedicated to scientific research and meteorological or environmental monitoring often curate and disseminate these datasets to promote scientific knowledge.

The utilization of specific data formats mentioned earlier serves critical roles in handling and representing this scientific data. For instance, NetCDF and HDF5 are widely employed in storing and sharing multidimensional scientific data, enabling efficient management and analysis of climate model outputs, atmospheric observations, and oceanographic datasets. GRIB, designed for weather forecasting, compactly encodes meteorological and oceanographic data, optimizing storage and transmission for numerical weather prediction models. Additionally, GeoJSON facilitates the representation of geospatial features, allowing for the integration of spatially referenced data, such as geographical boundaries, points of interest, and environmental features, into GIS applications and analysis. These formats not only enable efficient data storage and sharing but also contribute to advancing scientific knowledge and understanding of complex environmental processes and phenomena.

Scientific formats standardized within the community, such as NetCDF, HDF5, and other binary formats, prove useful because they encompass large data streams in accessible layers, removing the hurdles of maintaining and managing large information systems. Files from different formats can contain numerous variables distributed across space and time, making this information notably heavy. Depending on the type of environment where this data is running, typically a client-side installed application, the data formats are used for model processing and data interoperability. However, for web environments, this data has traditionally been saved and stored on servers that are interfaced through either APIs or direct SFTP connections. With new potential avenues of improvements in web environments, particularly client-side applications with the use of multithreading technology, fast message passing systems, and near-native-speed binary formats from other precompiled languages such as Web Assembly, the potential to create in-browser full-fledged applications can become more prevalent.

2.4. HydroRTC Use Cases

The primary objective of our library is to serve as a comprehensive resource facilitating server-to-client communication across a spectrum of functions, with a particular focus on data streaming, workload distribution, and leveraging client-side hardware. To fulfill this purpose, we have identified multiple use cases that demonstrate the library's application in diverse contexts.

The core concept is to establish a streamlined workflow for data transmission through either the server or client, enabling real-time decision-making without excessive reliance on server-side implementations. Instead, the implemented handlers for different data formats can be utilized across various use cases. An overview of the system's management can be observed in Figure 2.

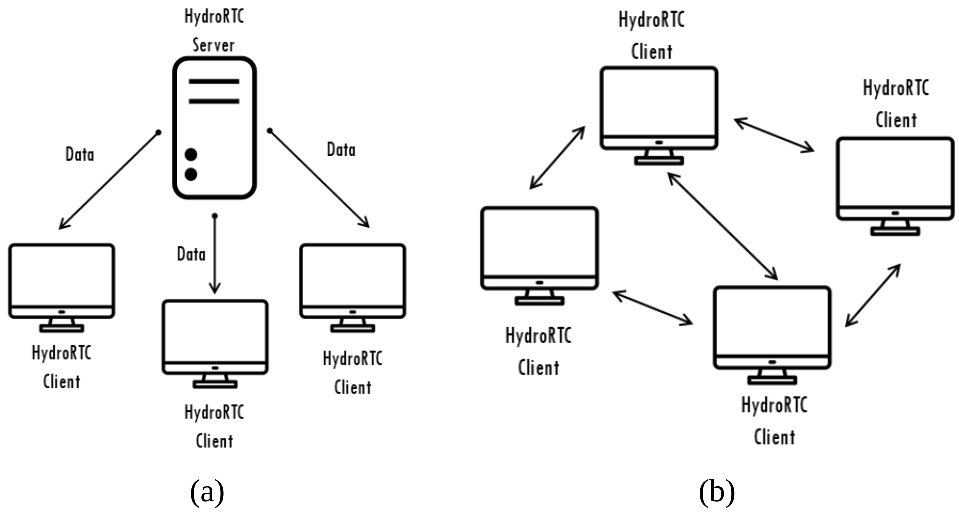

Figure 2. Connectivity between server-peer (a) and peer-peer (b) data exchange. Both interactions require the server as a host for keeping track of peers, however, the p2p implementation uses the server solely as a broker that starts the communication.

Server-to-Peer Data Exchange

<u>*File Transfer:*</u> This is the conventional method, where a server establishes connections with different peers to enable these peers to access various data types. This data could range from files stored within the server to diverse task categories, scheduling systems, or any other data format. We facilitate this interaction via Web sockets for information retrieval while incorporating a straightforward authentication layer to handle validation concerns. The available methods facilitate interaction with the server's folders and file distributions, enabling peers to view the type and size of stored data. Upon server approval, the file transfer process initiates, as depicted in Figure 3. Given that the library aims to allow the development of applications using server-client layers, we've incorporated mechanisms for interacting with data in both implementations. This design allows a client to request specific data from the server, preview this data before finalizing the request, and trigger a subset of information from the file via a handling method on the server.

