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Position Paper: Open Web-Distributed Integrated Geographic Modelling and Simulation to Enable Broader Participation and Applications

Min Chen[1,11,12], Alexey Voinov[2,13], Daniel P. Ames[3], Albert J. Kettner[4], Jonathan L. Goodall[5], Anthony J. Jakeman[6], Michael Barton[7,14], Quillon Harpham[8], Susan M. Cuddy[9], Cecelia DeLuca[10], Songshan Yue[1,11,12], Jin Wang[1,11,12], Fengyuan Zhang[1,11,12], Yongning Wen[1,11,12], Guonian Lü[1,11,12*]

1.Key Laboratory of Virtual Geographic Environment (Ministry of Education of PRC), Nanjing Normal University, Nanjing, PRC

2. Center on Persuasive Systems for Wise Adaptive Living (PERSWADE), Faculty of Engineering and IT, University of Sydney, AUS

3. Brigham Young University, Provo, Utah, USA

4. Community Surface Dynamics Modelling System (CSDMS), Institute of Arctic and Alpine Research (INSTAAR), University of Colorado, Boulder, Colorado, USA

5. Department of Engineering Systems and Environment, University of Virginia, Charlottesville, VA, USA

6. The Fenner School of Environment and Society, Australian National University, Canberra, AUS

7. School of Human Evolution and Social Change, Arizona State University, Tempe, Arizona, USA

8. HR Wallingford, Oxfordshire, UK

9. CSIRO Land and Water, Canberra, AUS

10. NOAA Earth System Research Laboratory, Boulder, USA

11. State Key Laboratory Cultivation Base of Geographical Environment Evolution (Jiangsu Province), Nanjing, PRC

12. Jiangsu Center for Collaborative Innovation in Geographical Information Resource Development and Application, Nanjing, PRC

13. Faculty of Engineering Technology, University of Twente, Netherlands

14. Center for Social Dynamics and Complexity, Arizona State University, Tempe, Arizona, USA

Corresponding author：Guonian Lü，gnlu@njnu.edu.cn

Abstract:

Integrated geographic modelling and simulation is a computational means to improve understanding of the environment. With the development of Service Oriented Architecture (SOA) and web technologies, it is possible to conduct open, extensible integrated geographic modelling across a network in which resources can be accessed and integrated, and further distributed geographic simulations can be performed. This open web-distributed modelling and simulation approach is likely to enhance the use of existing resources and can attract diverse participants. With this approach, participants from different physical locations or domains of expertise can perform comprehensive modelling and simulation tasks collaboratively. This paper reviews past integrated modelling and simulation systems, highlighting the associated development challenges when moving to an open web-distributed system. A conceptual framework is proposed to introduce a roadmap from a system design perspective, with potential use cases provided. The four components of this conceptual framework - a set of standards, a resource sharing environment, a collaborative integrated modelling environment, and a distributed simulation environment - are also discussed in detail with the goal of advancing this emerging field.

Keywords: Open; Web-Distributed; Integrated geographic modelling; Geographic simulation; Geographic Research

1. Introduction

The geographic environment is the surface on which human societies exist and thrive (Churchill and Friedrich 1968; Matthews and Herbert 2008). It is a comprehensive system consisting of natural, social, cultural, and economic factors and their interactions (Lin et al. 2013a). Geographic modelling and simulation have been extensively used to better understand the geographic environment and improve decision making (Demeritt and Wainwright 2005).

The objectives of geographic modelling are generally to analyze and better understand the evolving processes and interactions among the factors that constitute the geographic environment, and to build interpretable models that serve decision-makers (Wei et al. 2005; Xu et al. 2017). In short, geographic modelling is a representation of geographic entities, events, interactions and their logical consequences (Smyth 1998). Following the sequence of "representation-simulation-prediction", geographic simulation can be regarded as an application step of geographic modelling (Batty 2011), and it can be conducted to reflect and predict specific geographic patterns and processes (Lin et al. 2015a; Zhang et al. 2016; Goodchild 2018; Rossi et al. 2019). Geographic modelling and simulation can contribute to geographic research and decision making; for instance, numerical geographic experiments can be conducted instead of real-world geographic experiments which can be costly, time consuming, or practically infeasible (Lin et al. 2013b; Lin et al. 2015b; Chen et al. 2018). Doing so, the influences of changes to geosystem factors can be assessed (e.g., Benenson and Torrens 2004).

To date, researchers worldwide have developed numerous geographic simulation models for different applicable areas, at different spatial and temporal scales, and for different processes (e.g., hydrological [e.g., Liu et al. 2014, 2016; Lai et al. 2016, 2018; Zhu et al. 2019; Salas et al. 2020], atmospheric [e.g., Zhang et al. 2014; Yan et al. 2016; Ning et al. 2019], geomorphological [e.g., Shobe et al. 2017; Barnhart et al. 2018; Reichenbach et al. 2018; Batista et al. 2019; Rossi et al. 2019; Broeckx et al. 2020]). However, these are typically single-domain and single-scale models, and as such, they have limited capacity for simulating comprehensive geographic phenomena (Lu et al. 2011; Harpham et al. 2014; Gianni et al. 2018). For example, when studying the socioenvironmental impacts of intense precipitation in a watershed on areas located downstream, several dynamic processes are involved. These include precipitation, infiltration, soil saturation, surface and subsurface runoff, streamflow, and flow-routing, over the background of a static physical environment (slope, elevation, river network, landcover, etc.) and human structures. Furthermore, in comprehensive decision-making, social settings should also be considered, which might include, for example, the distribution of endangered groups and individuals and potential evacuation strategies. Thus, it is difficult to incorporate all the relevant physical and socioenvironmental process dynamics comprehensively in a single model. Such a model would require a wide variety of disciplines and could quickly fall behind the latest developments in each discipline; indeed, such a model would likely be too cumbersome to maintain. From this perspective, integrated modelling provides a potentially useful reference to enable comprehensive simulations (e.g., Oxley et al. 2004; Peckham et al. 2013, Peckham 2014). As a type of integrated modelling (EPA, 2007, 2008a, 2008b), integrated geographic modelling can be defined as employing a set of interdependent resources (e.g., geographic simulation models, geographic data) that together form an appropriate geographic modelling system.

Focusing on this research topic, and bearing in mind the trend towards open science (e.g., Woelfle et al. 2011; Nosek et al. 2015), this article lays out a vision for an open web-distributed integrated geographic modelling and simulation approach that encourages wide participation and combines different disciplines in one framework. Here, the term "open" implies that (1) modelling and simulation resources (models, data, and even computational resources) can be openly shared, discovered, and accessed among communities; (2) integrated modelling and simulation tasks can be openly performed using these open resources; and (3) the open community can grow and expand organically through a well-defined extensibility paradigm. Moreover, the term "web-distributed" reflects a technical feature associated with achieving the target of openness in an internet-based environment.

