Client-side Web-based Model Coupling using Basic Model Interface for Hydrology and Water Resources

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Highlights:

- We present the Basic Model Interface (BMI) specification for the JavaScript programming language.
- We present how BMI may be used as a common standard to couple client-side, hydroinformatics web resources.
- For developers, BMI for JavaScript simplifies the effort needed to implement an API for their resource.
- For users, BMI for JavaScript accelerates learning and working with a new resource.

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Abstract

A recent trend in hydroinformatics has been the growing number of data, models, and cyber tools which are web accessible, each aiming to improve common research tasks in hydrology through web technologies. Coupling web-based models and tools holds great promise for an integrated environment that can facilitate community participation, collaboration, and scientific replication. There are many examples of server-side, hydroinformatics resource coupling, where a common standard serves as an interface. Yet, there are few, if any, examples of client-side, resource coupling, particularly cases where a common specification is employed. Towards this end, we implemented the Basic Model Interface (BMI) specification in the JavaScript programming language, the most widely used programming language on the web. Using the BMI, we coupled two comprehensive, client-side hydrological applications (HydroLang and HLM-Web) to perform rainfall-runoff simulations of historical events as a case study demonstration. Through this process, we present how a common and often tedious task – the coupling of two independent web-resources – can be made easier through the adoption of a common standard. Furthermore, applying the standard has facilitated a step towards the possibility of client-side model as a service for hydrological models.

Keywords: Basic Model Interface, hydroinformatics, Integrated Modelling, Web-based Simulation, Web Frameworks

Software availability

Name	BMI-JS
Developers	Gregory Ewing, Carlos Erazo Ramirez, Ashani Vaidya, Ibrahim Demir
Contact information	300 S. Riverside Dr., Iowa City, IA 52246 USA
Software required	Web Browser
Program language	JavaScript, HTML, CSS
Availability and cost	The code is open-source and free to use, and can be accessed on GitHub.
Code repository	https://github.com/uihilab/BMI-JS

1. Introduction

A recent trend in hydroinformatics has been the growing number of data, models, and other tools which are web accessible. For example, online community services are openly available which allow people to connect to and leverage server-side resources to perform modeling, simulation, and data storage tasks, such as the Community Surface Dynamics Modelling System (CSDMS) (Peckham et al. 2013; Peckham 2015) and HydroShare (Horsburgh et al. 2016). Likewise, governmental and proprietary services – such as the National Water Information System (NWIS) from the United States Geological Survey (USGS 2022) and the Envirofacts Data Service from the United States Environmental Protection Agency (EPA 2022) – offer access to environmental and hydrometeorological data through interactive web services and Application Programming Interfaces (APIs). Individually, these products each aim to improve common tasks and subtasks in hydrology with web technologies. Together, these open web services and community driven repositories hold great promise to create a web-based environment that meets the community goals of access, participation, documentation, distribution, and scientific replication (Teague et al. 2021; de Boer 2014).

There are many efforts for web-based data analytics (Xu et al. 2019; Alabbad et al. 2022), information portals (Sit et al. 2021a; Yildirim & Demir 2021), and decision systems (Ewing & Demir 2021) in hydrology and water resources. In comparison, community focused modeling frameworks and integration is rather limited. Coupling of hydrological models with web-accessible data is presently a non-trivial task. Resource coupling can require a large amount of programming time and effort, specific understanding of each product's codebase (and their idiosyncrasies) and typically input from source code authors (Peckham 2014). Issues may arise when two or more distinct models are coupled (e.g., having to merge and recreate features and methodologies) ultimately limiting the scalability and reproducibility required for community growth. These activities put a significant burden on end users, limit the extent, and speed to which hydrologic data, models, and applications can integrate for beneficial use for research and the public. Thus, there still exists the need to further lower barriers to couple web-enabled, hydrologic resources.

One option to standardize the coupling of modeling and data resources is the Basic Model Interface (BMI.) BMI is a specification library containing a set of standard control and query functions with predefined inputs and outputs, along with data type descriptions and any other information pertaining to specific models (Hutton et al. 2020). BMI is among a broad range of standards applicable to earth sciences, including OpenMI (Gregersen et al. 2007), CCA (Larson Uni. 2006), SIDL (Laval Uni. 2013), MPI (Uni. Tennessee 2021), XML (W3C 1998) and other applicable OGC standards (OGC 1994). These aim to expand the scope and ease of data interaction between any type of computing service – whether on a server or client side. In particular, the BMI specification promotes loosely coupled models and data resources that can be reused and scaled by the community without any manipulation of the resources internally. Currently, the BMI specification is available in five programming languages: C, C++, Fortran, Java, and Python (CSDMS 2022).