<u>*Smart Data Transmission:*</u> A common challenge when accessing data from a server to a peer is the need to access information at specific time intervals or spatial coordinates through a region of interest. This requirement is to seamlessly integrate with existing application logic or establish a smoother, more accessible workflow, as illustrated in Figure 4. To address this, we've developed a smart data transmission feature that enables users to instruct the server regarding when, in terms of time and space, a particular set of files for a specific region should be

transmitted back to them. This functionality tracks user-requested data and determines the necessary transmission, which is useful when retrieving multiple files from the server, such as multiple TIFF, geoTIFF, or image files depicting the evolving state of a specific area.

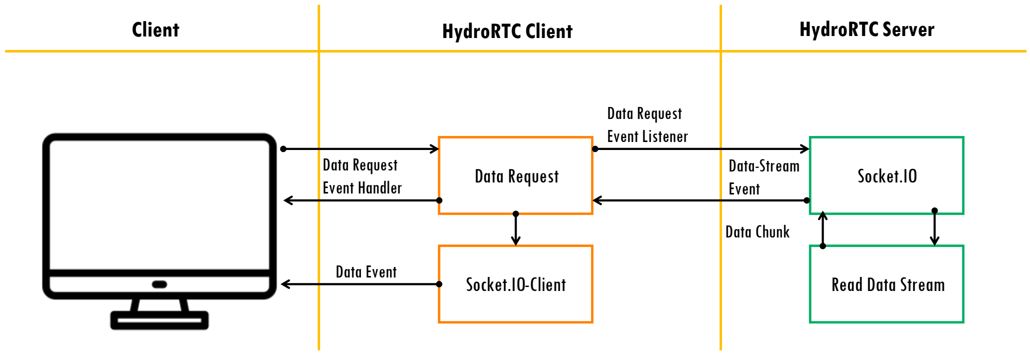

Figure 3. Access data from the server to the user and save the information in the local machine either in the web application or download in the local machine.

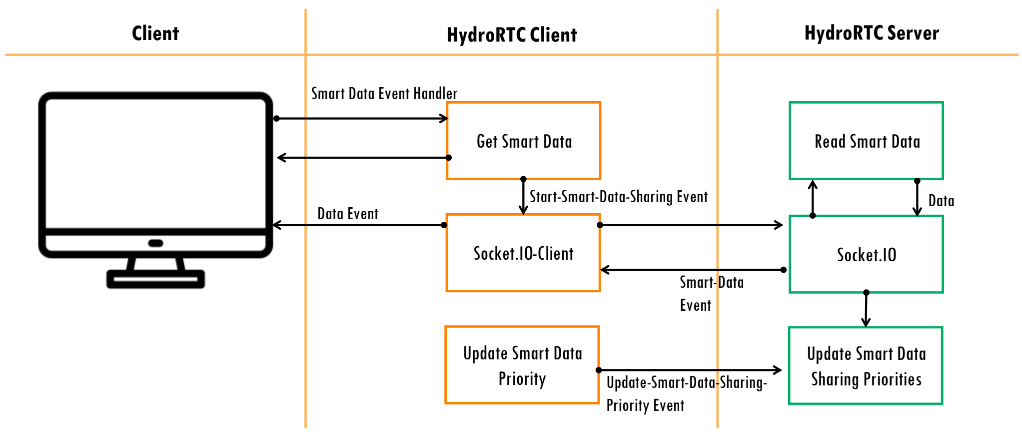

Figure 4. Smart data transmission scheme for file(s) from the server to the client. The client decides the schedule of when the data should be transferred.

Distributed Tasks: Leveraging on the system's capability to connect multiple users to the same server session, as well as utilizing diverse hardware resources available to each user, the distributed task feature enables multiple users to collaborate on shared workloads. Through an ID-Task system, users receive multiple tasks distributed by an admin peer from the server, allowing them to work on their own computers. The tasks and data used by each peer are based on the requirements of the project; however, all the connectivity is set up by the admin. The tasks are submitted to each of the peers, and once they are completed, the results are sent back to the server and stored in a specified folder dedicated to distributed task results, as depicted in Figure 5. This system efficiently allocates tasks based on user and data requirements, facilitating collaborative work and data processing.