The motivation and content of this paper draws from an early design concept of Open Geographic Modelling and Simulation Systems (OpenGMS), later modified and extended through a series of workshops and conference sessions on open modelling (Table 1). These events were organized to explore an international open science and community around forming an ecosystem of reusable and interoperable models for studying complex interactions between humans and the environment. This paper mainly focuses on supporting openness through the accessibility and usability of geographic modelling and simulation resources as web-distributed services, thereby introducing a roadmap for implementation.

Table 1 Related international events

Date	Address	Topic	Form
2017/8/17-19	Nanjing, China	International Workshop on Open Geographical Modelling and Simulation	Workshop
2018/6/24-28	Fort Collins, USA	The 9th International Congress on Environmental Modelling and Software (iEMSs 2018) -- Open Socio-environmental Modelling and Simulation	Session
2018/6/29-30	Colorado, USA	Open Modelling Foundation: An international alliance for scientific computational modelling standards	Workshop
2019/5/18-20	Nanjing, China	The 1st Regional Conference on Environmental Modelling and Software (Asian Region)	Conference
2019/12/2	Canberra, Australia	The 23rd International Congress on Modelling and Simulation (MODSIM2019) -- Cloud and web applications for environmental data analysis and modelling	Session
2019/12/4	Canberra, Australia	Workshop of Open Modelling Foundation: Standards for Model Documentation	Workshop

The remainder of this article is structured as follows. Section 2 summarizes several existing integrated modelling and simulation systems and their openness levels, along with a discussion of their corresponding development challenges. A conceptual framework is proposed in Section 3 from a system design perspective that includes four components: (i) a set of standards, (ii) a resource sharing environment, (iii) a collaborative integrated modelling environment, and (iv) a distributed simulation environment. Section 4 provides use cases based on the combination of different components. To move toward implementation, each component and its development roadmaps are discussed in detail in Section 5. Finally, conclusions and suggestions for further research are presented in Section 6.

2. Existing integrated modelling and simulation systems

2.1 Features of the existing integrated modelling and simulation systems

Beginning in the early 1990s, bolstered by continually improving database management systems, model management strategies and corresponding decision-support systems have undergone accelerated development (e.g., Dolk 1993, Dolk and Kottemann 1993; Oxley et al. 2004). Integrated modelling at this time was mainly at the operational level, and models were integrated or linked through hard-coded approaches (Dolk and Kottemann 1993). Later, more logical and semantically clear chains were developed that enabled model assembly and integration; thus, more component-based integrated modelling approaches and corresponding modularized model solutions were introduced (Argent et al. 2004, 2006). Table 2 lists some well-known component-based systems/tools (Table 2). These component-based systems are characterized by object-oriented design methods, including the encapsulation of analytical codes and computational application programming interfaces (APIs) to standardize interoperability among model components. While these software systems have lowered many barriers to model integration, it remains difficult to integrate models across different hardware and software systems, computational environments, and system architectures (Granell et al. 2013a), and there are still barriers to model sharing among the existing "model clusters" (Zhang et al. 2019).

Table 2 Some typical component-based systems (in no particular order)

Name	Features	References
The Community Surface Dynamics Modeling System (CSDMS)	CSDMS is a diverse community of experts promoting the modelling of earth surface processes by developing, supporting, and disseminating integrated software modules that predict the movement of fluids, and the flux (production, erosion, transport, and deposition) of sediment and solutes in landscapes and their sedimentary basins.	Peckham et al. 2013
Spatial Modelling Environment (SME)	SME is an integrated environment for high performance spatial modelling which transparently links icon-based modelling tools with advanced computing resources to support dynamic spatial modelling of complex systems	Maxwell and Costanza 1997a, 1997b

Dynamic Information Architecture System (DIAS)	DIAS is a flexible, extensible, object-based framework for developing and maintaining complex multidisciplinary simulations of a wide variety of application contexts.	Simunich et al. 2002; Hummel and Christiansen 2002
Common Component Architecture (CCA)	CCA supports parallel and distributed computing as well as local high-performance connections between components in a language-independent manner.	Kumfert et al. 2006; Bernholdt et al. 2006
Earth System Modelling Framework (ESMF)	ESMF is based on the principle that complicated applications are broken into smaller components with standard calling interfaces. A model component that implements the ESMF standard interface can communicate with the ESMF shell and inter-operate with other models.	Hill et al. 2004; Collins et al. 2005; DeLuca et al. 2012
Object Modelling System (OMS)	OMS allows model construction and model application based on components. OMS v3.+ is a highly interoperable and lightweight modelling framework for component-based model and simulation development on multiple platforms.	Skrlisch et al. 2005; Ahuja et al. 2005
Open Modelling Interface (OpenMI)	The OpenMI compliant components can run simultaneously and share information at each timestep making model integration feasible at the operational level.	Moore and Tindall 2005; Gregersen et al. 2005, 2007; Harpham et al. 2014
FluidEarth	The FluidEarth platform is based on the concept of writing a 'wrapper' for software codes, and on providing a generic linking mechanism so that any model can be linked to any other.	Harpham et al. 2014
System for Environmental and Agricultural Modeling; Linking European Science and Society (SEAMLESS)	The SEAMLESS project developed science and a computerized framework for integrated assessment of agricultural systems and the environment.	Janssen et al. 2011; Van et al. 2008
FRAMES	A feed forward modelling framework, employs the component-based approach and incorporates data dictionaries for data exchange. Wrappers are written for each component to read and write data to the dictionaries. The framework then manages transfer of data between components during runtime through an inter-component communication API.	Whelan et al. 2014
Common Modelling Protocol (CMP)	CMP defines a transport protocol and describes a message based mechanism for packing and unpacking data, executable entry points, and a set of defined messages to transfer variables and events from one model and/or component to others involved in a simulation.	Moore et al. 2007
BioMA/APES	The focus of BioMA is to run integrated modelling products against spatial databases. It is a direct result from the previous component-based framework called APES, which is aimed to estimate the biophysical behavior of agricultural production systems in response to the interaction of weather, soil and agro-technical management options.	Donatelli et al. 2010
The Invisible Modelling Environment (TIME)	TIME simplifies the task by providing a high level, metadata driven environment for automating common tasks, such as creating user interfaces for models, or optimizing model parameters. This reduces the learning curve for new developers while the use of commercial programming languages gives advanced users unbridled flexibility.	Stenson et al. 2011