BMI has been applied to several web-based hydrological applications, such as the Tethys Platform (Swain et al. 2015), the Group on Earth Observations Platform (Christian 2005) (Giuliani et al. 2013), EMELI (Peckham 2014), workflow systems such as the MINT framework (Gil 2018) the 3Di platform (Baart et al. 2014), among others. Further, the CSDMS has established a web service architecture that allows for fast computing and data resources through the use of the BMI standard (Jiang et al. 2017). These implementations have primarily applied the BMI specification and its standard naming conventions to facilitate directives from the client to a server-based resource. Thus, many of these applications rely exclusively on using server-side resources for running models and clients' local hardware for browser-based interfaces (e.g., make calls to the servers, receive and display data). As a consequence, there are still opportunities to further couple services, particularly those operating in client-side environments. In the literature, there are few, if any, examples of client-side hydroinformatics resource coupling

(Sermet & Demir 2022). Moreover, no implementation of the BMI specification has been found that relies entirely on JavaScript, the most widely used and suitable programming language for web development.

Previous work in server-side resource coupling provides a strong case to adopt a standards-based approach for client-side resources. Towards this end, we implemented the Basic Model Interface (BMI) specification in the JavaScript programming language. Later through the BMI specification, we coupled two comprehensive, client-side hydrological applications (HydroLang and HLM-Web) to perform rainfall-runoff simulations of historical events as a case study demonstration.

The remainder of the paper is as follows. In the materials and methods section, we outline the BMI implementation in JavaScript; describe the client-side resources used, HLM-Web and HydroLang, and the process to make them BMI-compliant; and outline the catchment and the data sources used for the simulation. In the results and discussion section we share the procedure to couple the client-side resources to support rainfall-runoff modeling of a historical event. We also present the simulation results of a catchment using HLM-Web with different web-available precipitation products. Further, we discuss the use of the BMI specification in JavaScript and its ability to facilitate a web-based hydrological workflow. Finally, we conclude with potential areas for future work.

2. Materials and Methods

In this section we first describe the implementation of the BMI specification in JavaScript. Next, we describe the client-side modeling and programming frameworks, HLM-Web and HydroLang. Finally, we describe the study area and data used to simulate historical events for the case study.

2.1. BMI-JS

The BMI standard prescribes to developers a set of functions to implement on their model or data source, which enables it to communicate to external resources through syntactical variable naming. In total, the current version of the standard describes 41 functions, falling within six functional groups (Table 1,) that must be implemented for a resource to be considered BMI-compliant (Hutton et al. 2020).

Table 1. BMI categorical groups, adopted from (CSDMS 2022).

Functional Group	Examples
Model control	*initialize, update, finalize*
Model information	*get_input_var_names, get_output_item_count*
Variable information	*get_var_units, get_var_location*
Time	*get_start_time, get_time_step*
Variable getter and setter	*get_value, set_value*
Model grid	*get_grid_size, get_grid_shape*

Because JavaScript is a high-level, interpreted, object-oriented programming language, the BMI implementation was done through class definition to keep similar behavior as the other languages. The specification was done as such with all functions defined in the specification as methods on the BMI class. The BMI class is used via inheritance by resources implementing the specification. This ensures that the specification's functions are properly overwritten during subsequent implementation by a resource, otherwise the function call returns an error defined in the BMI parent class. As is common for every new language implementation of the BMI specification, a standard heat model that solves the diffusion equation on a uniform rectangular plate with Dirichlet boundary conditions was built and released in the GitHub repository for testing and validation.

2.2. HLM-Web

HLM-Web is a modeling framework and simulation engine capable of performing distributed, physically based rainfall-runoff simulations entirely in a modern web browser. Its development and uses have previously been reported in the literature (Ewing et al. 2022). HLM-Web is the JavaScript implementation of the Hillslope Link Model (HLM) (Mantilla 2022).

