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1 **HydroMP – A Computing Platform for Hydrodynamic Simulation based on Cloud**  
2 **Computing**

3  
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12  
13 **ABSTRACT**

14 Modern water management decisions are increasingly dependent on efficient numerical  
15 simulations of multiple scenarios with multi-models. In this paper, a service mode for the  
16 hydrodynamic simulation based on cloud computing is proposed, and the relevant frameworks of  
17 the Hydrologic/Hydraulic Modeling Platform (HydroMP) are designed and implemented.  
18 Various hydro-models can be integrated into HydroMP dynamically without the need of program  
19 recompiling, since it achieves the scheduling of computing resources to provide end users with  
20 the rapid computing capacity of concurrent scenario simulations in the form of a Web service.  
21 The present study focuses on the dynamic model integration, resource scheduling, system  
22 communication and data structure design, and achieved the following four objectives: (1) Two  
23 model integration approaches, including executable program file (EXE) mode and program  
24 interactive integration mode (PIIM). The former is used to realize the rapid legacy model  
25 integration and the latter ensures real-time communications between the model and platform  
26 during computing process; (2) Based on the two-layer computing resource scheduling framework

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27 and scheduling rule of the simulation scenario level, the self-adaptive scheduling and concurrent  
28 control of the cloud computing resources are proposed; (3) Through API provided by the  
29 Windows HPC Pack, a scalable integration of the platform, HPC Cluster, is established and the  
30 scenario data and hydro-models are integrated; (4) A web service is used to provide the hydraulic  
31 simulations, result feedbacks and other interfaces to fulfill the computing service. To use the  
32 present one-dimensional hydrodynamic cloud computing as a prototype, different integration  
33 methods will be applied to construct the CE-QUAL-RIV1 and JPWSPC (Joint Point Water Stage  
34 Prediction and Correction) models, thereby to investigate real-time scheduling of the water  
35 transfer channels in the South-to-North Water Diversion (SNWD) project. The results showed  
36 that massive modeling scenarios by use of different hydrodynamic models, if submitted  
37 concurrently, can be processed simultaneously in the HydroMP. The data structure of the  
38 proposed framework can also be extended to two-dimensional and three-dimensional  
39 hydrodynamic situations.

40

41 **Keywords:** cloud computing; hydrodynamic model; model integration; web service; HydroMP

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43

## 1 BACKGROUND

44 Hydraulic calculation is an important aspect of the environmental simulations. With the  
45 development of numerical analysis techniques and hydraulic theories (Lauder and Spalding,  
46 1974), numerical simulations of the hydraulic systems have been rapidly developed and also  
47 widely applied, and are now playing an important role in the water management (Wei et al., 2008;  
48 Reed et al., 2007; Blöschl et al., 2008). As the requirement on elaboration and real-time in water  
49 management increases, hydraulic modeling is facing great changes and challenges. An elaborate

50 simulation requires the high computing precision, as manifested by finer simulation granularity  
51 in a large system domain. Besides, a real-time requirement necessitates the rapid acquisition of  
52 simulation results of multiple scenarios for the decision-making. For example, in the event of  
53 sudden flooding or water pollution, multiple scheduling plans need to be simultaneously and  
54 rapidly considered to propose optimum solutions through comparisons (Zeng et al., 2010; Wu  
55 and Wang, 2010; Wang et al., 2009). Therefore, the trend of elaborate and real-time management  
56 raises the necessity of concurrent parallel running of multiple scenarios and rapid simulations  
57 during the decision-making. The multiple scenarios need to be computed concurrently in order to  
58 meet the demand of rapid simulations, especially the demand of rapid optimization during the  
59 water management decision-making. This poses a great challenge to the scalable computing  
60 resources, and associated efficient, reliable data communication mechanisms. Thus a new  
61 generation of modeling tools or services should be imperiously established, which allows for the  
62 integration of multi-models and scalable computing resources.

63 Over the past decades, especially with the publication and continuous development of the  
64 OpenMI standard of the EU Water Framework Directive (Gregersen et al., 2007), multi-model  
65 integrated systems have been developed rapidly. OpenMI provides a standard for coupling  
66 between multiple interdisciplinary models in step simulation, including model component  
67 interface specifications, definitions of data exchange objects, definitions of object linking and  
68 definitions of triggering methods. Several model integration systems based on OpenMI have  
69 been released, and HydroModeler is one typical application (Ames et al., 2012; Castronova et al.,  
70 2013). In HydroModeler modules, boundary data needed for the model component can be  
71 obtained by connecting DbReader components that meet the OpenMI specifications. Studies  
72 related to OpenMI specifications also included the integration of script models (Bulatewicz et al.,

73 2013) and evaluation on the performance of data exchanges between OpenMI-compliant  
74 components. Castronova and Goodall (2013) used OpenMI standards to split their rainfall-runoff  
75 model into three independent OpenMI-compatible model components forming a loosely coupled  
76 model system and performance tests showed the loosely coupled model did not affect the  
77 performance of the original system. In addition to integration platforms using the OpenMI  
78 standard, other integration platforms have also been built, e.g., the Object Modeling System  
79 (OMS), the Community Surface Dynamics Modeling System (CSDMS) and the Common  
80 Modeling Platform (CommonMP)<sup>†</sup>. The model developers who understood integration standards  
81 of the platform were able to implement the integration and reuse of the models by modifying  
82 only a small amount of code (David et al, 2013). CSDMS is a platform for model integration and  
83 sharing, which can provide high-performance computing capacity, and models integrated into  
84 this system can use its computing resources (Silva et al., 2012; Overeem et al., 2013).  
85 CommonMP is a platform that integrates multiple hydraulic and hydrology models; it manages  
86 the registration and use of these models via a model library. Schmitz et al (2014) developed an  
87 accumulator, a programmable general-purpose model building block executing custom scaling  
88 operations at model runtime, which can characterize runtime information of input and output  
89 variables required for the implementation of scaling operations between component models with  
90 different discretization. A processing conversion and parallel control platform (PCsP) is proposed  
91 for transitioning serial hydrodynamic simulators to a cluster-computing system (Shang et al.,  
92 2016).

93 These previous studies improved the overall level of model integration and simulation  
94 application services. However, all of the above integrated systems share a common feature, i.e.,

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<sup>†</sup><http://framework.nilim.go.jp/en/index.html>.

95 the source code must be modified in the model integration process, so as to rewrite the prototype  
96 engine into model components defined by the system. This would be difficult for a majority of  
97 legacy model developers, and thus to certain extent hinder the use and sharing of the legacy  
98 models. Meanwhile, existing studies have not focused on the rapid simulation of parallel  
99 multiple scenarios in a decision-making process, as well as the simulation as a service with the  
100 integration of computing resources. Although the CSDMS framework provides the HPC cluster,  
101 only model developers can use this feature; the use of the HPC cluster has not yet been converted  
102 into a modeling service that users can access via the Web. Model users and decision-makers are  
103 often unable to find solutions at computing resource bottlenecks to make the decision-making  
104 more efficient and obtain the most reliable and optimized outcome possible via concurrent  
105 massive scenarios. In particular, in a real-time hydraulic scenario optimized scheduling, typically  
106 hundreds of computing scenarios need to be simulated simultaneously, which poses a challenge  
107 to the computational capacity of the server. In the event that computing capacity struggles to  
108 meet the concurrent computing requirement, a newer, high-performance server needs to be  
109 purchased. This could cause a high investment and low usage. In a review on integrated  
110 environment modeling, Laniak et al. (2013) mentioned “modern and visionary work using  
111 concepts such as cloud-based computing and Web services to achieve a higher level of  
112 functionality in next generation IEM modeling frameworks,” and proposed that cloud computing  
113 and Web services are another important technique in addition to the model coupling. They  
114 pointed out that relative to traditional computing, the cloud computing has various advantages,  
115 such as saving cost, reducing development time, rapid integration of model components, and  
116 good capacity for simulation after the environment disintegration. The cloud computing thus  
117 dynamically packages the interactive services into a custom simulation system. In addition, cloud

118 computing also promotes the development of a strong integration modeling community via  
119 service sharing such as through a Web service.