The Library of Hydro-Ecological Modules (LHEM)	LHEM (http://giee.uvm.edu/LHEM) was designed to create flexible landscape model structures that can be easily modified and extended to suit the requirements of a variety of goals and case studies.	Voinov et al. 2004
JGrass-NewAge	JGrass-NewAge is a system for hydrological forecasting and modelling of water resources at the basin scale. It has been designed and implemented to emphasize the comparison of modelling solutions and reproduce hydrological modelling results in a straightforward manner.	Formetta et al. 2014
Science and Policy Integration for Coastal System Assessment (SPICOSA)	The multi-disciplinary project SPICOSA used a common, component-based simulation framework for environmental modelling.	de Kok et al., 2015
Tarsier	The framework facilitates fast, powerful model development by providing a system for implementing separate model elements as autonomous modules, which may then be tightly and flexibility integrated. It is object-oriented, with integration of modules achieved through the sharing of common objects (and was the precursor of TIME)	Watson and Rahman, 2004
Artificial Intelligence for Ecosystem Services (ARIES)	A web application to assess ecosystem services and illuminate their values to humans in order to make environmental decisions easier and more effective	Villa et al. 2009 Bagstad et al. 2013.

Recently, the development of Service Oriented Architecture (SOA) and cloud computing has promoted web-based (including service-based and resource-based) model sharing technologies (e.g., Feng et al. 2009; Fook et al. 2009; Castronova et al. 2013a; Granell et al. 2013b; Wen et al. 2013; Wen et al. 2017), related web-based simulation resource management systems (e.g., HydroShare, [Horsburgh et al. 2016; Morsy et al. 2017]) and distributed model integration strategies (e.g., Yue et al. 2016; Belete et al. 2017) have emerged. Object Modelling Systems (OMS) upgraded its OMS3 release to scale models by capitalizing on cloud infrastructure and SOAs and launched its Cloud Services Innovation Platform (CSIP) (David et al. 2013). Meanwhile, the Open Geospatial Consortium (OGC) adopted OpenMI 2.0 as a standard to improve the sharing of models, and researchers have extended this standard for the integration of models using service-based modelling (e.g., Castronova et al. 2013b; Buahin and Horsburgh 2015; Harpham et al. 2019). The Community Surface Dynamics Modelling System (CSDMS) developed pymt, an open source python package that provides the tools needed to run and couple models that expose the Basic Model Interface (BMI) (Hutton and Piper, 2020). Besides preforming simulation utilizing pymt on a HPC or desktop, cloud based access to Jupyter Notebooks make it possible to couple and run models in the pymt framework through the web.The Open Geographic Modelling and Simulation System (OpenGMS) has provided a platform where users can explore and share resources related to geographic modelling and simulation, thus forming an open community where researchers can reuse resources for geographic exploration online (e.g., Wen et al. 2013; Zhang et al. 2019; Chen et al. 2019; Wang et al. 2020). Clearly, model sharing and integration over the web is a growing field, particularly in environmental and geographic modelling, allowing integrated modelling to be conducted in unique and innovative ways, spanning the boundaries of software, hardware, research domains, and even crossing sociopolitical boundaries (Granell et al. 2013a). Com Using the three criteria for "Open" described above, i.e. (1) open resource sharing, (2) open integrated modeling and simulation and (3) open community, Table 3 lists some typical web-based systems/tools and shows the extent to which they support openness.

Table 3 Web-based platforms/systems

	Open resource sharing	Open integrated modelling and simulation	Open community	Reference
Esri ArcGIS Online	√(part, commercial-based)	√(part, commercial-based)	√(part)	https://www.esri.com/en-us/arcgis/products/arcgis-online/overview
CyberGIS	√		√	Li et al. 2013; Nyerges et al. 2013
OpenGMS	√	√(part)	√	Chen et al. 2013; Chen et al. 2019; Zhang et al. 2019; Wang et al. 2020
HydroShare	√	√(part)	√	Tarboton et al. 2014; Horsburgh et al. 2016; Gan et al., 2020
SWATShare	√	√(part)	√	Rajib et al. 2014, 2016
CSDMS	√	√(part)	√	Peckham et al. 2013; Peckham and Goodall et al. 2013
OpenMI	√(Part)	√(part)	√	Moore and Tindall 2005; Gregersen et al. 2007; Harpham et al. 2019
(Hydrologic Information System) HIS	√		√	Goodall et al. 2010; Castronova et al. 2013
AWARE		√(part)		Granell et al. 2010
eHabitat		√(part)		Dubois et al. 2013
Group On Earth Observations (GEOSS) Platform	√			Christian 2005; Butterfield et al. 2008; Giuliani et al. 2013
Geospatial Data Cloud	√			https://www.gscloud.cn/
National Special Environment and Function of Observation and Research Station Shared Service Platform	√			http://www.crensed.ac.cn/portal/
Tethys Platform: e.g., SWATOnline	√		√	Swain 2015; Swain et al. 2015
The Hydrologic and Water Quality System (HAWQS)	√			Yen et al. 2016

Despite the many achievements of these systems, only a few of them fully support openness in integrated geographic modeling and simulation, a key 'open' criteria. This demonstrates and highlights the urgent need to address this gap.

2.2 Challenges with open integrated geographic modelling and simulation

To move toward open integrated geographic modelling and simulation, relevant challenges need to be carefully analyzed before designing an appropriate architecture. Other studies have reviewed some of the challenges related to integrated modelling. For example, Voinov and Cerco (2010) discussed the heterogeneity of models and related data transformation; Kelly et al. (2013) presented the challenges with choosing model integration methods; Sutherland et al. (2014, 2019) analyzed the challenges associated with universally applying integrated modelling technologies from a required systematic basis, and Elsawah et al. (2020) highlighted the eight key challenges to overcome in socio-environmental systems modeling. This article focuses on the challenges associated with the open web approach.

2.2.1 From a resource perspective

The fundamental challenge from a resource perspective is determining how to properly describe a wider range of modelling and simulation resources to bridge different resource users and providers. If providers can construct clear and concise descriptions of their resources, then users can reuse these resources more effectively and correctly in a given network (Harpham and Danovaro, 2015). However, openness will inevitably introduce an even wider array of variation, and traditional standards cannot bridge all of the possible variations and gaps. It is difficult to design standards that can carefully balance flexibility with depth and breadth of detail. Standards that seek to cover every eventuality will be too complicated to use; and standards that are too specific will solve few integration problems.