HLM uses the concept of landscape decomposition into just two elements: hillslopes and channel links. Hillslopes are irregular-shaped polygons where the conversion of rainfall to runoff takes place. Each hillslope is uniquely associated with a channel link. A hillslope's runoff, both surface and subsurface, drains to the corresponding link and the links make the river network. Mathematically, the physical processes involved in runoff generation and transport are described as a set of ordinary differential equations. Within the HLM framework there is a good deal of flexibility for the level of detail desired to describe the physical processes. The simulations presented here use a non-linear concept of storage at the hillslope level and a non-linear channel velocity.

HLM-Web uses the object-oriented programming paradigm with the hillslope-link pair as the basis for the object model. Each hillslope-link object contains all necessary components to step forward the hillslope's simulation as object methods and properties. In general, these methods and properties can be categorized into four groups: forcing data (i.e., evaporation potential and precipitation,) physical attributes (e.g., hillslope area, total upstream area, channel length,) model structure (equations which describe the physical processes,) and numerical solver. All necessary properties and methods are added at object instantiation via input and configuration files and can also be altered prior to simulation execution.

BMI Implementation: To comply with the BMI specification, the HLM-Web code required some refactoring. As stated above, the original HLM-Web codebase uses the hillslope-links as the basis for the object model. To achieve BMI compliance, hillslope-link objects are packaged, or wrapped, within a new HLM class. This new HLM class then complies with the BMI specification through the implementation of its methods. The HLM class also holds the metadata associated with the simulation. Very little information has been lifted to the HLM class from the individual hillslope link objects, in effect keeping their functionality the same.

2.3. HydroLang

HydroLang.js is a community-driven, open-source computational framework for hydrological research and education (Erazo et al. 2022a). HydroLang.js supports programming using both

JavaScript and HTML like markup language (Erazo et al. 2022b). HydroLang.js consists of four low cohesive modules: (1) Data, for retrieving data from various data sources (i.e., APIs,); (2) Visualize, for data visualization; (3) Maps, for creating maps rendered on the browser to view georeferenced data and data selection; and (4) Analyze, for performing hydrological, statistical, and neural network subroutines used in academia and industry. The library was created using JavaScript for its ease on online application development, integrating with other open-source libraries while maintaining industry standards, and having lexical commands that aids in implementation. HydroLang greatly decreases the amount of programming required to do any of the included subroutines, allowing users to complete analyses in just a few lines of code as a one-stop resource.

BMI Implementation: When implementing BMI-compliance into HydroLang, it was important to maintain the original framework's functionality. To achieve this, a `HydroLangBMI` class was created to extend the framework, adding the BMI functions but only as method caller. As a result, HydroLang BMI achieves compliance without the need to reprogram existing methods. A new instance of the compliant class is made through variable declaration (i.e., 'new HydroLangBMI("config.json")'). All HydroLang modules and functions can be accessed using configuration files with BMI implementation, provided they match the framework's criteria.

The HydroLangBMI class was expanded even further to provide interaction with the data model APIs used in the case study demonstration. (The specific data products are given in the following section.) By overriding the time methods as well as the variable getter and setter routines, the class extends the HydrolangBMI implementation. The API calls are then made using the handle configuration function built into the parent class, which is accessed via additional helper functions that modify the results of each call so that they are readily available for ingestion into a BMI-compliant resource, in this case the HLM rainfall-runoff model.

2.4. Study Area and Experimental Setup

The Clear Creek Watershed (HUC-10: 0708020904) was chosen for this study. Clear Creek is in eastern Iowa and is a tributary of the Iowa River (Figure 1). Clear Creek watershed has a total area of 260 km^2, its land use is predominantly agricultural, and its elevation ranges from 189 meters to 278 meters. The watershed has been widely studied (e.g., accounting for unsteady and steady flow simulations (Zhang et al. 2013; Lai Yong et al. 2020), and hysteresis monitoring (Muste et al. 2020)) among others. For this study, the discharge point of the catchment was chosen as slightly upstream of the outlet to the Iowa River, to correspond with where the USGS gauge 05454300 is located. Thus, the modeled area, approximately 255 km^2, is slightly smaller than the total catchment area. The catchment area and hillslope-link parameters required for HLM were delineated using a 10-meter resolution DEM.