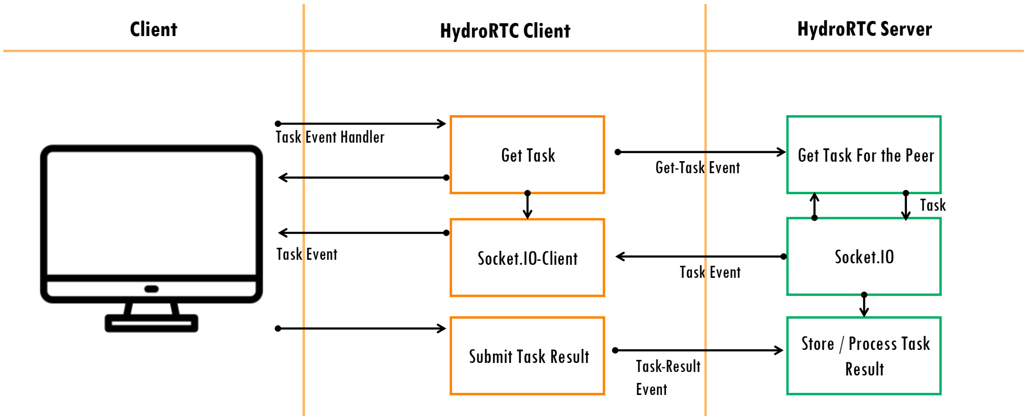

Figure 5. The requestor peer asks the server to distribute tasks among the connected peers.

Peer to Peer Data Exchange

Enabling direct peer-to-peer connections involves establishing communication and data channels through SocketIO. The library serves as a versatile toolbox applicable across a wide spectrum of applications. It creates a bidirectional channel between two peers, ensuring reliable connectivity adhering to the WebRTC standard via Socket.IO signaling servers, as depicted in Figures 6 and 7. When one peer requests a connection with another, the requested peer receives a notification to validate the connection request. Mechanisms facilitated by Peer.js are used to establish connections between users, after the server is used to verify the ability to connect between peers.

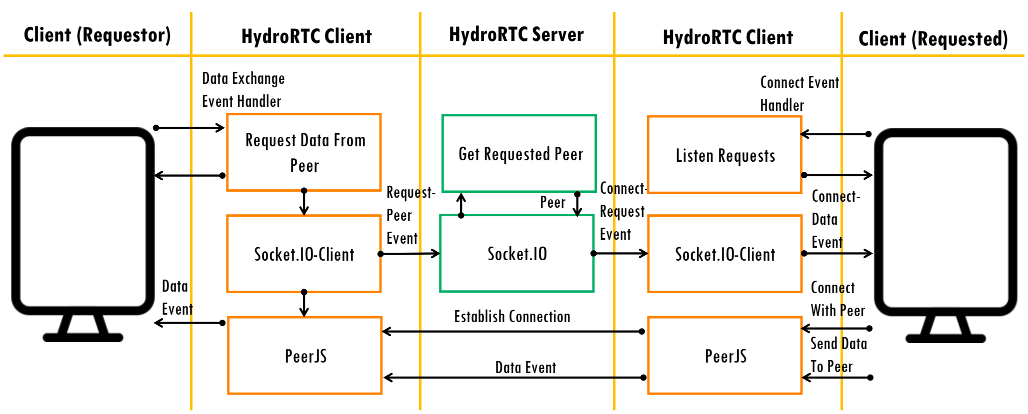

Figure 6. Peer-to-peer connection. Socket.IO serves a signaling server to establish TURN/STUN server connection between peers.

<u>*Data Request from Another Peer:*</u> Once a connection is established, communication—whether it involves live media such as audio, video, data, or messages—is achieved through distinct mechanisms integrated within the client's implementation. A client can request data from a connected peer, or the connected peer can initiate a data transfer. This data is segmented into chunks and streamed to the requesting peer, allowing real-time viewing of the data. The purpose of the latter is to submit large data files through the data channels and not congest or block the

user interface. Different server methods specifically designed for managing various types of data stored on the server facilitate this process.