2.2.2 From a resource provider perspective

Resource providers are responsible for providing geographic simulation models, data and servers for online reuse and integration. Several challenges exist for resource providers who wish to participate in open modelling tasks. Here, we summarize these challenges based on the processes that occur before, during and after sharing.

First, motivation is a determining factor that stimulates people to act. Rewarding provider(s) is a key element in motivating people or institutions to share resources. Therefore, designing a suitable business model to provide the incentive for the implementation of a vision is a challenge. An incentive should not be overly complex but should provide encouragement and thus enhance the sustainability of the resource sharing and reuse communities.

A second challenge is determining how to make resource sharing as convenient for resource providers as it is for users. From this perspective, the user experience is an important factor that affects the intentions of resource providers. Usable and user-friendly tools are still needed to facilitate tasks such as model encapsulation, data preparation, and serve sharing in a standardized way.

Last, honoring ownership and copyright policies is another challenge. Although various types of licenses (e.g., permissive and copyleft) have been designed for open source projects from a legal perspective, more strategies are needed to protect providers' intellectual property. For example, while many open source software codes are provided under well-established open source licenses such as MIT, BSD, GPL or MPL, a lack of awareness (or disregard for license conditions) may still result in infringements of intellectual property.

2.2.3 From a resource user perspective

Resource users are practitioners using modelling and simulation resources in a web environment. There are two main categories of users to consider: (i) experts, who are knowledgeable about certain aspects of the topic, but not necessarily about all of the various processes and scales, and (ii) general stakeholders, individuals and groups, who may be impacted by the system considered, but might know less about it from a scientific perspective, though they could have ample indigenous and intuitive knowledge about the topic. Obviously, these two types of users will possess different sets of user requirements, the handling of which may be a significant challenge.

A second challenge is finding the most suitable resources among the numerous resources available online. When simulation resources (including models, data, and servers) are openly shared, it can be daunting for users to find resources easily and timely when the bulk of typical or customized resources are widely available by different resource providers.

The third challenge is properly using resources in the web environment to complete open integrated geographic modelling and simulation tasks, compared to the usage of centralized systems. Several points should be considered, including how to access and reuse resources through the network, how to perform collaborative modelling tasks following typical modelling processes, and how to manage integrated simulation processes when the resources are distributed on the web. This includes, for example, data management and transfer through the web and the real-time monitoring of online servers during model execution.

3. A conceptual framework for open web-distributed integrated geographic modelling and simulation

As previously mentioned, some typical characteristics distinguish open web-distributed integrated geographic modelling and simulation systems from other modelling systems. First, with open web-distributed systems, resources can be shared and accessed through the web for wide reuse. Second, entire geographic model integration and simulation processes can be implemented and adjusted along with distributed resources through the web environment. Finally, users can join in geographic exploration and idea exchange more easily with lower thresholds than they face with some centralized or closed systems.

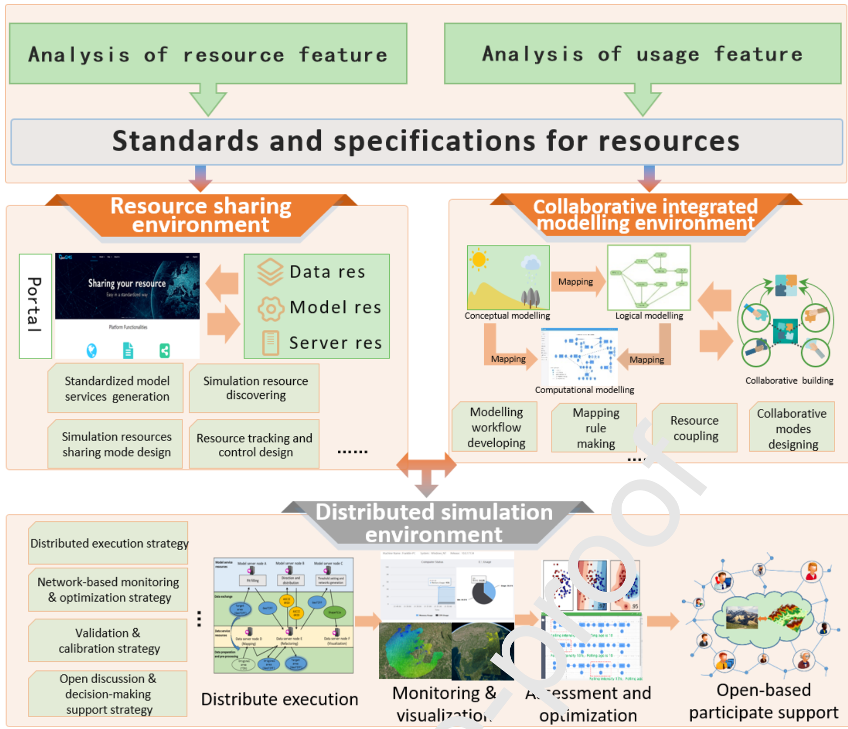

Figure 1 Conceptual framework for open web-distributed integrated geographic modelling and simulation

To achieve these goals, a conceptual framework is proposed (Figure 1). The conceptual framework for open web-distributed integrated geographic modelling and simulation consists of four main components: (i) standards and specifications for resources, (ii) a resource sharing environment, (iii) a collaborative integrated modelling environment, and (iv) a distributed simulation environment. The main functions are introduced sequentially in this section, and the detailed implementation road maps are illustrated in Section 5.

First, the precepts of open web-distributed integrated geographic modelling and simulation should be founded on the standards and specifications for resources in the network. Using standards and specifications will help to standardize heterogeneous resources, including models, data, and server resources, thus facilitating resource sharing abilities and knowledge exchange capabilities for a broader user group. Standards and specifications will also benefit model interoperability between modelling platforms during the entire integrated modelling and distributed simulation processes (https://csdms.colorado.edu/wiki/Interoperability). Some standards and specifications have been formulated for specific domains. For example, Crosier et al. (2003) presented a six-stage method for describing environmental models on the web, and Grimm et al. (2006, 2010) and Müller et al. (2013) proposed the ODD standard for agent-based models. Projects such as HydroShare used the Open Archive Initiative's Object Reuse and Exchange (ORI-ORE) standard to describe their hydrological models and data (Lagoze et al. 2007; Tarboton et al. 2014; Horsburgh et al. 2016), and Schema.org and Geoscience Cyberinfrastructure for Open Discovery in the Earth Sciences (GEOCODES) of the USA-

NSF supported EarthCube program are engaged in developing data standards and web standards for resources. However, the standards and specifications for broadly describing geographic modelling resources are still under discussion (Harpham and Danovaro, 2015). Several issues may need to be considered in the process of design: (1) What should such a standard include? (2) What are the minimal requirements? (3) How will modelers who meet this standard be recognized? (4) How can model developers/scientists be incentivized to meet these standards? (5) How should these standards be reviewed, adopted, and disseminated? Many of these design challenges have not yet been adequately addressed, but at least, resource standards and specifications should be formulated by analyzing the features of both resources and usage.