120       Regarding the advantages of cloud computing, in the last two years many scholars and  
121 relevant agencies have conducted studies on simulation services and integration platforms based  
122 on cloud computing. Sun (2013) used Environmental Decision Support System (EDSS) tools in  
123 the cloud services provided by Google Drive to solve high cost problems, to ease difficulty in  
124 information sharing and other problems in joint decision-making. Burger et al. (2012) applied the  
125 concept of cloud computing to integrate the computing power of supercomputer and hydrological  
126 models, and used GUI and other interfaces to provide the users with real-time simulation  
127 services of the ParFlow hydrological model. Lloyd et al. (2012) used Eucalyptus technology to  
128 build a virtual machine (VM)-based Cloud Services Innovation Platform (CSIP). Brooking and  
129 Hunter (2013) developed a Web-based repository to provide high-speed, interactive access to  
130 online simulations of hydrological models. Shi et al (2015) proposed a general framework for a  
131 service-oriented architecture (SOA) for ensemble flood forecast based on numerical weather  
132 prediction (NWP). Arango et al. (2014) developed a new version of Agent Swarm Optimization,  
133 taking advantages of the Cloud Service provided from the Windows Azure to support the  
134 analysis of a high number of scenarios. Glenis et al (2013) developed a parameter sweep version  
135 of the urban flood modelling, analysis and visualization software "CityCat". This can be  
136 deployed in a cloud environment to make use of the cloud computing resources, so as to be able  
137 to estimate the spatial and temporal flood risk at a whole city scale, which is much larger than  
138 what had previously been possible through using the cloud computing resources via the  
139 HTCondor. Besides, Rodriguez et al. (2014) developed a cloud-based Early Warning System  
140 (EWS) platform HIDROMET for real-time urban flood warning data, where the users can

141 connect to the system through Internet by any device and the platform can integrate the user data  
142 and system data for warning analysis.

143 The above systems based on the cloud services are still under development or being  
144 improved. Some are able to implement the integration of particular models, and most focus on  
145 Web-based scenario searching and information presentation services. Based on the user demand  
146 for the integration of multiple models and for rapid concurrent computing, in the present study it  
147 is proposed to integrate hydraulic models with high-performance computing resources, and to  
148 provide modeling services using the computing power integrated in the system in the form of a  
149 Web service, i.e., Hydro-Modeling as a Service (HMaaS). HMaaS provides conceptual and  
150 technical support for model integration and the use of scalable computing resources from the  
151 idea of "scalability, automation, low-cost and efficient use of resources" in cloud computing  
152 (Hwang et al., 2011; Ari and Muhtaroglu, 2013; Gupta et al., 2013; Caballer et al., 2013; Huang  
153 et al., 2013). It achieves unlimited scalability of computing power with the idea of "Rapid  
154 elasticity" reduces cost with "customizable demand and usage-based billing" and implements  
155 streamlined and automated data management and computing services with the idea of a  
156 "resource pooling". The users only need to learn a few methods for calling simulation interfaces  
157 or for using the terminal system, and do not need to understand the principles, implementation or  
158 the computing capacity of the cloud computing based modeling platform. In the present  
159 framework of web service and cloud computing, a cloud computing service platform for  
160 hydrodynamic simulation, HydroMP, has been developed. The objective of developing such a  
161 cloud computing based hydro-modelling platform is similar to that of the several others (Arango  
162 et al., 2014; Glenis et al., 2013; Rodriguez et al., 2014) in that all of them address the needs of  
163 multi-scenario and prompt feedback under highly intensive computing resources. **On the other**

164 hand, most hydrodynamic and hydrological models are site-specific and they may not perform  
165 equally satisfactorily in other areas. Just to improve this situation, the cloud-computing based  
166 HydroMP platform aims to integrate the various conceptual and physical mechanisms together  
167 with the unified data structure and operational mode. Therefore, the users can freely select the  
168 most appropriate scenarios to run the models based on the available site information and the  
169 adaptability of each model to the region. The HydroMP platform system assumes its unique  
170 feature in the following three aspects: (1) Not only address the multi-scenario situation,  
171 HydroMP can also dynamically integrate different models and algorithms efficiently; (2)  
172 HydroMP adopts a two-layer structure framework for the system deployment and resource  
173 regulation, thus can have more potentials in its extendibility; and (3) HydroMP makes full use of  
174 the cloud computing resources through the constructed HPC clusters, therefore adopts a different  
175 way in exploring the cloud environment and its computing sources and technologies. The main  
176 characteristics of the HydroMP platform are as follows: (1) The hydro-models and the computing  
177 resources are highly integrated, and the unlimited computing power provided by distributed,  
178 scalable computing resources is used to meet the demands of multi-client, multi-scenario,  
179 simultaneous rapid simulations; (2) “Plug and play” integration between the platform and the  
180 models is achieved, and the provided universal model integration methods include all types of  
181 models, e.g. a large number of legacy models, so the users can choose the best adaptive one for a  
182 particular research region freely; (3) The platform provides scenario submission, progress inquiry,  
183 result feedback and other interfaces via Web services; (4) The platform provides open SDK  
184 (including data structure, method and interface), so that any client can reference the data  
185 structure and use the Web service to develop application systems (terminal) for a variety of  
186 purposes. In the application systems, there is no need for the computing power and hydro-models,

187 because the system can call the interface via Web service to use these resources. In addition,  
188 HydroMP also employs a distributed computing framework, including a HydroMP center and  
189 some HydroMP servers. The HydroMP center and HydroMP servers can be deployed in  
190 distributed high-performance computing HPC clusters independently and the number of  
191 HydroMP servers is also extensible. The present HydroMP platform is very similar to other  
192 Software as a Service (SaaS) but it mainly serves the HPC computing clusters. Meanwhile,  
193 HydroMP is also a model integration system to provide different simulation models and  
194 algorithms to the user community. After multi-model integration, the unique advantage of  
195 HydroMP is that it can carry out a variety of model setups and solution algorithms based on only  
196 one dataset source.

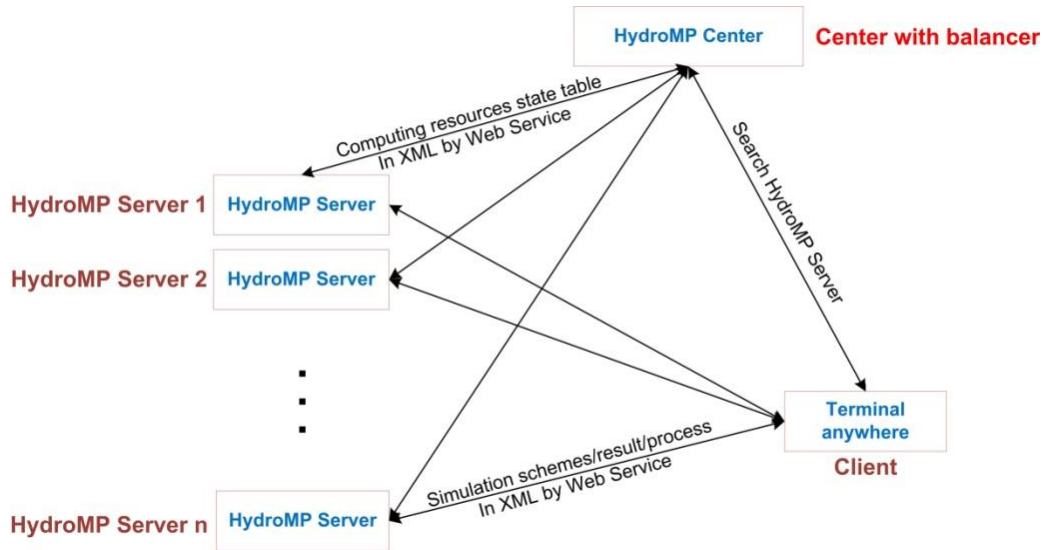
197 To design and realize a cloud computing-based hydraulic modeling platform, the following  
198 technical issues need to be addressed: (1) fast, convenient, dynamic and standardized integration  
199 of the hydro-models; (2) employing, scheduling the computing resources; (3) data exchange and  
200 real-time communication between different programs and processes on the platform; (4)  
201 standardization of call interfaces and fast data transmission based on Web services. The present  
202 paper describes the details of key technologies to construct the framework of HydroMP.  
203 Subsequent parts of the paper are organized as follows: the next section is a general description  
204 of the platform and the framework of HydroMP server deployed in distributed HPC clusters;  
205 Section 3 describes the model integration method, resource scheduling, concurrent scenario  
206 simulation management, communication between multiple systems and multiple processes,  
207 implementation of Web service interfaces and other key technologies and methods used in the  
208 HydroMP platform; Section 4 describes the implementation of the HydroMP platform and the  
209 integration of 2 one-dimensional hydrodynamic models; Section 5 describes a practical case of

210 the HydroMP application; the last section includes the conclusion and future prospects of  
211 HydroMP.