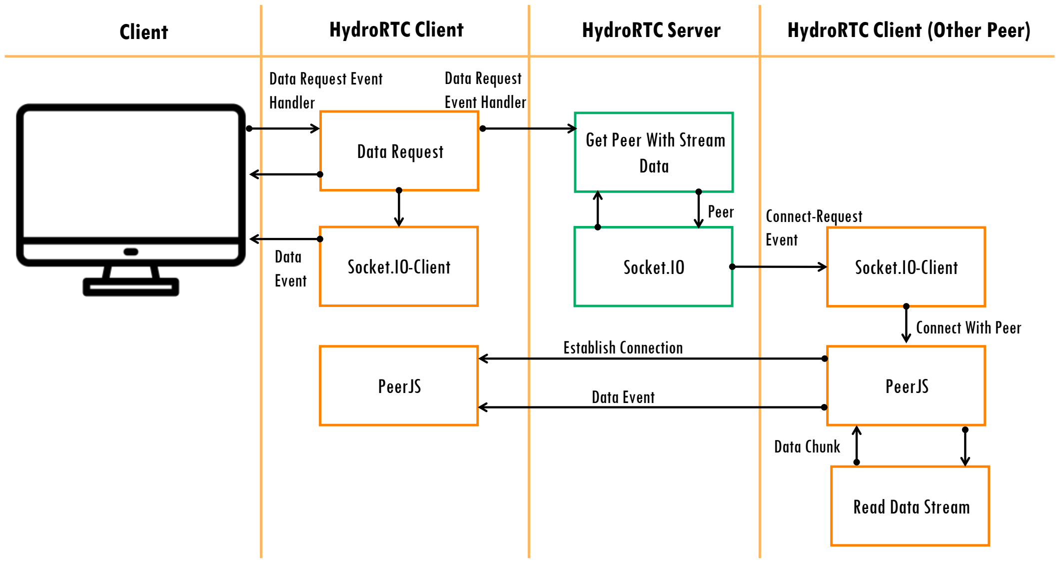

Figure 7. On a two-way peer connection, a requestor peer asks for a requested peer for data, and uses Peer.js data channel to send data streams.

The HydroRTC library offers a comprehensive solution for server-to-client communication, focusing on data streaming, workload distribution, and maximizing client-side hardware utilization. It has been developed for traditional server-to-peer file transfers by ensuring secure interactions through Web sockets and authentication layers. Users benefit from the ability to request specific data, preview content, and trigger subset retrievals, fostering seamless interactions across server-client layers. Facilitating direct peer-to-peer connections by establishing robust communication and data channels using SocketIO and WebRTC standards, users can establish bidirectional channels for live data exchange, ensuring real-time viewing without compromising the user interface. These capabilities collectively enhance the user experience across various functionalities and applications, making the use of our library an appealing choice for seamless and efficient communication and data exchange.

3. Results and Discussion

The testing and development phase of the project utilized an Intel Core i7-6700HQ @ 2.60GHz with 32GB of RAM, running a 64-bit Windows 10 operating system. Data storage allocation for web browser storage and server-side development was conducted on a 10TB hard drive. The application incorporates various mechanisms facilitating data transmission and storage within a unified space, allowing for versatile exploration of different hardware under diverse conditions. To assess request resolution in the outlined case studies, we utilized Google Chrome's admin server diagnostics and Socket.IO. This facilitated comprehensive event tracking, enabling the monitoring of events triggered and transferred from the submitted requests to the server.

Additionally, for peer-to-peer connections, we implemented throughput calculation methods to monitor diverse tracking mechanisms and evaluate packet transmissions upon completion.

Four in-browser applications have been developed and tested using the library:

a) Server-to-peer: (Case Study 1) a data transmission use case for large data streaming
b) Server-to-peer: (Case Study 2) smart data transmission incorporating user-interfaced decision-making scheduling.
c) Peer-to-peer: (Case Study 3) a chat interface that allows data transmissions from each user's local machine.
d) Peer-to-peer: (Case Study 4) task scheduling for distributed computing.

The development details for each application are available in the library's repository. As the library primarily focuses on data solutions, two distinct scenarios were tested in the high-level users' context: user load testing within the server-to-peer scenario and data transferring throughput in the peer-to-peer scenario.

3.1. Case Study 1: Smart Data Transmission and Load Testing

The application involved in the server-to-peer case conducted smart data transmission of various data types, including netCDF, GRIBB, TIFF, and HDF5 files. Figure 8 shows the workflow following the case study. These files ranged in size from 1MB to 2.6GB. The primary objective of the load testing was to stress the server and assess its behavior under increasing client requests, considering the current hardware limitations. This aimed to understand how the server would handle concurrent requests for the same data from multiple clients. For each data type, the server managed requests using distinct handlers, introducing performance variations based on data complexity. Notably, during testing, it was observed that manipulating TIFF files exhibited faster performance compared to parsing and abstracting information from HDF5 files, irrespective of data size. Node.js file system was used for file streaming, using chunks of up to 10 MB. Once the server finished streaming a file, a pop-up window displayed various file-associated features.