Second, the resource sharing environment should support the open sharing of various types of reusable resources. Sharing and reusing simulation resources can bridge the gap between resource providers and resource users, avoid wasting resources (Granell et al. 2013a), and benefit integrated modelling and simulation (e.g., Frakes et al. 2005; Laniak et al. 2013; Belete et al. 2017). In such an environment, strategies are needed to support resource sharing and reuse, including standardized model services generation, simulation resource discovery, design of resource sharing modes, and authentication and access control methods. A standardized model services generation strategy aims to reduce the heterogeneity of different model resources. From this perspective, sharing geographic simulation models as services is a feasible way to improve the efficiency of model reuse on the web (Lu et al. 2019). Simulation resource discovery strategies foster identifying and accessing individual and suitable resources (including models, data, and servers). The design of resource tracking and control strategies is intended to provide protection for resources and their providers, with the objective of ensuring security and privacy for networked resources. The design of a simulation resource-sharing mode aims to promote communication through virtual communities or networks, to facilitate use and provide feedback and to encourage different resource providers to contribute their resources (Zare et al. 2020).

Third, the collaborative modelling environment supports building integrated models as a team through the internet, by taking full advantage of existing shared resources. The collaborative modelling environment proposed in this paper is intended to provide a workspace for integrated modelling tasks suitable for geographically distributed experts, who each may represent different domain specific research expertise, to conduct specific modelling tasks. At a minimum, the collaborative modelling environment should support the basic function of integrated modelling; that is, it can support combining resources together to build a computational solution. In this environment, the modelling workflow can be parsed into several stages, e.g., from conceptual to logical modelling and then to computational modelling (as explained in more detail in Section 5.3). The conceptual modelling process can be regarded as a step in parsing the geographic problem to be solved and categorizing the relationships among different geographic entities and processes. The logical modelling process can use tools such as process-flow diagrams, UMLs or flow charts to describe the inner structure (e.g., nested and combined sub model component structures) and behavior (e.g., when to run which sub model) of the integrated models. The computational modelling finally forms an integrated computational solution combined with appropriate resources. A mapping schema with rules needs to be developed to advance the mapping process from the conceptual model to the logical model and then to the computational model. To generate a real computational model, existing shared resources must be connected by resource coupling strategies. The new model that is built during this step could then also be reused in resource sharing environments. Within the entire process, collaborative-mode design strategies are necessary to facilitate open web-distributed geographic modelling among distributed users to investigate comprehensive geographic challenges. As such, participants, even if they have no modelling resources at hand, can work collaboratively through the web to design new geographic conceptual models, analyze the logic underlying each geographic process, and link different model services and data resources together to form an integrated model.

Finally, the distributed simulation environment can be regarded as a workspace for implementing integrated geographic computational models. As resources that form the integrated model may be distributed in the internet, the distributed simulation environment should be designed to support the execution and control of all geographic simulation processes with distributed resources. From this perspective, the strategies for distributed execution of resources should be considered first. Then, network-oriented monitoring and visualization must be included to help users control the simulation processes and understand the results. To ensure the quality of modelling and simulation, online assessment (e.g., calibration, validation, goodness of fit) is also needed, and if the results are not satisfactory, optimization (e.g., replace resources, adjust simulation processes) may be required. Last but equally important, to support broad participation, involvement of (e.g., decision makers and others interested in the geographic problems being addressed) with open discussions on creating decision-making tools and strategies must be part of the design process.

4. Use cases of open web-distributed integrated geographic modelling and simulation systems

The process for understanding a system normally starts with the cognition of its use cases (Goodchild, 2008, 2012). To improve the recognition of open web-distributed integrated geographic modelling and simulation systems, this section focuses on illustrating some use cases in different application scenarios. Based on the combination of the different components of the proposed conceptual framework, the main use cases can be illustrated as shown in Figure 2.

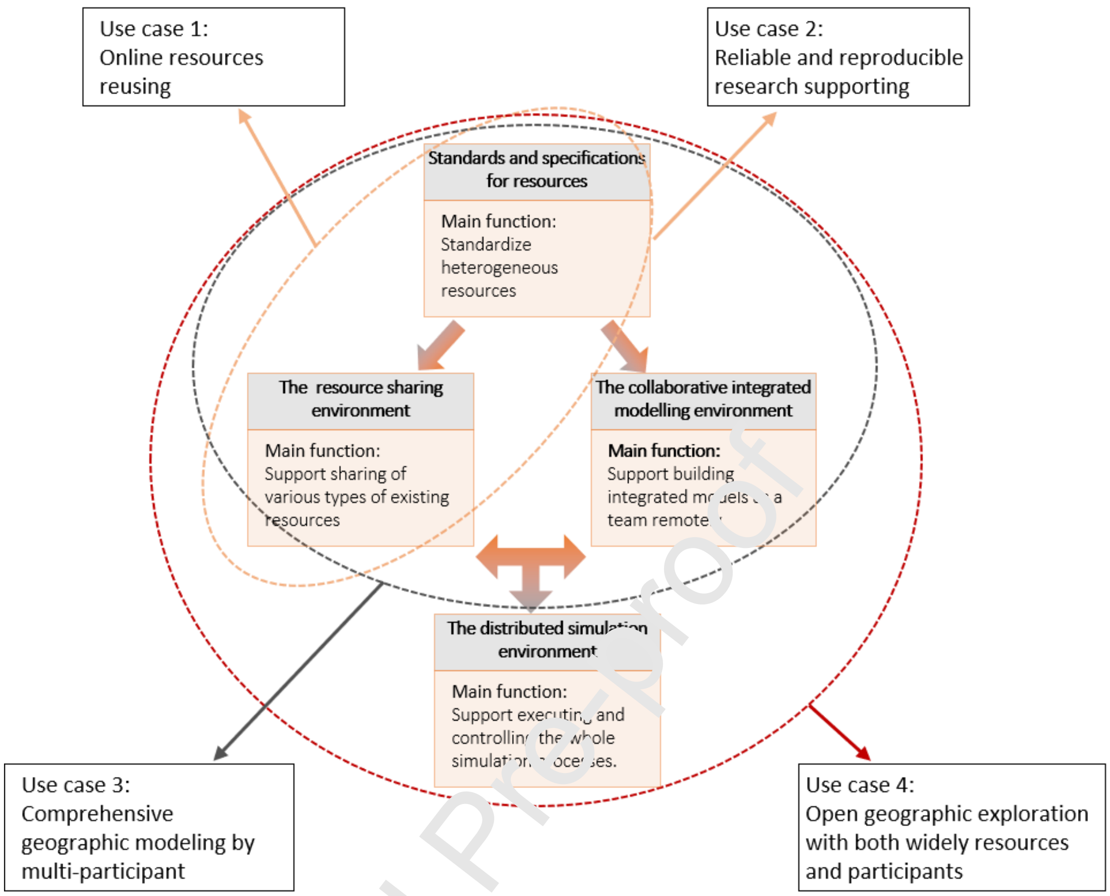

Figure 2 User cases of open web-distributed integrated geographic modelling and simulation at different levels