## 212 **2 HydroMP FRAMEWORK**

213 The HydroMP platform consists of a star-topology deployment structure, including a HydroMP  
214 center and a number of distributed HydroMP servers. Each HydroMP server is an individual  
215 computing service platform, and the HydroMP center is a load balancer between the HydroMP  
216 servers, as well as the entrance for terminals. The client can connect directly to the HydroMP  
217 servers, or connect to the HydroMP center and be forwarded to one HydroMP server via the  
218 balancer of the center. The deployment structure of the HydroMP platform is shown in Figure 1.

219 In the lab test environment, three HPC clusters are used to deploy the computing services; one  
220 cluster is used as the HydroMP center, the second HPC cluster as a private HPC in Tsinghua  
221 University is used to deployed a HydroMP server, and the third HPC cluster was constructed in a  
222 commercial cloud computing platform Windows Azure in China, which is used to deploy a  
223 HydroMP server. During the running process, each HydroMP server dynamically sends the  
224 computing resource usage rate, the number of online users and status of simulating scenarios to  
225 the HydroMP center to analyze each server's load for granularity scheduling. Each HydroMP  
226 server can also be independently called by PC clients, mobile clients, tablet PC clients, through  
227 12 service interfaces based on Web services. The HydroMP server can be registered to HydroMP  
228 center dynamically, and as the third HPC cluster, can be constructed in the cloud computing  
229 environment to provide elastic computing resources, so the HydroMP is supposed to a cloud  
230 computing based framework which can provide the elastic computing resources.



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Fig. 1. Distribution of deployment of the HydroMP server

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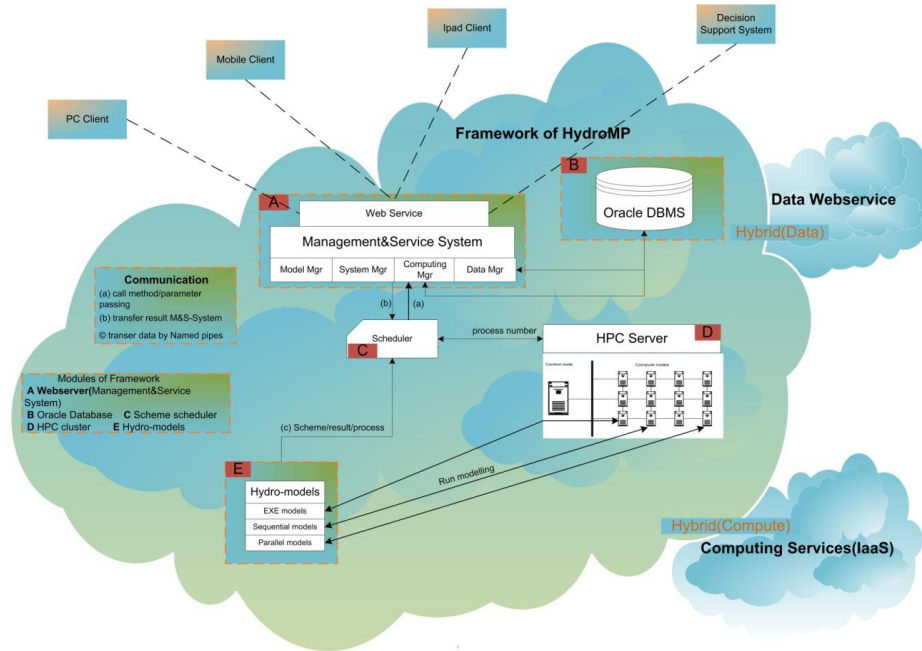
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The HydroMP server in each cluster consists of five components: the management service system (A), the database system (B), the scheduler (C), the HPC cluster (D) and the hydro-models (E), as illustrated in Figure 2. Among these, the management service system is the general management platform and the window for providing services, including scenario management modules, computing management modules, model management modules and system management modules. It is responsible for the addition and deletion of scenario data, management of the model database, result inquiries and system management. All computing service interfaces need to be wrapped in the management service platform via a Web service. The management of all data, models and computing statuses on the HydroMP platform is also completed by the management service system. The HydroMP platform uses Oracle as the management tool for the unified management of basic data, scenario data, model registration and other information, and realizes the association between different data and union queries using a foreign key relationship. The scheduler is responsible for the startup, pause, restart, computing core allocation and computing workflow control, in order to achieve effective scheduling of computing resources. Windows HPC Server 2012 is used to manage the computing resources of

248 the HPC Cluster, and the scheduler uses job management and task management APIs provided  
 249 by the HPC server for job scheduling and computer core allocation. Hydro-models registered to  
 250 the platform include executable programs and related DLL files, and the modeling programs  
 251 used named pipes to communicate with the scheduler, including receiving the data, uploading  
 252 progress and results.



253

254

Fig. 2. Framework of HydroMP

### 255 3 MODEL INTEGRATION AND RESOURCE SCHEDULING IN HydroMP

256 HydroMP is constructed on a pool of HPC computing resources and hydro-models, so the  
 257 platform needs to have the capacity to integrate and schedule the computing resources, and to  
 258 have the ability to integrate multiple models. Some Web service interfaces to receive external  
 259 calls are needed to provide the concurrent submissions and result queries of massive numbers of  
 260 scenarios. As a multi-system and multi-process collaborative platform, the communication  
 261 between various subsystems and processes is also very complex. To this end, the system must  
 262 address four key issues: universal model integration, resource scheduling and concurrent

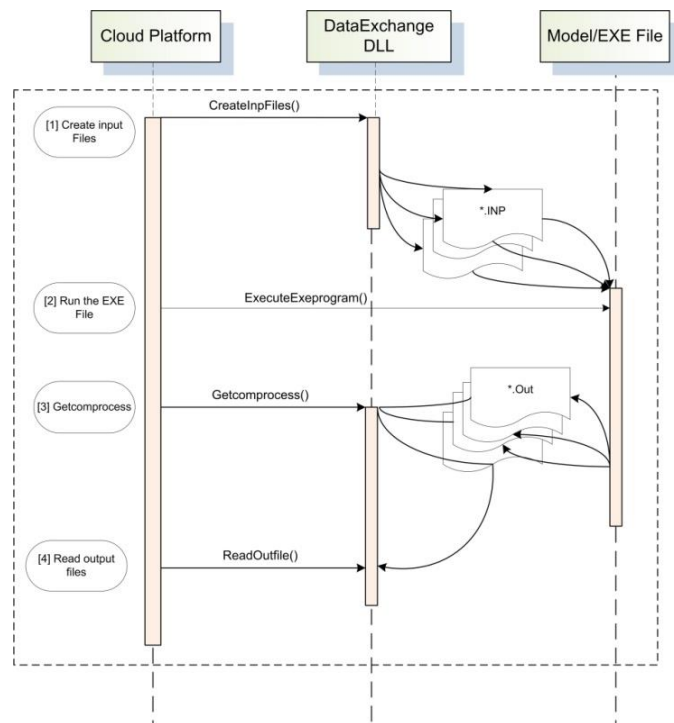
263 processing, combined combinations between multiple systems and processes, and design of a  
264 Web service interface ("cloud - terminal" interaction).

### 265 **3.1 Universal model integration methods**

266 Existing model integration methods (e.g., OMS, CSDMS) requires the rewiring of the model  
267 code. Hence, it poses a challenge to the integration of legacy models. For this reason, the present  
268 study investigated a large number of legacy models, such as CE-QUAL series, Environmental  
269 Fluid Dynamics Code (EFDC), QUAKE2K and some models currently used in Chinese research  
270 institutes. By taking into account the different characteristics of different models, HydroMP  
271 offers two model integration methods.

272 (1) EXE integration mode: Through analysis, it was found that the extent to which the  
273 inputs and outputs are structured in a large number of hydraulic simulation legacy models is  
274 relatively low, and typically the model developers customize the input and output file formats.  
275 The steps of model use are to first use a text editor (e.g., Notepad, Ultra Edit) to edit an input file  
276 needed for running the model, followed by starting the simulation; the model reads the input files  
277 during initialization, and after the completion of calculation it saves the results to certain output  
278 files using the customized format. Based on this, HydroMP uses loosely coupled  
279 communications between the platform and the models for integration. In this way the data I/O  
280 converter established between the platform and the models conducts the conversion, and the  
281 communication between the platform and the models is realized via size of output file for  
282 interaction. When the model is called, four steps (creating the input file, starting the simulation,  
283 reading the progress, and reading the result file) are executed by calling CreateInpFile(),  
284 ExecuteExeprogram(), GetComprocess() and ReadOutfile(), respectively, as shown in Figure 3.  
285 With this method there is no need to make any modifications on the code of the original models.