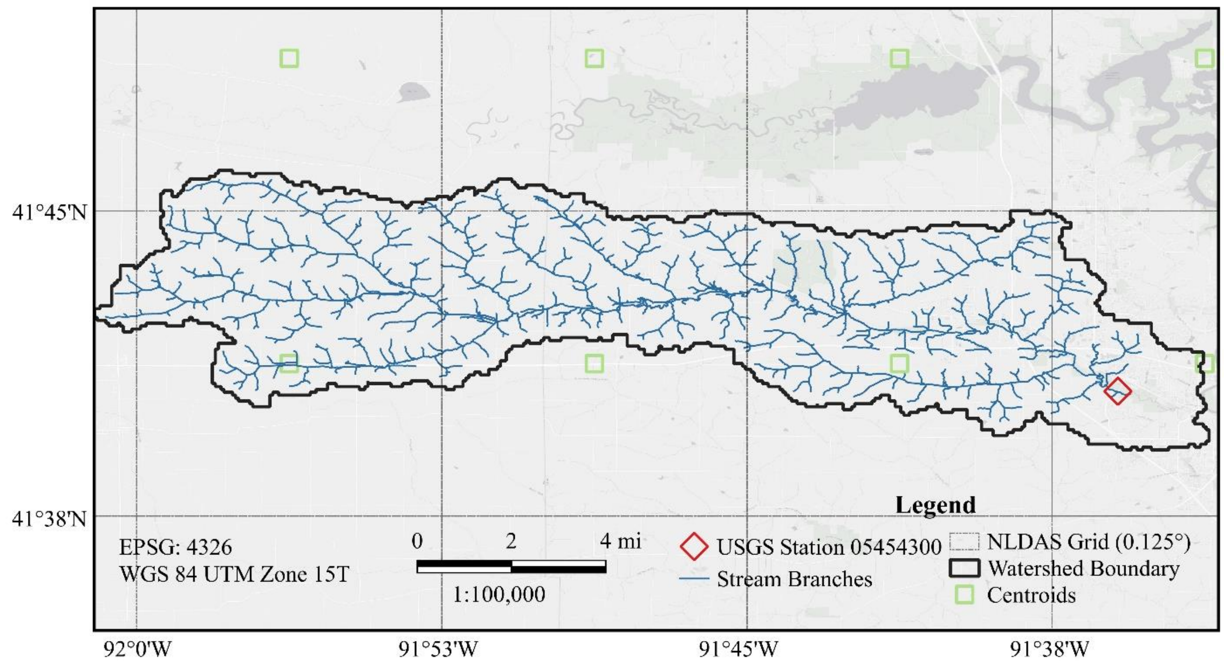

Figure 1. Map of the Clear Creek watershed, chosen as the study catchment. The grid and centroid indicate the NLDAS locations within which each stream branches would fall.

Two rainfall products were used for this case study. The first data product is preprocessed MRMS data retrieved from and hosted by the Iowa Flood Center for flood forecasting in Iowa (Smith et al. 2016; Quintero et al. 2020). This data was transformed into JSON objects and hosted as a public dataset accessible via a RESTful API to communicate with the HydroLang data service. The second data product is a gridded precipitation model from the North American Data Assimilation System (NLDAS) (Mitchell et al. 2004; Xia et al. 2012). This product contains hourly rainfall from 1979 to the present day at a 0.125 degree resolution. This data was accessed externally via the EPA's Hydrologic Micro Services (Parmar 2018), which provides historical data from different rainfall products.

For each data model, an instance of the HydroLangBMI class and its data functions were used to retrieve, analyze, and change the service calls' retrieved data. With the MRMS product, data requests are accessible synchronously as the configuration file is loaded into the model. With the NLDAS product, data requests are asynchronous. In all situations, the call results were internally modified and stored in a global variable to await BMI-compliant function calls.

3. Results and Discussion

In this section we share the procedure to couple the client-side resources to support rainfall-runoff modeling of historical events. We also present the simulation results of a study catchment using HLM-Web with different web-available precipitation products. Further, we discuss the use of the BMI specification in JavaScript and its ability to facilitate a web-based, hydrological modeling workflow.

Shared getter and setter methods couple BMI-compliant versions of HLM and HydroLang. Figures 2 and 3 show the coupling routine's pseudocode and flowchart. Our approach initializes each resource, then performs QA/QC checks to ensure compatibility. Next, a while loop advances the simulation. The while loop retrieves HydroLang precipitation information at model time, the HLM-Web simulation uses these numbers as precipitation. Both resources are updated after the values are set. After the simulation, each resource is shut down and HLM-Web simulation results are graphed with the HydroLang visualization module.