4.1 Online resource sharing

Online resource sharing is a basic use case. Enabling modelling and simulation resources to be searchable, accessible, interoperable, reusable and able to be integrated through the internet is a worthwhile effort that can allow widespread usage (Wang 2010; Goodall et al. 2011; Wang et al. 2013; Harpham et al. 2017; Lu et al. 2019). Combined with standards and a resource sharing environment, at the very least, the duplication of efforts would be reduced, thus saving resources. When an individual or team wants to conduct a specific simulation, they could employ these resources directly for their research without investing in the redevelopment of a set of models, or spending resources on software installation or hardware preparation.

4.2 Reliable and reproducible research support

Accelerating transparent resource reuse is a meaningful way to support reliable and reproducible research (Sui 2014; Essawy et al. 2018). With the open sharing approach, the operating steps of simulation resources can be tracked and accessed through the internet. Consequently, others would be able to follow the steps in previously reported simulations, ensuring that they could interactively repeat the experiments and improve the reliability of the initial research—not just read the reported results in scientific publications or project reports.

Making available operating steps of simulation resources would be beneficial for both resource promotion and trust enhancement.

4.3 Comprehensive geographic modelling by multiple participants

The collaborative integrated modelling environment allows the integrated modelling process to be discussed and coordinated by distributed experts and stakeholders from a wide variety of domains as a team. Collaboration is meaningful to scientific research, which involves complex problems, rapidly changing technology, and dynamic knowledge growth (Hara et al. 2003). For an integrated geographic modelling study, participants may be physically distributed, and not all have detailed, individual process knowledge of all processes that are involved in the comprehensive modelling scenario. For example, when modelling air pollution for the Yangtze River Delta, a meteorologist may have expertise on the meteorological conditions and processes, an air pollution expert may know how to analyze pollutant sources, and a geomorphologist may know well how to incorporate and adequately model the underlying interacting surfaces. Even though they may be located in different parts of the world, with the collaborative integrated modelling environment, and the previous described two components, such a team could collaboratively employ and integrate a set of modelling resources from the internet to represent such comprehensive geographical phenomena. These experts might even replace or adjust components to explore different solutions and improve the results without physically meeting.

4.4 Open geographic exploration with broader resources and participants

An open web-distributed strategy would effectively provide chances for both experts and general stakeholders to engage in geographic exploration tasks (Chen et al. 2019). Foldit (Cooper et al. 2010), for example, was developed to encourage the public to engage in protein assembly tasks. The unexpected success of this approach shows that involving the public has the potential to solve extremely complex problems (Cooper et al. 2010; Khatib et al. 2011). Such crowdsourcing-based research methods have been increasingly applied in bioinformatics (Good and Su 2013). Geographic research includes topics of great concern to stakeholders who care about the changing of geographic environment around them. When modelling and simulation process and results can be accessed openly, general stakeholders will have more opportunities to conveniently explore the geographic environment according to their interests. These stakeholders could combine a variety of resources to explore geographic processes or conduct different geographic simulations. More geographic knowledge could also be collected and contributed from stakeholders to improve the overall understanding of complex geographic processes (Haklay 2013; Bergez et al. 2013; Johnson et al. 2015). Sometimes, geographic simulations, especially microscale simulations, require more precise and real-time data (Sagintayev et al. 2012; Eisman et al. 2017; Sun et al. 2018; Barker and Macleod 2019); thus, volunteered geographic information (VGI)-based data can be collected and used with the distributed simulations, thus benefitting stakeholders by making them more aware of the local environments (e.g., investigating sound pollution around their house). By doing this, the action caused by environmental awareness can be refreshed, and the data can be continually collected for additional simulations (Chen et al. 2017).

5. Detailed road maps for each component in the conceptual framework

5.1 Standards and specifications

In the geographic domain, large quantities of geographic simulation models and data resources exist, and they have been developed and shaped by different disciplines (Lu et al. 2019). The heterogeneity of these resources is not only due to the intrinsic properties of the resources themselves but also due to the methods used to describe the corresponding metadata, semantics, spatial references, etc. (Yue et al. 2015). Moreover, these models and data resources may have been created and used in different operating systems (e.g., Windows, MacOS, and Linux) (Belete et al. 2017). The heterogeneity of these resources may lead to difficulties in: (1) reusing shared resources, (2) integrating shared resources (Jiang et al. 2017), and (3) sharing ideas among modelers (Heuschele et al. 2017). Therefore, standards and specifications need to be established before resources are shared and integrated.

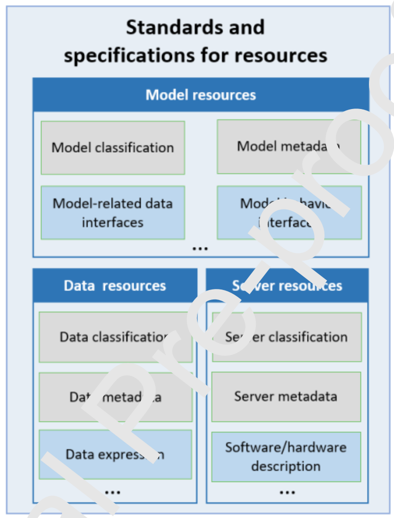

Figure 3 Standards and specifications for geographic modelling and imulation resources

With the continued emergence of shared resources on the web, classification and metadata standardization is important, thereby allowing users to discover, locate and access their target resources. If these resources are classified properly, then they can be easily found and accessed. Metadata specifications provide a way to describe these simulation resources in a standardized and unambiguous way for reuse and interoperation. In addition to classification and metadata, other standards and specifications should also be designed for each resource type, as shown in Figure 3.