286 Instead, only the platform's software development kit (SDK) needs to be referenced and the  
 287 corresponding interfaces need to be implemented, thereby achieving the “non-invasive”  
 288 integration of the original models. EXE integration cannot realize the bidirectional model link  
 289 between the different components while unidirectional model link is allowed through the  
 290 platform operation. However, in practice it has been found that unidirectional model link is also  
 291 quite common to address quite a few real needs. For example, most hydrodynamic and  
 292 hydrological models fall into this category. By integrating the multi-models in the HydroMP  
 293 platform, sensitivity analysis can be made on different numerical algorithms so as to eliminate  
 294 the uncertainties of the simulation results.



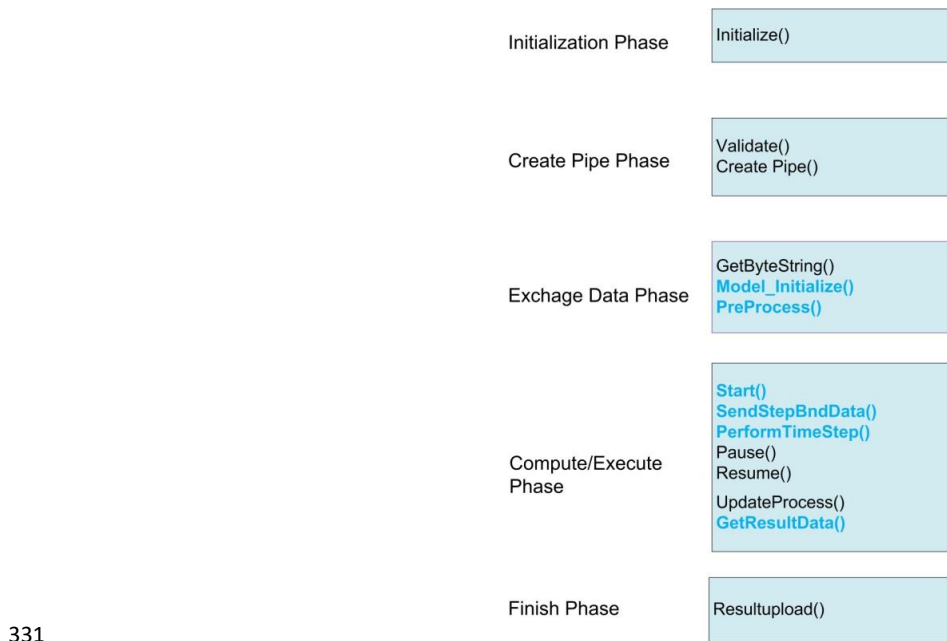
295

296 Fig. 3. Execution process and component interaction in EXE integration mode

297 (2) Program interactive integration mode (PIIM): To enable real-time interaction between a  
 298 running model process and platform, the present study proposes PIIM. PIIM develops a  
 299 standardized model wrapper program for communication between model process and the

300 computing scheduler of platform via named pipes, and uses five standardized communication  
301 interfaces to implement communication. The types of communication include the initialization,  
302 model execution, model pause, progress acquisition and results reading. The simulation platform  
303 sends all requests and the standardized wrapper program responses to the requests, and then  
304 returns the corresponding data, thereby realizing the control of simulation workflow by the  
305 platform. Inside the wrapper program, model initialization, preprocessing, simulation startup,  
306 single-step boundary updates, single-step execution, calculation completion and other interfaces  
307 are used to call methods in the model components, as illustrated in Figure 4. In the model  
308 integration, the model needs to be rewritten into a model component Model.DLL that fits  
309 specifications similar to the OpenMI interface standard, and when the wrapper program calls the  
310 model component it is compiled to a new executable file. There exist some kinds of difference  
311 between the PIIM and OpenMI integrations in that: (1) PIIM integration is implemented through  
312 the HydroMP platform regulator to control the simulation progress via the Named Pipes, while in  
313 the OpenMI the linkable component uses the event mechanism to drive model integration; (2)  
314 Different data transfer modes are implemented in the two systems, since HydroMP uses the HPC  
315 cluster for multiple and large scenario simulation which requires the linkage models to run on  
316 different computing nodes So PIIM uses the dataflow to transfer information via the Named  
317 Pipes and the designed standard platform data structure is similar to that in OpenMI, while  
318 OpenMI exchanges the data directly among the different components using the pull-driven  
319 approach via the memory. In this sense, the promising feature of the PIIM integration is that it  
320 can conveniently achieve the complex multi-model and multi-scenario analysis, for example,  
321 while simulating a flood event in a catchment area, it needs the coupling of hydrological and  
322 hydrodynamic models but usually the end-users are not very familiar with the runoff and channel

323 conditions. There are three different runoff engines including Xin'anjiang runoff model, Horton  
 324 runoff model and SAC runoff model, and two flood routing models including the diffusion wave  
 325 model based the routing and dynamic Muskingum model. Through the data exchange in  
 326 HydroMP, totally six runoff-routing coupling models could be created on five computing  
 327 processes. This kind of flexibility is one attractive feature of the HydroMP platform to meet its  
 328 multi-purpose target. The model integration framework, converse relation between original  
 329 model code, data exchange file (DLL file), standard wrapper and executive file (EXE file), and  
 330 the data conversion between executive file and HydroMP is shown in Figure 5.



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Fig. 4. Execution process in the PIIM integration mode