Require: `config-hlm-web.json`, `config-hydrolang.json`
Ensure: Two models stepped to end of simulation time

```
HLModel ← new instance of HLM from config-hlm-web.json
dataModel ← new instance of HydroLang from config-hydrolang.json
errors ← Check for startup errors
if errors then
    break, throw error;
end if
while simulation time < simulation end do
    \\ use method: get_values_at_indices
    precipValues ← current precipitation values from dataModel

    \\ use method: set_values_at_indices
    HLM precip values at each link ← precipValues

    \\ use method: update
    update HLModel one time step
    update dataModel one time step
end while
\\ use method: finalize
tear down models, output simulation results
```

Figure 2. Pseudocode to couple the client-side data and model resources via the BMI specification.

Simulations of the rainfall-runoff response of Clear Creek watershed were performed using both preprocessed MRMS precipitation data and data gathered directly from an EPA-hosted, grid-based rainfall API for a 17-day period, from September 28, 2018 to October 15, 2018. All simulations were performed within Google's Chrome browser, with the V8 JavaScript interpreter, on a Dell XPS 9560 with an Intel(R) Core(TM) i7-7700HQ CPU @ 2.80GHz.

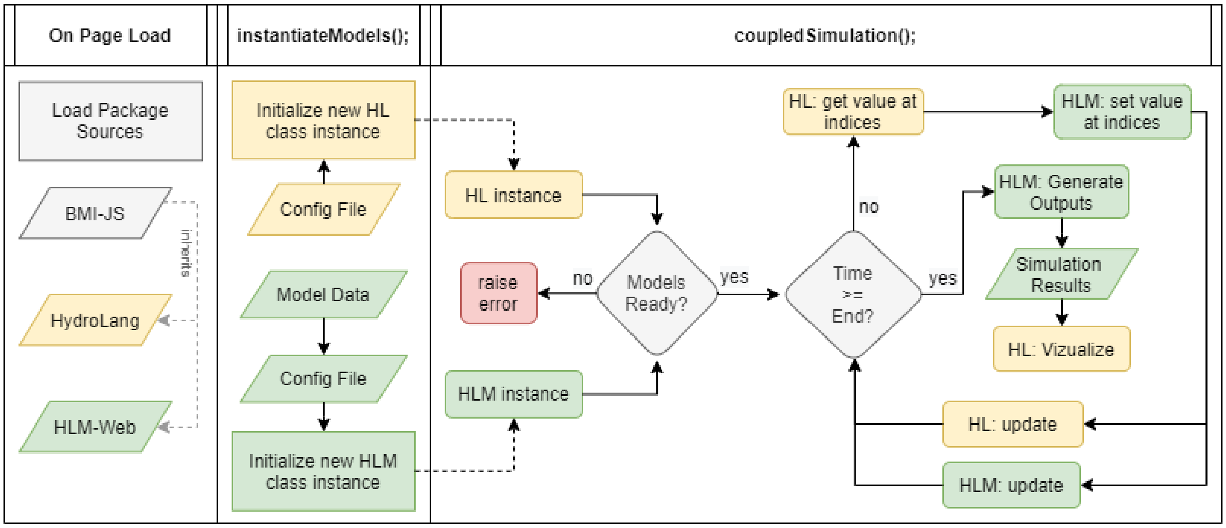

Figure 3. Flowchart to couple the client-side data and model resources via the BMI specification.