Beyond classification and metadata, at least two other types of standards for model resources should be considered. First, different models have different data requirements, which can be represented using model-related data interfaces. Model-related data interfaces mainly describe the input/output (I/O) of models, including any limits on the amounts of I/O data, and the related semantic and spatial reference information of the I/O data. Second, different models have different behavior interfaces. The behavior interfaces refer to the internal module structures and the external commands needed to invoke models and model features. For example, complex integrated geographic simulation models may consist of sub-modules; thus, these integrated models may have their own methods for assembling these modules. Moreover, different models may have different invocation methods (e.g., EXE files and JAR files have different invocation methods) and invocation sequences (e.g., the execution of one model may depend on the output of another model). Additionally, some models may require external input to continue running, and so on. These heterogeneous model behaviors may need to be described in a standard way to help users implement these models after they are shared as resources. Therefore, standards to describe model-related data interfaces and behavior interfaces are important to support "model standardization".

For data resources, due to the heterogeneity of multisource geographic data and the potential variety of model data requirements, barriers still could exist between geographic simulation models and the related data resources (Lü et al. 2015). To prepare a model with corrected data resources, in addition to classification and metadata standards, a data expression standard should be proposed that can universally describe data resources. Yue et al. (2016) suggested that a data expression standard should include the data structure, data semantics, units, spatial references, etc., thus providing a solid basis for model invocation and data exchange. Some examples are the data representation model (DRM) of the Source for Environmental Data Representation & Interchange (SEDRIS) project (http://www.sedris.org/) and the universal data eXchange (UDX) model of the OpenGMS platform (Yue et al. 2015).

Server resources, which can be distributed in the network, are the hosts of model(s) and data resources. The server capacity and performance are crucial factors in model invocation and data scheduling. To describe a server, both a software description, which includes the operating environment, library dependencies, etc., and a hardware description, which includes disk capacity, memory size, CPU performance, etc., should be considered when designing standards for server resources (Wen et al. 2017).

5.2 Resource sharing environment

A resource sharing environment aims to bridge the gaps between geographic simulation resource providers and users. To create this environment, there are at least four key items that should be considered: resource sharing, resource discovery, resource tracking and control, and share-oriented aided design (see Figure 4).

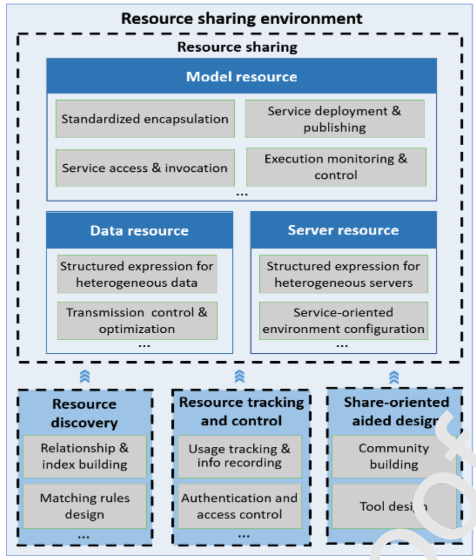

Figure 4 Key points to resource sharing environment

5.2.1 Resource sharing

Supported by resource standards and specifications, the goal of resource sharing is to provide carriers (e.g., portals), strategies (e.g., model service generation strategies) and tools to help resource providers share their resources.

Because web services support remote reuse and allow more participants to join conveniently (Zhang et al. 2019), we are primarily interested in sharing models as web services.In this case, standardized encapsulation, service deployment and publishing, service access and invocation, and model execution monitoring and control must all be considered to support resource sharing. Standardized encapsulation refers to methods for wrapping model resources to form universal services in the network. Castronova et al. (2013a) and Qiao et al. (2019) provided paradigms based on the Web Processing Service (WPS) protocol. Zhang et al. (2019) presented a service-oriented strategy for model wrapping in the OpenGMS platform on the web, CSDMS developed the BMI interfaces to wrap models such that they can be coupled in a framework (Peckham et al. 2013), and the Open Modelling Interface 2.0 (OpenMI) (Donchyts et al. 2010) and Web Process Standard 2.0 (Müller and Pross, 2015), have been designed and implemented to "wrap" models to expose them as web services. Service deployment and publishing involve methods designed for deploying and publishing models as services. Several related studies can be referenced to design such methods. For instance, Rubio-Loyola et al. (2011) presented a scalable service deployment method for an open software-defined network infrastructure; Smaragdakis et al. (2014) presented a scalable and distributed solution for optimizing resource deployment in the network; and Wen et al. (2017) proposed a service-oriented deployment strategy for sharing geo-analysis models in a web environment. Service access and invocation are aimed at providing methods or tools such that users can access and invoke model services; these include both user interface (UI) and software development kit (SDK) approaches. Execution monitoring and control require methods or tools to help users obtain real-time model status at runtime and interact with the models. MonPaas (Calero et al.

2015), a service-oriented monitoring method in which each cloud consumer is allowed to customize the monitoring metrics, can be used as a reference.

For data resource sharing, structured expressions for heterogeneous data, and control and optimization of data transmission are important. A structured expression of heterogeneous data aims to provide methods for universally describing heterogeneous data; such expressions benefit users' understanding and communication and are crucial for further data conversion and model integration. Yue et al. (2015) presented the UDX model to describe data structurally, enabling users to better understand the data. With UDX model, Wang et al. (2018) designed data processing services to support model running and data conversion in the web environment. Transmission control is expected to be designed to enhance security and ensure completeness and traceability during the data transmission process; while transmission optimization is intended to optimize the efficiency of data transfer over the network. To guarantee security and respect ownership, digital watermarking is one method to help control this issue for data (Shih et al. 2017). Jiao et al. (2018) presented a method to ensure data completeness during transmission. Zhang et al. (2017) designed a method to trace the provenance of data being used. Regarding methods for enhancing data transmission efficiency, many spatial data transmission algorithms have been developed and can be used as references (e.g., Falls et al. 2014; Bhattacharya et al. 2015).

When sharing a server resource, at a minimum, the structured expression of heterogeneous servers and service-oriented environment configurations need to be considered. A structured description method for heterogeneous servers aims to describe server features, including the hardware environments (CPU types, memory sizes, etc.), operating systems (versions of Windows, Linux, MacOS, etc.) and software environments (e.g., Geospatial Data Abstraction Library (GDAL) or Python). A service-oriented environment configuration initially provides basic methods for configuring hardware and software environments to support server sharing. After server resources are shared, methods should also be provided to support the remote configuration of hardware and software in the server environment according to the deployed service requirements. For instance, if a computer is shared as a server, after it is registered on the web, when a model with a different hardware/software requirement than those for which the server has been configured needs to be deployed on the server, the server owner (or the users, if given sufficient permissions) should be able to configure the server with the suitable hardware/software.