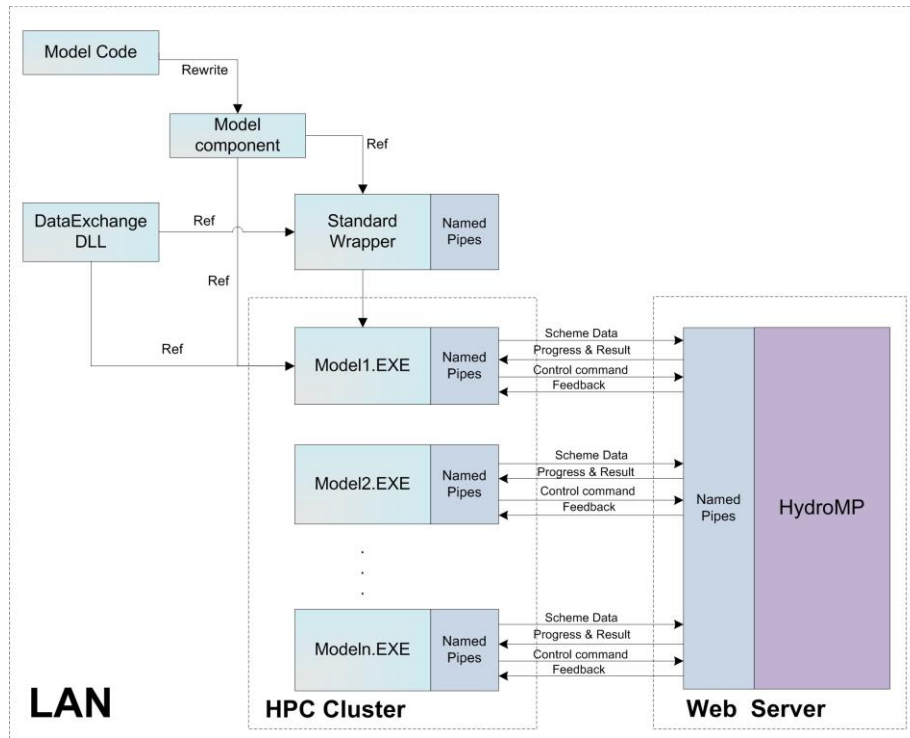


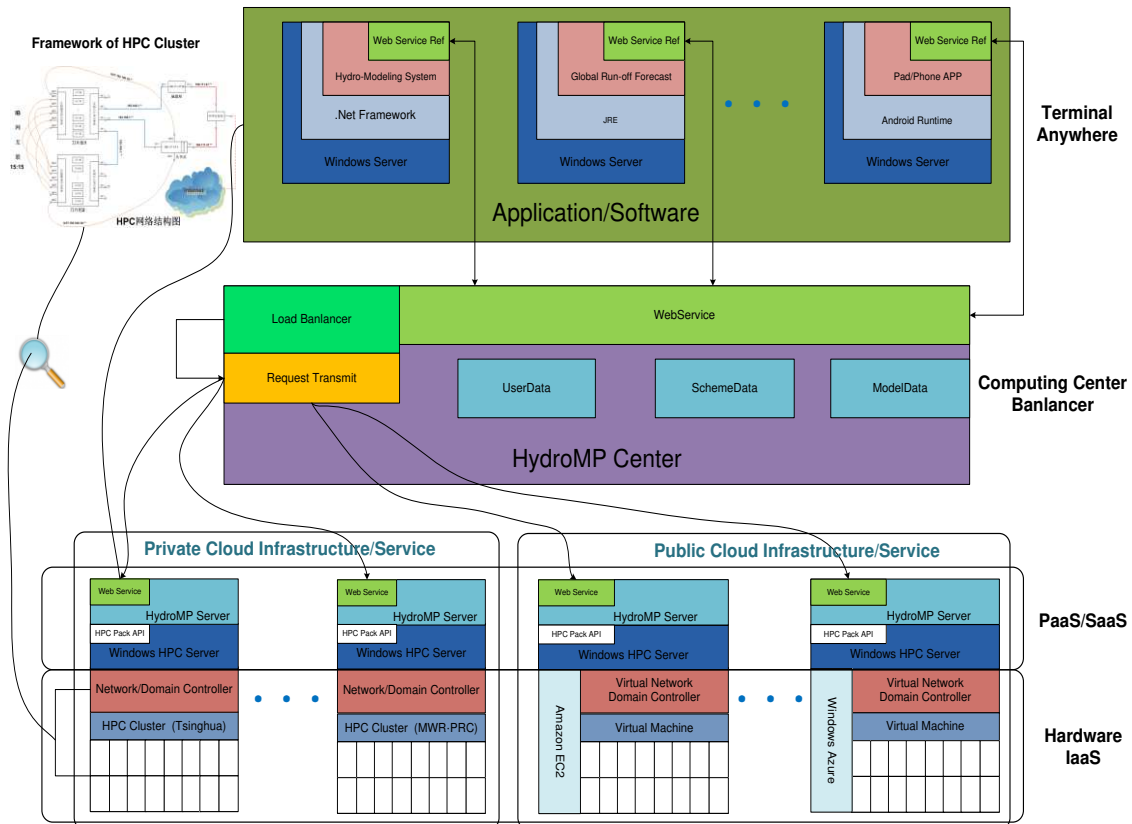
Fig. 5. The integration workflow and data conversion in PIIM mode

### 3.2 Computing resource scheduling

HydroMP is a distributed deployed simulation cloud platform with a HydroMP center and several HydroMP servers. The HydroMP server can be a standalone simulation platform as well as a branch center of HydroMP center. The HydroMP is a classic hybrid cloud computing framework. Each HydroMP server can provide partial computing resources to the public, and also be a computing platform for internal simulations as a private cloud computing service.

This design framework of HydroMP benefits the coupling of the public cloud computing and private one. The institute owning the computing resources can deploy a HydroMP server for the hydrodynamic simulation and rent some computing resources as a public cloud computing service when the computing resources are more than the needs of their institute, because the HydroMP center dynamically provides the HydroMP server registration. To a user who needs the

347 computing resource can select the HydroMP center as well as any HydroMP server to drive the  
 348 hydrodynamic simulation. The HydroMP center and HydroMP server can be deployed in a  
 349 public cloud platform (i.e. The Amazon EC2 or Windows Azure) as well as in the private HPC  
 350 clusters. The framework of the HydroMP and interactions between the center and servers are  
 351 shown in Figure 6.



352  
 353 Fig. 6. The framework of HydroMP

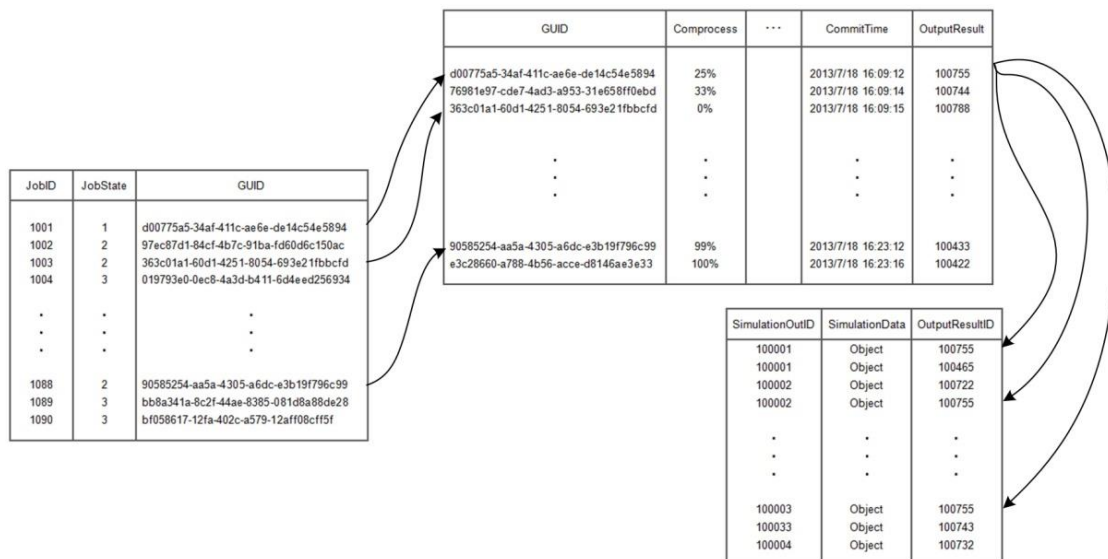
354 The computing resources scheduling includes the balancing between HydroMP servers and  
 355 the allocations in each individual HydroMP server. Firstly, the HydroMP center gets the available  
 356 computing resources of each HydroMP server. Then it analyses the simulation tasks to evaluate  
 357 the computing resource requirement and occupied time of each task. Lastly, the tasks are  
 358 allocated to different HydroMP servers based on the load distribution matrix of all HydroMP  
 359 servers using a particle swarm optimization algorithm. The objective of computing resources

360 scheduling among all HydroMP servers is to reach the load balance between the HydroMP  
361 servers.

362 As an individual computing server, the HydroMP server will schedule the computing  
363 resources in their HPC servers after receiving the computing tasks from HydroMP center. A  
364 computing scheduling principle based on different levels of urgency and user is proposed in this  
365 paper. This scheduling principle is adapted for the needs of multi-users and different computing  
366 requirements. The core principle includes three aspects, the first one is that the urgent simulation  
367 task should be computed in real-time even if the other computing tasks need to be paused or  
368 stopped. The second one is that the task of paying users should be computing preferentially. The  
369 third one is that the intermediate results of paused tasks should be timely saved. In computing the  
370 resources scheduling, there are three different priority levels for computing the use: emergency  
371 computing, paying user computing and free user computing. The platform must ensure that the  
372 emergency computing is executed. When the unoccupied computing resources cannot meet the  
373 emergency computing scenario, some of the non-emergency computing should be paused. The  
374 computing scheduler is designed to implement the rules of resource scheduling. The schedulers  
375 are the bridge of resource allocations and data communications between the platform and the  
376 HPC management system.