The testing featured key aspects of client-server connections, employing different transport mechanisms: web sockets and HTTP long polling. The latter involved clients requesting data from the server and waiting for communication to be relayed once other requests had been completed. The server efficiently managed an unspecified number of clients, allowing those who finished to transition to web sockets. The test initiated a specified number of client requests at 5-second intervals, waiting until any server disconnection occurred to log the time taken for the server to cease operations and enter an unhealthy state.

The load testing results demonstrate the effectiveness of the implemented server-to-peer feature in responding to varying request loads, up to a specific number of clients, depending on data complexity. Figure 9 depicts how, during a 200-client request test, the server managed a large number of requests through long-polling until it eventually disconnected while processing data requests. Additionally, Figure 10 illustrates the duration taken for the server to cease operations across different file sizes and types. This highlights the impact of data complexity, parsing, and information delivery on the server's operational stability for example, in the transmissions of HDF5 files that took a longer amount of time to process one instance of the file as much as doing the same for further requests in comparison to other handlers.

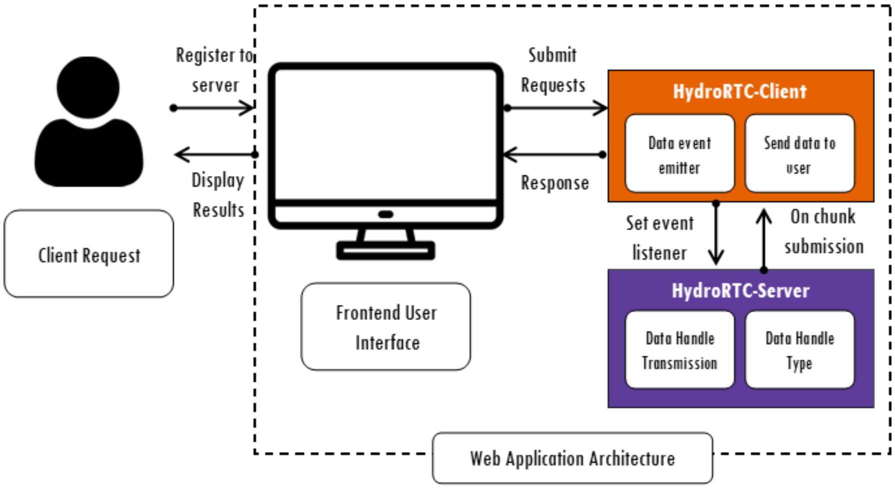

Figure 8. Application outline and workflow.

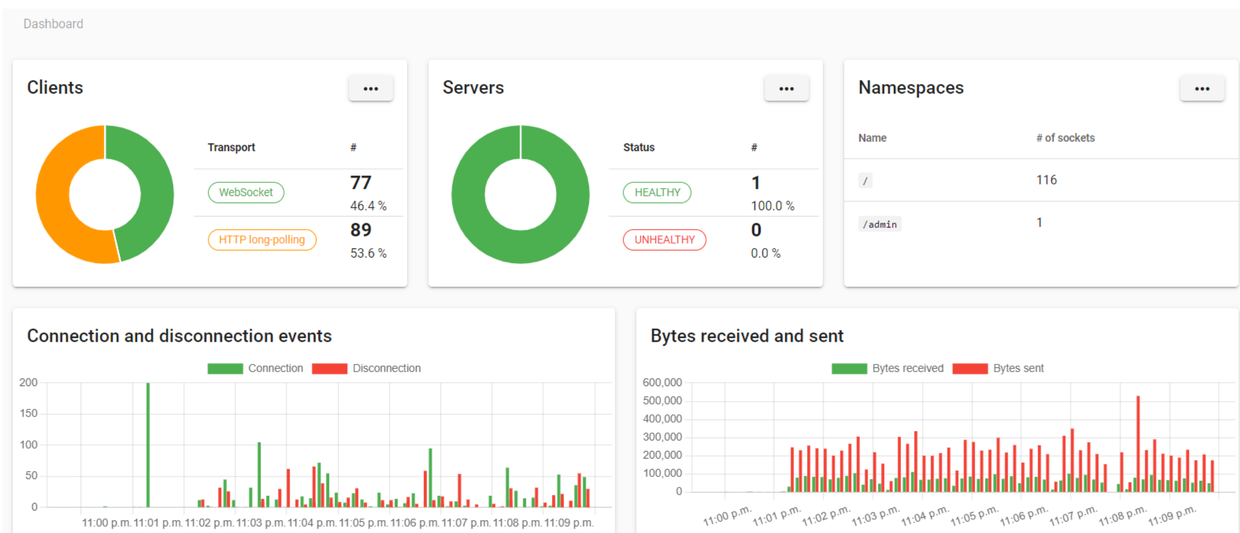

Figure 9. Example results on 200 client loading test on the server requesting for 11mb hdf5 files