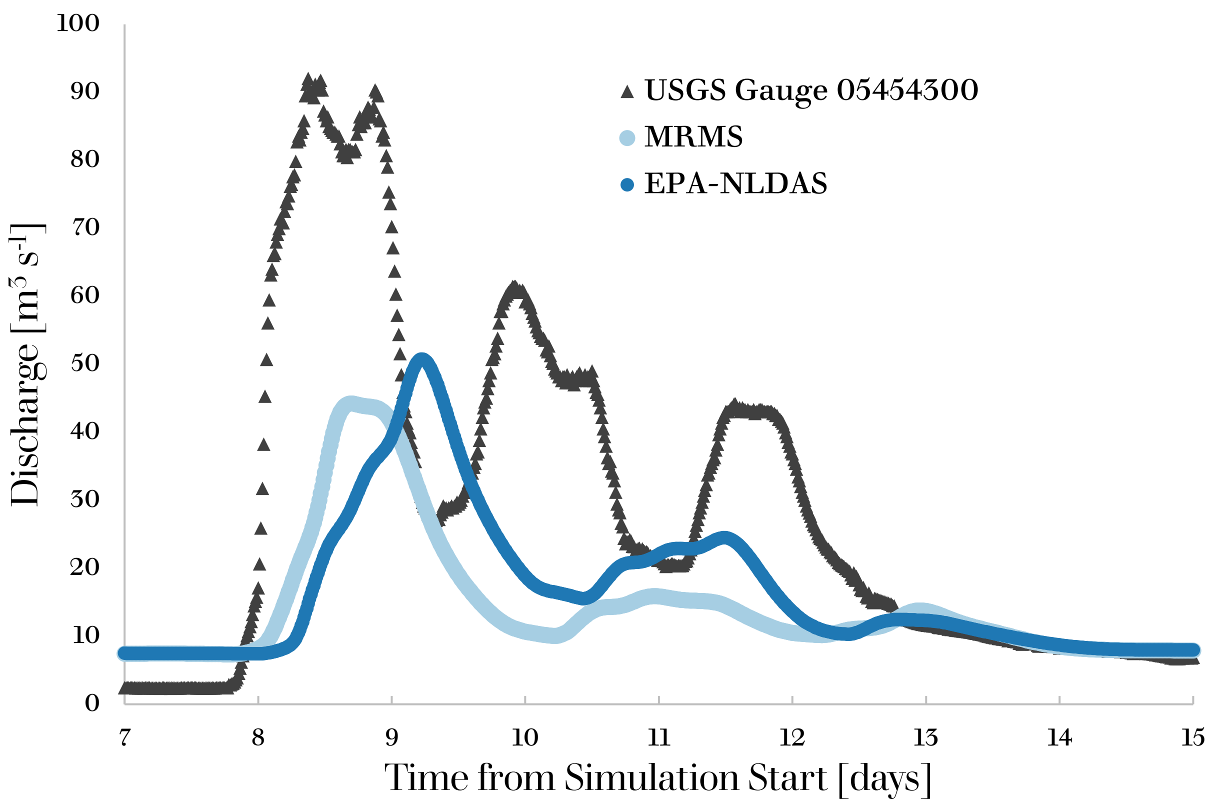

Figure 4. Simulation results of the HLM rainfall-runoff model using MRMS and NLDAS data compared to the observed measurements at USGS Gauge 05454300. Simulation runs were started on September 28, 2018 and ended on October 15, 2018. Results shown here capture a precipitation event beginning on October 5, 2018 until simulation end.

3.1. Discussions

Increasingly, JavaScript is used in both client-side and server-side environments. This versatility offers a single language for use at any level of the stack. Owing to this versatility, JavaScript continuously ranks as one of the most used programming languages over the past decade (StackOverflow 2021). Further, JavaScript possesses many characteristics which make it a candidate for use in a number of science-related applications (Walker & Chapra 2014).

The BMI standard facilitates model development and coupling, as described in the literature (Jiang et al. 2017; Goodall 2016). For example, the standard's agnostic framework enables it to be applied to any model. Further, the standard allows easy inter-model communication via its use of standard naming for both the specified functions (i.e., object methods) and the standard naming for model variables. These features can benefit a wide range of modeling domains.

Upon reflection, we observe the benefit of a standards-based approach for resource coupling in a web environment. First, using a common standard as the template for an API greatly simplifies the effort needed to implement an API for a project. Doing so allows a development team to focus on their project's compliance rather than a whole-cloth effort of designing and implementing from scratch (i.e., designing data flows, data structures, input and output, methods, etc.). This difference in focus can represent significant time savings. Second, adopting a common API advantages users. A common API should accelerate learning and working with a new resource. Likewise, as new resources become available and coupled through a common standard, the effort required by other users to do the same decreases. This is not always the case when "one-off" connections are made.

Indeed, both HLM-Web and HydroLang benefited from adding BMI compliance. For HLM-Web, the refactored version encapsulates all model elements within a single model object. This design feature improves how users manipulate the model and interact with its features. Furthermore, the refactored code may improve memory management of the resource, i.e., improve the capability and performance of in-browser simulation. For HydroLang, BMI-compliance improves its flexibility, scalability, and complexity. First, configuration objects are flexible and easy to use. Instead of invoking methods or function, the "initialize" function of the BMI standard allows the framework's usage through configuration objects that contain user prescribed methods. Second, configuration objects enable easy data query changes. This feature allows data service reuse by adjusting location, timeframe, or queried variables. Finally, users can access several functions from different modules in a single BMI class instance. For example, visualization or data analysis elements can be added to a class instance and be used with external or simulated data.