377 In the present paper, a set of scenario computing status management tables have been  
378 designed to realize the sharing of computing status data among different sessions and different  
379 terminals. These tables include the Job-Scenario table, the Scenario-State table and  
380 Scenario-Result table, as shown in Figure 7. They record information of the association between  
381 the HPC and computing scenarios, the computing status and progress of the scenarios, and the  
382 results of the scenario calculation, respectively. The scheduler implements the resources

383 allocation and scenario simulation progress management via a set of program flows including the  
 384 new task create, status update, error report, results append, result storage, scenario resume, and  
 385 task restart.  
 386



387  
 388 Fig. 7. Scenario computing status management tables

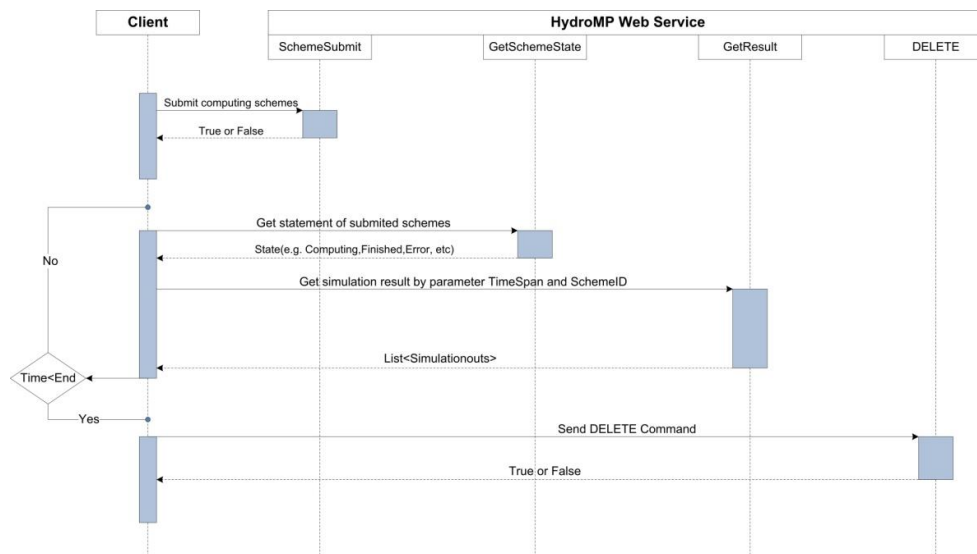
389 **3.3 The communication between multiple systems and processes**

390 As shown in Figure 1, HydroMP can be divided into the management and service system, the  
 391 HPC Server, the database system, the scheduler, and the model program. The "communication  
 392 pairs" include: 1) communication between the management service system and the scheduler via  
 393 the class referencing; 2) communication between the management service system and the  
 394 database system via the Oracle data provider; 3) communication between the scheduler and the  
 395 HPC clusters via the HPC computing resources scheduling interface; and 4) communication  
 396 between the scheduler and the mathematical models via the Named pipes or in-out files.

397  
 398 **3.4 Web service interface**

399 HydroMP provides scenario calculations, progress inquiries and simulation results acquisition  
 400 services through 12 Web service interfaces, including GetModels() for acquiring computing  
 401 model information, ScenarioSubmit() for scenario submissions, GetState() for computing status  
 402 queries, GetResult() for acquiring results, DownloadScenario() for downloading scenario data,  
 403 DeleteScenario for deleting scenario, EditTimeSpan() for modifications of simulation timespan,  
 404 and so on. Figure 8 illustrates the schematic process of user submission, status acquisition,  
 405 real-time acquisition of the results and scenario deletion after acquisition of all results. The web  
 406 service interface list and detailed information is shown in Table 1.

407



408

409 Fig. 8. Interactions between Client and HydroMP

410

Table1. Web Service List of HydroMP

No	InterfaceName	Parameters	Comments
1	UserLogin	UserName	To validate the log user
		Password	
		UserAddress	
2	GetModels	ModelType	To get the model list
3	ScenarioSubmit	ScenarioList	To submit the scenario or scenario list
		ModelID	

4	GetProgress	ScenarioID	To get the simulation progress of scenario
5	GetState	ScenarioID	To get the simulation state of scenario
6	GetSimulationOut	ScenarioID	To get the simulation results
7	EditTimeSpan	ScenarioID Start-Time End-Time	To edit the simulation timespan of the scenario
8	GetScenarioByID	ScenarioID	To get the scenario information by ScenarioID
9	DeleteScenario	ScenarioID	To delete the appointed scenario
10	GetResult	ScenarioID	To get the simulation result of scenario(s)
11	DelModel	ModelID	To delete a model engine
12	AddModel	ModelID	To register a model engine

411

## 412 **4 PLATFORM IMPLEMENTATION**

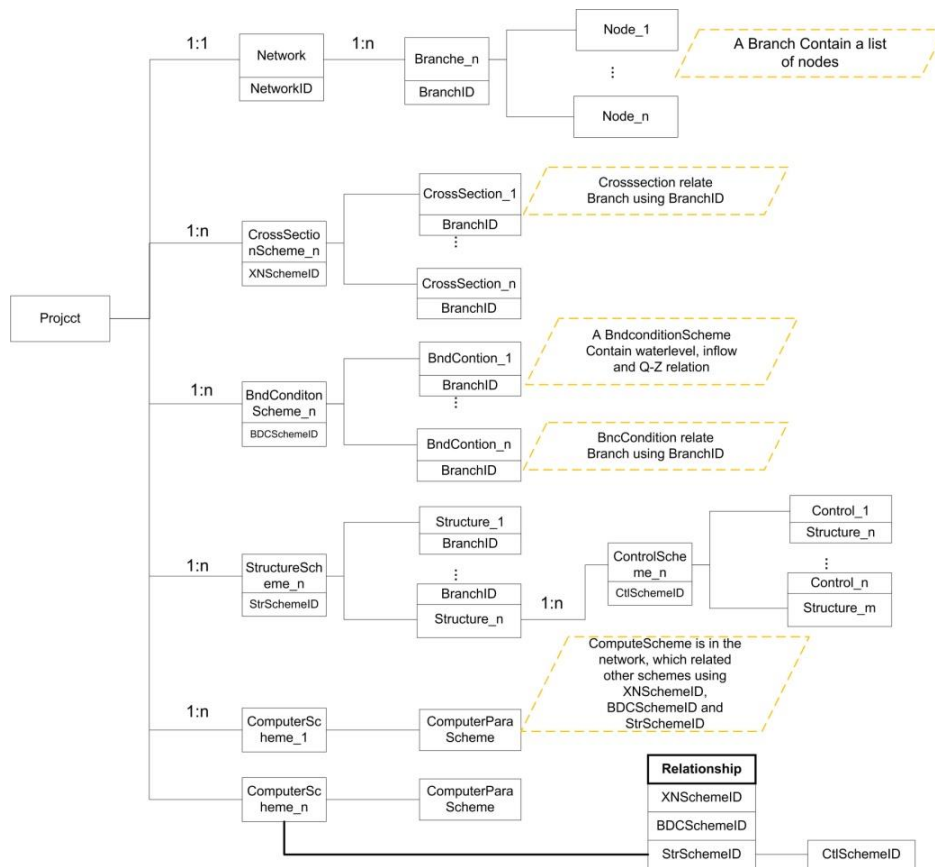
413 Currently, the HydroMP system provides a one-dimensional hydrodynamic library, the following  
414 describes the one-dimensional hydrodynamic modeling data structure design method and data  
415 hierarchy in HydroMP, the already integrated models in HydroMP and critical processes in  
416 integration, and the development method and functions of Cloud-Hydro1D (desktop software for  
417 one-dimensional hydrodynamic modeling and cloud computing established by using SDK and  
418 Web service of HydroMP).

419

### 420 **4.1 Design of Hydro1D data structure**

421 HydroMP decomposes the complex systems for abstract description and hierarchical storage  
422 based on an object-oriented modeling method (Booch et al., 2007). Two association structures,  
423 i.e. single scenario storage and multi-scenario storage based on the object-oriented program,  
424 were proposed. The multi-scenario storage aims at reducing the amount of data transmissions  
425 during the submission of multiple scenarios. In general, the different scenarios have the same

426 base data including the river network and topology, and the differences between different  
 427 scenarios are the upper river segment discharges and boundary conditions. In multi-scenario  
 428 storage, each project includes one network structure and multiple scenario groups designed on  
 429 this river network structure. Each scenario group includes a set of scenarios of a specific type. In  
 430 this way, a large amount of traffic data can be saved in the submission of multiple scenarios via  
 431 the Web, and the topology of the data structure is shown in Figure 9. In a single scenario storage  
 432 structure, one scenario stores the single river network structure, the single cross section scenario,  
 433 the single boundary scenario, the single building scenario, the single control scenario and  
 434 simulation parameter scenario in parallel. The data structure of objects in the second layer is the  
 435 same as that in a multi-scenario storage.



436

437

Fig. 9. Data structure of the one-dimensional hydrodynamic model

## 438 **4.2 Registered hydro-models and model management**

439 The platform implements the integration of CE-QUAL-RIV1<sup>‡</sup> and JPWSPC (Zhu et al., 2011)  
440 through the standardized interfaces. The CE-QUAL-RIV1 model is a one-dimensional  
441 hydrodynamic model developed by the U.S. Army Corps, and in the present study it is integrated  
442 using the EXE mode. The JPWSPC model is a river network hydrodynamic model proposed by  
443 Zhu. This model uses a junction point water stage prediction-correct method to solve the  
444 complex river network modeling (Zhu et al., 2011). In the present study, the integration of  
445 JPWSPC is achieved separately using SPIIM and PPIIM.