3.2. Case Study 2: Chat Interface with Bidirectional Data Exchange

In order to assess data transmission using peer-to-peer communication, a chat interface was created to facilitate communication between two peers, enabling data sharing as depicted in Figure 11. The shared data could be of various types, benefiting from the implemented handlers within the system, granting users the capability to create visualizations utilizing server-side tools. The data used for analysis resided in the local machine of the requested peer while the requesting peer awaited the arrival of the data. The testing methodology involved sharing precipitation gridded netCDF files of varying sizes, ranging from 1 to 9 GB. This evaluation aimed to assess different data chunks sent and analyze how both data size and chunking impacted the overall performance of the application. Data throughput was calculated by measuring the duration taken to stream the entire data size at specific intervals.

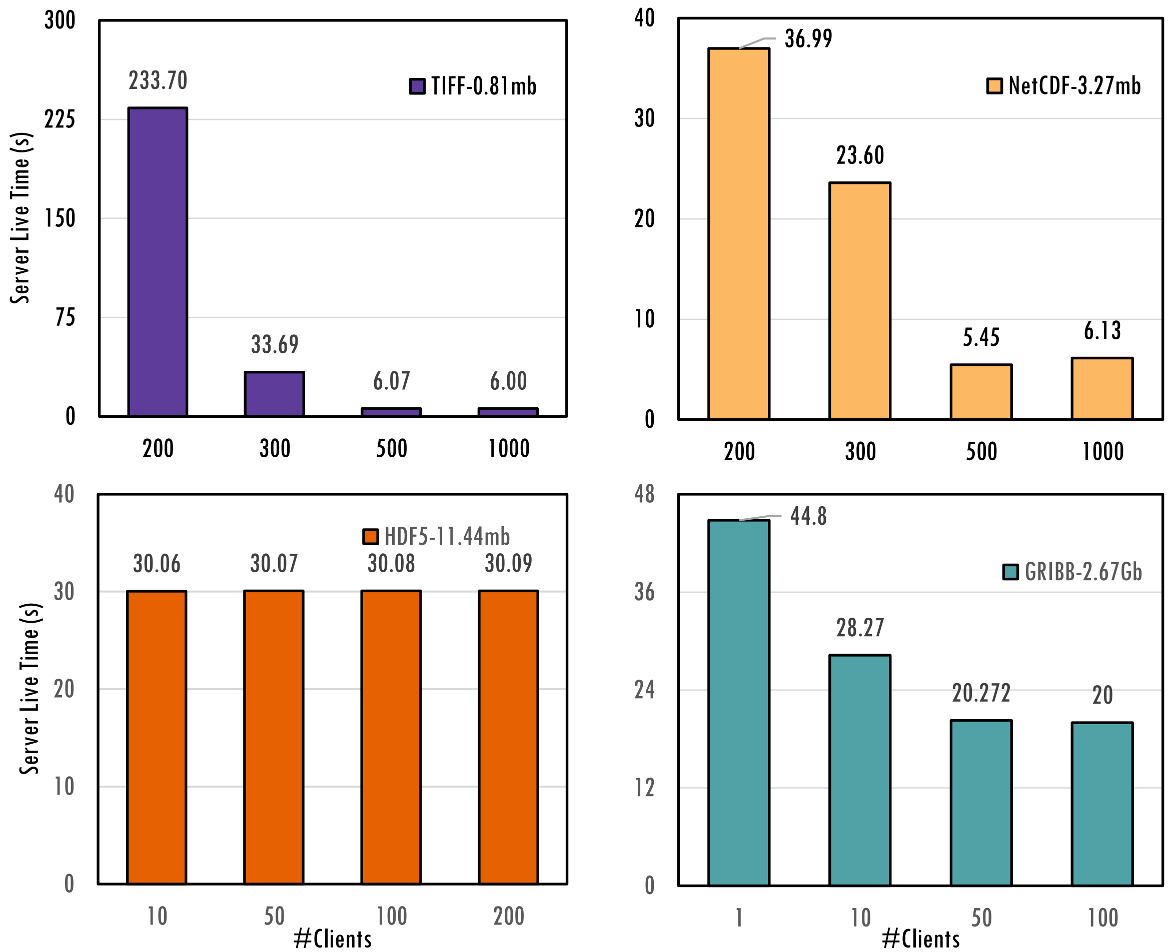

Figure 10. Different data sizes and types being tested on the server until failure.