From an operational perspective, coupling via BMI made the simulation workflow easier. Using the data service to supply forcing data meant that only data required for a given simulation was loaded locally. This removed the overhead of managing a database or local data store, extracting the appropriate time segment, and supplying it in the required format.

Limitations, however, do exist to both the applicability of client-side technologies to scientific computation and the standards-based approach to couple client-side resources. As compared to the other languages that are heavily used for modeling, there are clear limitations on JavaScript's performance. Many of these limitations stem directly from its interpretative nature and lack of low-level control. First, runtimes of scripts with heavy computation are slowed due to sluggish bitwise operations, which convert 32-bit signed integers to 64-bit floating point numbers. For example, a recent like-for-like comparison between JavaScript and C++ (i.e., a compiled language) suggests that JavaScript is approximately two times slower (Hinkelmann 2019). Second, web browsers were originally designed with a single thread to interpret and perform JavaScript code. This design limits multithreading and multiprocessing, where tasks can be efficiently lifted by the end user's environment. Recently, however, the web standard WebWorkers offers some workarounds to multithreading (W3Cb 2021) Finally, JavaScript does not support multiple inheritance, a feature widely used when developing environmental models. There is, however, an object-oriented workaround to achieve similar functionality.

There are also limits to the benefit of adopting a web-based, connected simulation workflow. For example, though HydroLang allows for easy integration of external data sources via APIs, it cannot guarantee its data quality which is a common limitation for any programming library. The number of calls available to retrieve the required data is limited by the type of resource used to serve the data (a model or real-time acquired data) and the number of calls available to serve the data (HTTPS request limits, CORS policy). For the development of this project, the NLDAS data quality process via automated quality control (Xia et al. 2019) ensures that the data obtained from the model is continuously monitored. Similarly, the preprocessed MRMS data is backed up by the team in charge of quality control and assurance (Tang et al. 2020). In short, easily connecting to a data resource does not dismiss the due diligence required before its use.

Using the standard with already-implemented models often requires refactoring the model's codebase. When doing so, resolving the tradeoffs between internal model needs and generic I/O operations can present additional time to bring the codebase in line with the specification. Limitations acknowledged, there remain strong benefits to simulation and modeling in JavaScript, as evidenced by the ease with which external data and visualization packages can be employed.

4. Conclusion

The Basic Model Interface (BMI) is a specification library containing a set of standard control and query functions. Previously, BMI has been implemented in the programming languages commonly used for computational modeling in geosciences. Further, previous work in the literature has demonstrated how the qualities of the BMI specification can be leveraged to achieve model/resource coupling in offline and server-side environments. Here, we first present the implementation of the specification for the JavaScript programming language. We then use the BMI specification to couple web-based data resources via a hydrological programming library and a web-based rainfall-runoff model. Finally, we use these coupled, web-based resources to simulate Clear Creek's hydrological response to an historical event. Through this process, we show how a common and often tedious task – the coupling of two independent web-resources – can be made easier through the adoption of a common standard. Furthermore, applying the standard has facilitated a step towards the possibility of client-side model as a service (MaaS) (Roman et al. 2009) for hydrological models.

Future work related to BMI-compliant coupling on the web broadly takes on three overlapping fronts. The first is to implement the specification for other web technologies. For example, WebGL (Khronos 2022) is used to quickly render 2d and 3d visualizations in browsers for web-based communication and virtual reality applications in hydrology (Sermet & Demir 2020). Mathematical transformations can be applied natively within the standard, allowing model and simulation tasks to be performed on a computer's graphics hardware. Results could be accessed via the BMI standard and used elsewhere. Second, expanding the application of BMI to other resources would allow easy connectivity to a further range of data and models; for example, we propose adding BMI compliance to parsimonious flood extent estimation models (Li et al. 2022; Hu & Demir 2021) and data driven forecast models (Sit et al. 2021b). The third front of future work is to develop and share fit-to-purpose web applications that rely on BMI-coupled resources. Such applications could be in-browser flood event forecasting, where users can easily mix and match model forcings (i.e., MRMS, NLDAS, HRRR, etc.) and different BMI-compliant models (e.g., HLM-Web, data driven machine learning models, NWM, etc.) Given the ease of coupling, many more applications abound and can be as diverse as the community of modelers and developers who use them.

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