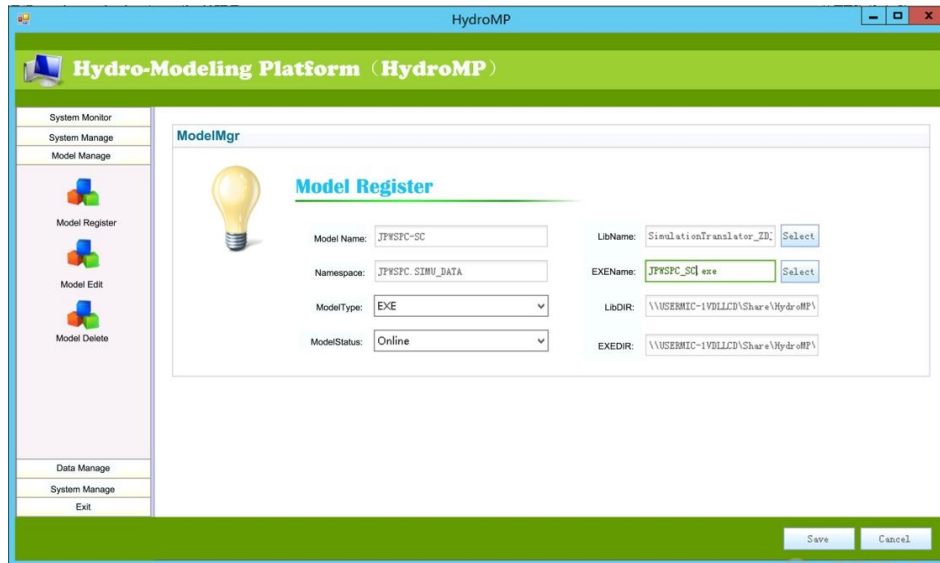
446 CE-UQAL-RIV1 is integrated in an EXE mode (non-invasive). The InputFileCreate(),  
447 GetProcess(), and OutFileRead() interface was implemented, and the GetProcess() interface is  
448 implemented based on the relations between the output file size and simulation process. The  
449 JPWSPC model was rewritten using PIIM. The original program was rewritten into four  
450 functions, Initialize(), PerformTimeStep(), UpdateBndData() and GetTimeStepResult().

451 In addition, in the present study, the parallel integration of the JPWSPC model was also  
452 implemented. In parallel programs, MPI is used for communication between the master and slave  
453 processes, and the method and interface for communication between the master process and the  
454 platform (computing scheduler) are the same as in the PIIM mode.

455 The system uses a database to keep information on the models that have already been  
456 integrated, including the model name, the model type, the location of execution files and the data  
457 exchange DLL files. The hydro-models can be registered and cancelled dynamically by changing  
458 the hydro-model state in the database. and Figure 10 shows the model registration GUI.

---

<sup>‡</sup><http://www.epa.gov/athens/wwqtsc/html/epd-riv1.html>.



459

460

Fig. 10. Graphic user interface for model registration

461

462

To test the concurrent capacity and Web service of the platform, a desktop client based on C#, CloudHydroID, was developed, which provides the functions for editing the multi-scenario data, submitting the scenario simulations and simulation results display.

463

464

## 465 5 CASE STUDY

466

467

468

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470

471

### 472 5.1 Project introduction

473

474

SNWD is a major water allocation project to solve the water shortages in northern China. The central route diverts water from the Taocha hub of the Danjiangkou Reservoir, and runs to

475 Beijing with a total length of 1277 km. Along all the routes, there are 61 sluices, 78 outlets, and  
476 42 back outlets. The project diverts water in an open channel; during water diversion, changes in  
477 the water flow at any outlet or in the opening of any sluice will lead to changes in the  
478 hydrodynamic process downstream or even along the entire route. A schematic view of the route  
479 of SNWD is shown in Figure 11. To ensure the safety of water diversion, the water flow  
480 adjustment and control strategy of the main route via the opening and closing of sluices, outlet  
481 gates and back outlet gates should be applied in the channel operation to maintain a relative  
482 constant upstream water level of sluices and to reduce the complex hydraulic response in the  
483 negative feedback way. The method of controlling the opening and closing of the sluices, outlet  
484 gates and back outlet gates (timing of opening and closing, and gate opening angle) is a complex  
485 problem, and an optimal or suboptimal adjustment scenario can only be obtained through testing  
486 and optimizing different gate opening and closing scenarios using hydrodynamic models and  
487 gate control models. In particular, when the flows at certain water-drawing stations change  
488 drastically, the question of how to control the gates along the route to ensure the fastest recovery  
489 to a water drawing-water pumping balance is an issue that must be solved during the real-time  
490 scheduling process. The real-time sluice operation at different levels and relevant  
491 decision-making processes in SNWD require a most optimum solution plan among enormous  
492 viable options in a multi-dimensional scenario. It demands extensive computing resources to  
493 satisfy the promptness and efficiency of various regulation procedures, which would be  
494 impossible to implement under conventional serial computing environment. The current level of  
495 water diversion service along the middle route is achieved through the standard practice without  
496 multi-scenario simulation and multi-system analysis and the operational mode is in series but not  
497 in parallel. Thus it is difficult to realize the optimum regularisation and efficient management

498 control. The HydroMP system will be able to improve the situation by overcoming these existing  
499 limitations. Thus here we will explore the potentials of cloud computing based on HydroMP  
500 platform in this study to demonstrate the applicability of parallel computing technique and its  
501 efficiency in engineering practice. In the present study a multi-scenario automatic comparison  
502 method was used for hydrodynamic simulation, verification and optimization of multiple gate  
503 control scenarios in order to obtain the optimized scenario.

504

## 505 **5.2 Scenarios description**

506 Due to the limitations set by the amount of water available at water-pumping stations and the  
507 varying amounts of water needed in the water importing area, water diversion in the main canal  
508 is an uneven process. Changes in the water flow at any canal segment will cause fluctuations in  
509 the canal's water level. In the present study, hydraulic transition processes under certain extreme  
510 operating modes were investigated: the water flow at the Taocha headworks linearly changed to  
511 another level within a certain amount of time; the water flows at different outlets changed  
512 linearly and synchronously; the different sluices were opened from the initial opening angle to  
513 the target opening angle.



Fig. 11. The middle route of South-North Water Diversion project

514

515

516

517 Flow at the Taocha headworks has two operating modes: decrease and increase: (1) Assume  
 518 that in the initial state the canal contains 70% of the design flow, and in a given amount of time it  
 519 is reduced to 50% and 10% of the flow; (2) Assume that in the initial state the canal contains  
 520 70% and 10% of the design flow, which respectively increases to 80% and 70% of the design  
 521 flow. Based on the amplitude and time of flow changes at the headworks, four operating modes  
 522 are planned. For operating modes 1 and 2, the gate opening needs to be reduced, whereas for  
 523 operating modes 3 and 4, the gate opening needs to be enlarged. Detailed parameters of the  
 524 operating modes are shown in Table 2.

525

526 Table 2. Parameters for water flow changes in the main canal under different operating modes

Operating mode	flow change at headworks		Time of flow changes at headworks	Time of gate opening changes	Time of flow changes at outlets	Scheduling strategy	Computing model
	starting time	ending time	(min)	(min)	(min)		
1	70%	50%	10	10	10	Sequential control	JPWSPC-PC
						Synchronized control	JPWSPC-PC
						Temporal sequence control	JPWSPC-PC
2	70%	10%	30	30	30	Sequential control	JPWSPC-MPI
						Synchronized control	JPWSPC-MPI
						Temporal sequence control	JPWSPC-MPI
3	70%	80%	10	10	10	Sequential control	JPWSPC-PC
						Synchronized control	JPWSPC-PC
						Temporal sequence control	JPWSPC-PC
4	10%	70%	30	30	30	Sequential control	JPWSPC-MPI
						Synchronized control	JPWSPC-MPI
						Temporal sequence control	JPWSPC-MPI

527

528 In the above conditions, different scheduling strategies and computing models were used.

529 The total combinations included 12 scenarios, consisting of 12 different processes for gate

530 opening/closing. Through the Web service interface provided by the HydroMP platform, the

531 scenarios were submitted to the cloud end for calculation. Based on the feedbacks from the

532 calculation results, upstream water levels and the maximum amplitude of changes in gate

533 opening were evaluated. Gate opening/closing was fine-tuned accordingly before beginning the

534 next round of calculations. The number of adjustment was set to 10, and the optimal scenario

535 was selected among the last fine-tuned group of scenarios.