An observed linear relationship highlighted the correlation between the speed of data transfer and the sizes of chunks or larger data sets. However, limitations in Node.js memory and the browser's JavaScript runtime environment prevented accurate assessment of high transfer rates. Smaller data transfers exhibited better stability and performance within the application due to these constraints. For chunk sizes ranging from 3 to 80 MB per chunk, no significant improvements in transfer speeds were observed compared to data chunks between 0.1 and 3 MB each, as shown in Figures 12 and 13. This observation led to the development of smart data transmission rates between peers that dynamically evaluate latency, data size, and available storage to optimize and switch between specified transfer speeds accordingly.

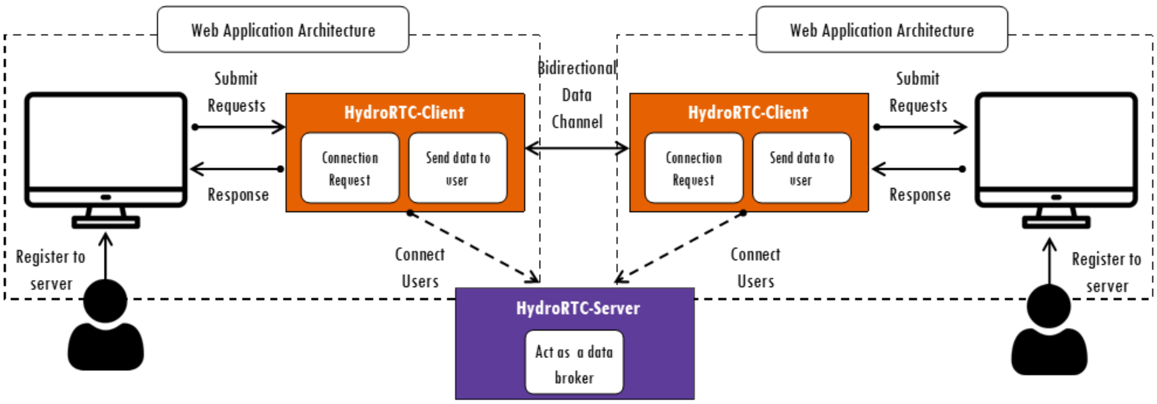

Figure 11. Application workflow for Case Study 2.

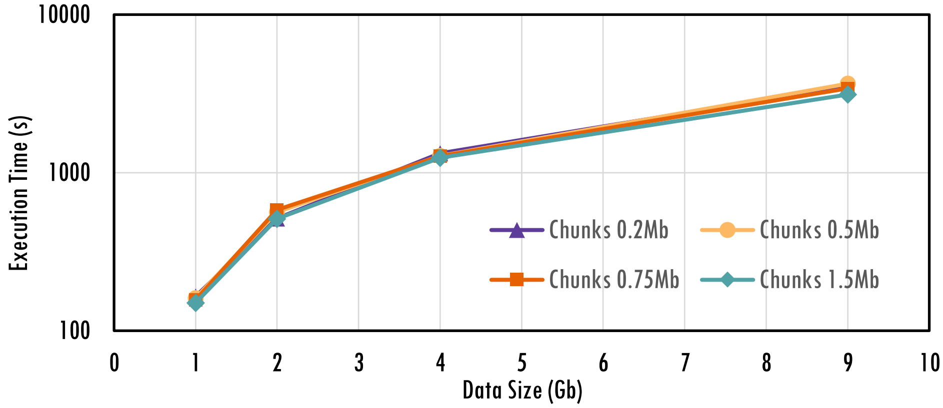

Figure 12. Results from transmitting on a bidirectional channel 1,2,4,and 9Gb data throughput using chunks of 0.1Mb through 1.5Mb in semi-log scale.