536

537 **5.3 Multi-scenario submission**

538 In addition to the backstage submissions, the PC terminal CloudHydro1D provides a user  
 539 interface for data editing, scenario submissions and result displays. After entering the "scenario  
 540 submission" GUI, the system lists, in real-time, all scenarios in the project and acquires the  
 541 model name that can be used for calculations according to the scenario type from the model  
 542 library in the HydroMP server. As the current scenario is a one-dimensional canal hydrodynamic  
 543 scenario, models that can be selected by the HydroMP server include CE-QUAL-RIV,  
 544 JPWSPC-SC and JPWSPC-MPI. During the scenario computing, CloudHydro1D calls the  
 545 GetProcess() interface for real-time access to computing progress and results, as shown in Figure  
 546 12. In Figure 12, the interface shows the time series of the average amplitude of upstream water  
 547 level at one outlet.

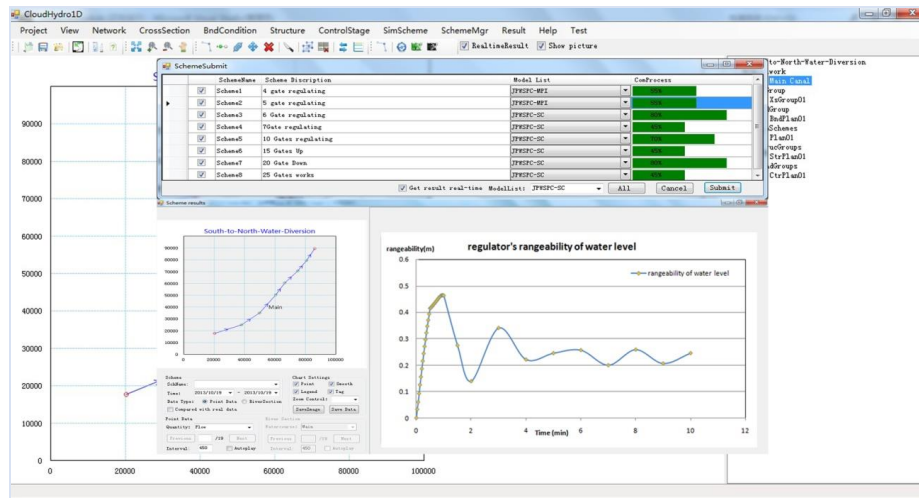


Fig. 12. Interface for scenario submission

## 5.4 Scenario results

551 In addition to a real-time display of calculation results during the computing, CloudHydro1D  
 552 also provides tools for the result demonstrations and analysis. The result demonstration tool can  
 553 be used to display the time series of flow and water level at a single point, water level animation  
 554 at a single cross section, branch flow profile and animation. The scenario analysis tool features a

555 function allowing the user to compare the results of different models and different scenarios. The  
 556 result analysis tool is a small tool for result evaluation and the user can first set specific  
 557 measured data at certain points, and then observe the automatic matching between the measured  
 558 data and the simulation results at these monitoring points through coordinate information.

559

560 **5.5 Test on the efficiency of HydroMP for concurrent simulation**

561 To test the capacity of the platform for concurrent processing, four different concurrent scenarios  
 562 were set: 3, 5, 10 and 20 users logged in simultaneously, respectively corresponding to 150, 500,  
 563 800 and 1000 concurrent scenarios submitting, and 800, 1200, 1500 and 1600 initialized  
 564 processes. The test results showed that the average response time was no longer than 0.4s, and  
 565 the average computing time of each single scenario was 4.5s, 4.8s, 5.2s and 5.32s, as illustrated  
 566 in Table 3. These results suggest that with the current hardware architecture and scheduling  
 567 methods, the platform has the capacity to process several hundred concurrent scenarios, yet the  
 568 response time increases notably after the number of concurrent scenarios submitted exceeds 500,  
 569 indicating there is competition for resources in the server where the HydroMP center  
 570 management service system is located. In the future, concurrency needs to be tested further,  
 571 especially on the processing capacity and hardware requirement of the HydroMP center after  
 572 expansion of HydroMP server.

573 Table 3. Response times in different concurrent submission scenarios

No.	Number of users	Number of concurrent scenarios	Number of initialized processes	Average submission response time (s)	Average computing time (s)
1	3	150	800	0.08	4.5
2	5	500	1200	0.25	4.8
3	10	800	1500	0.35	5.2
4	20	1000	1600	0.38	5.32

574

575 **6 CONCLUSION AND DISCUSSION**

576 Over the last three years, some researchers have recognized the promoting effect of cloud  
577 computing on water management and simulation computing, and have begun to develop a  
578 number of model integration and simulation service platforms based on the cloud computing and  
579 Web services. These platforms can be divided into three categories. One is a framework for data  
580 sharing and collaborative decision-making, e.g. HydroDesktop. The second type provides cloud  
581 service with a simulation function. These platforms use HPC Clusters similar to the one used in  
582 the present study for multi-use, multi-scenario concurrent computing. The third category is a  
583 platform based on model sharing and model coupling, e.g., the CSDMS system.

584 The cloud computing service mode proposed in the present paper shares certain  
585 commonalities with the above modes, e.g., use of HPC Cluster as a computing resource, and use  
586 of a Web service as a service interface. However, the method proposed in the present paper also  
587 has unique new characteristics, including the following: (1) it focuses on the dynamic integration  
588 of data exchange between the platform and the model, thereby providing the “single process,  
589 selection of multiple models” mode to the model users. This gives more choices to the users that  
590 need large-scale simulations compared with the other systems. The users can select the most  
591 appropriate model according to the scope, the computing times and other attributes of the  
592 different integrated models; (2) Regarding to the universal model integration, the HydroMP  
593 platform provides both a coarse-grained EXE integration approach and a program interactive  
594 integration method, using a standard component wrapper to implement the integration of model  
595 components as well as standardized communication between the model and the platform. Thus,  
596 the platform not only adapts to the future trend of multi-disciplinary model coupling and  
597 integration, but also enables the non-rewriting integration of legacy models, thereby providing

598 more choices for the model developers than other systems. (3) The HydroMP platform proposed  
599 in the present paper can be subjected to distributed deployment; through a HydroMP center, the  
600 load balancing between the various HydroMP servers is achieved, thereby ensuring computing  
601 resource scalability; (4) According to the time series model characteristics of hydraulic  
602 simulation in the HydroMP system, pause, restart and other methods are used to assist computing  
603 resources scheduling to meet the emergency scenario simulation. Using this method, the amount  
604 of computation required does not increase and the priority of emergency scenario is ensured.

605 Real-time optimization simulations of the SNWD and test results on platform performance  
606 show the robust model integration method, computing resources scheduling rule and the  
607 processing capacity of concurrent simulation. However, it should be noted that HydroMP needs  
608 improvement in security mechanisms and integration with other data and computing service  
609 platforms. Specifically, (1) A traditional mechanism, i.e., the password checking mechanism, is  
610 still used for the safe communication between the platform and the terminal, but cannot meet the  
611 safety requirements for data storage and transmission; (2) The integration between the HydroMP  
612 platform and other service platforms (i.e. HydroServer and other data sharing platforms) has not  
613 been realized; (3) The response speed for scenario simulation in HydroMP also depends on the  
614 network bandwidth. In the current testing of case study, the terminals and the HydroMP platform  
615 are in the same LAN, and the communication speed between the cloud and the terminal is 100  
616 Mb/s in theory.

617 The efficiency of parallelization heavily depends on the ratio between the computing load  
618 and the data access and communication. The larger the ratio is, the higher the parallelization  
619 efficiency could become. Compared with the 1D modelling, the ratios in 2D & 3D are much  
620 larger and thus we believe the latter should achieve higher parallelization benefit and thus have

621 more potential for the proposed HydroMP platform.

622       Currently our HydroMP system is not an open accessed one. However, a trial version is  
623 being commercialised and the relevant website is being constructed to collect user feedbacks  
624 aiming to further improve the HydroMP platform service.

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635

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