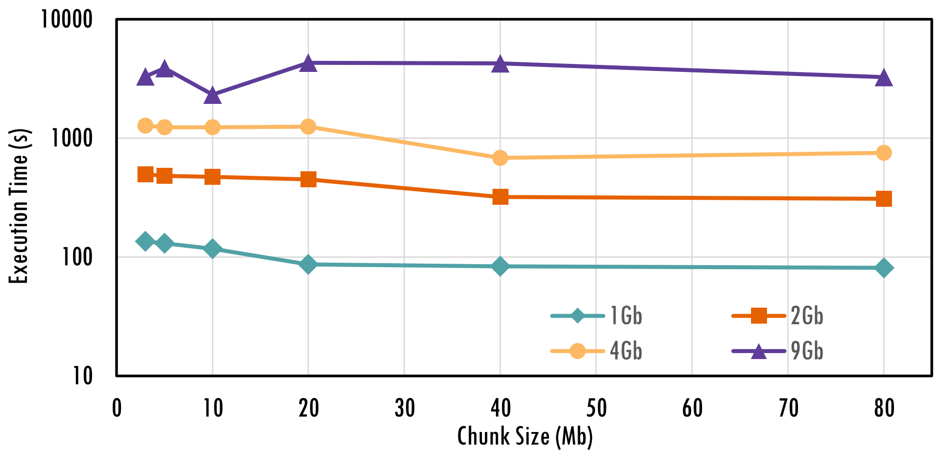

Figure 13. Execution times for data sharing from 1 through 9gb on different data chunks on semi-log scale.

4. Conclusions and Future Work

The HydroRTC library stands as a significant advancement in facilitating streamlined data handling within hydrologic sciences. Our approach has notably addressed challenges inherent in traditional methods by leveraging specific server and client-side technologies. By integrating tools and methods within the library, we have enabled versatile use-case scenarios, empowering smart data transmission, direct server-client data retrieval, peer-to-peer data sharing, and distributed work capabilities. This advancement represents a step towards employing decentralized systems for real-time and collaborative data and workflow sharing. Moreover, moving forward towards progressive web applications, integration with existing solutions for web hosting and data sharing such as cloud providers and institutional data solutions would be the next step for the library's growth.

The case studies' results depict the system's performance within controlled environments, acknowledging potential variations due to system architectures, available hardware configurations of client and server systems, network conditions, and other pertinent variables. Notably, while our library harnesses cutting-edge technology for both server-side and client-side applications, leveraging robust frameworks, these inherent challenges can be navigated and potentially debugged if necessary. The library is limited by data sizing limits, being able to streamline large data into smaller chunks that are used within the client depending on the final application to be used. However, issues such as event blocking, memory limitations, and variables such as network reliability and latency push the development to consider other solutions, such as the use of Web and Service Workers to move tasks like data grabbing, manipulation, and sharing towards a separate thread, distributed workloads, or tasks from the task-based use case.

The project has been developed as a prototype to showcase the usage of modern standards and web advancements within the hydrologic domain. However, there remain various aspects that require thorough exploration for comprehensive scalability. To address security concerns stemming from multiple users accessing a single server instance, an avenue worth exploring is the integration of blockchain technology. This exploration aims to ensure secure data transfer and robust tracking of application usage and connectivity, particularly within distributed work-sharing schemes. Moreover, this library is part of a larger scheme of tools aiming to provide a complete, all-encompassing solution for hydrological analysis on the web. Leveraging the capabilities offered by the current technological web landscape, the goal is to democratize access to information. This collective effort aims to expand on hydrological analysis tools, providing a one-stop solution that harnesses the potential of the contemporary web environment.

Abbreviations

AI	Artificial Intelligence
API	Application Programming Interface
CSS	Cascading Style Sheets
CPU	Central Processing Unit
CSV	Comma-Separated Values
DOM	Document Object Model
ES6	ECMAScript 6
GIS	Geographic Information System
GPU	Graphics Processing Unit
GRIB	Gridded Binary
HDF5	Hierarchical Data Format v5
HTML	Hypertext Markup Language
HTTP	Hypertext Transfer Protocol
HPC	High-Performance Computing
IO	Input/Output
IoT	Internet of Things
JavaScript (JS)	Programming Language
JSON	JavaScript Object Notation
JPEG	Joint Photographic Experts Group
MVC	Model-View-Controller
MPI	Message Passing Interface
NetCDF	Network Common Data Format
Node.js	JavaScript Runtime Environment
PNG	Portable Network Graphics
RTC	Real-Time Communication
S2P	Server-to-peer
SWMM	Storm Water Management Model
TCP/IP	Transmission Control Protocol/Internet Protocol
TIFF/GeoTIFF	Geographic Tagged Image File Format
UI	User Interface
WebGL	Web Graphics Library
WebRTC	Web Real Time Communication
W3C	World Wide Web Consortium
XML	Extensible Markup Language

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