5.2.2 Resource discovery

Finding suitable models, data or servers is a challenge for resource users (Goodall et al. 2011). Resource discovery, which is an supporting aspect of resource sharing, provides methods for making queries and locating target resources. Two steps may be involved in resource discovery: relationship and index building and matching rule design.

Index building involves building a storage structure that can be searched efficiently for target resources. Relationship building explores the different relationships among resources and links them; then, these resources can be queried based on the developed relationship network. For example, FigShare (Singh, 2011) creates different featured categories for their online shared data resources, and each resource is equipped with a Digital Object Identifier (DOI), allowing it to be tracked and searched. Chen et al. (2018) designed a data model to capture the relationships among geographic simulation models, actors (agencies and researchers), and application scenarios by considering their evolution processes.

Matching rule design involves building rules to support matches between simulation resource keywords and user requirements. Search engines, such as Google, and related scientific research tools, such as Stanford CoreNLP (Manning et al. 2014), have designed matching algorithms. When combined with resource classification and metadata, these matching algorithms can be referenced when building matching rules.

5.2.3 Resource tracking and control

Resource tracking and control, which aims to track the usage processes of resources and enable their security, has drawn increased attention in open web-distributed resource sharing (Gordon et al. 2003; Rong et al. 2013; Sicari et al. 2015). Resource tracking and control can be realized to some extent through usage tracking and information recording, and authentication and access control.

Usage tracking and information recording tasks are designed to make records of the usage process of resources as well as to store information related to the used resources. Tracking the usage process can provide a clear idea of the activities for which resources are used, e.g., a model is deployed on server A, and data are transferred through server B to Server C. Recording related information (e.g., authorship, contributors, copyrights) can provide resource context during the evolution process, and can thus help protect intellectual contributions .

Authentication and access control tasks are designed to improve the security of resources after they are provided as services. Such tasks may involve multiple methods to help to identify actors securely, enable access to allow actors, and use practices that prevent abuse. From this perspective, technologies related to network security (e.g., local network, private cloud), usage category assignment (e.g., free use, commercial use, or private use) and illegal usage control (e.g., cracking and decompilation) could be employed as references.

5.2.4 Sharing mode design

Encouraging resource owners to make their resources available to communities is another challenge in resource sharing processes (Bartol et al. 2002; Bassi et al. 2003; Chard et al. 2012) and involves at least two points. The first point is related to community building - forming teams that include resource owners, users and related stakeholders. A sustainable community is crucial for the achievement of open simulation resource sharing. Organizations such as CUAHSI (Universities Allied for Water Research), CSDMS, EarthCube, Unidata, CyberGIS, and SWITCH-ON (European Union Hydrologic data sharing) have established their respective communities to ensure sustainable development. In summary, these strategies include: (1) Governance and community organization (e.g., working groups, initiatives, committees); (2) participation rules, rights, rewards and responsibilities; (3) promotion of both communities and resources through multi-channel (e.g., workshops, training) ; (4) attention attraction (e.g., publishing related news and cutting-edge technologies; (5) use experience enhancement (e.g., providing user friendly tools); and (6) feedback channels design (e.g., comments and citation reports). Among these strategies, an important technical point is how to provide different kinds of tools (e.g., resource wrapping tools, resource publishing tools, resources invoking tools) to satisfy a diverse group of participants. User friendliness in design is a basic criterion. Because open integrated platforms attract many users with different backgrounds and usage habits, it is challenging to find a balance among a wide range of demands.

5.3 Collaborative integrated modelling environment

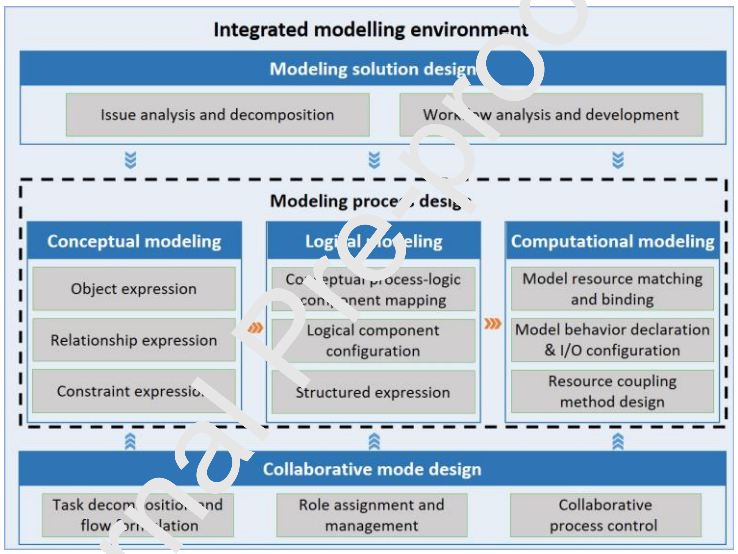

Figure 5 Key points of the integrated modelling environment

After resources are shared in the open web environment, modelers can create integrated compositions of geographic models using the shared resources in the network. In the evolution of geographic research, solving comprehensive geographic problems is an active research area (Fu et al. 2015, 2016). Due to the complexity of geographic environments, especially those that connect the human and natural environments (Chen et al. 2013; Hamilton et al. 2015), modelers from different disciplines may have different conceptions of geographic phenomena or processes. Thus, collaboration has been emphasized in comprehensive geographic research and integrated modelling (e.g., Wu et al. 2015; You et al. 2016; Basco-Carrera et al. 2017; Evers et al. 2017; Harpham et al. 2014; Bandaragoda et al. 2019), and is especially valuable in the open web-distributed approach. Such collaboration fosters communication and cooperation, helps in forming common understandings among multiple researchers through the web, and further guides the integrated geographic modelling process. The design of a collaborative integrated modelling environment should consider: the design of the modelling solution, the modelling process and the collaborative modelling mode (Figure 4). The modelling process is the core of integrated geographic modelling; the modelling solution guides the detailed modelling processes; and the collaborative mode provides implementation strategies to support the entire integrated modelling process in a collaborative way through the web.

5.3.1 Modelling solution design

The modelling solution, which is a critical foundation for integrated geographic modelling, can be regarded as a decomposition and analysis process for the complex geographic problems to be analyzed. It can also help translate the modelling purpose into a model description. Before considering integrated modelling for comprehensive geographic phenomena or processes, first, the research questions should be determined and decomposed. For example, to better understand the growth process of plants in certain areas, precipitation, photosynthesis and soil nutrient cycling processes may need to be decomposed, so experts in the related domains can be invited to participate. Then, the modelling workflow is analyzed and developed to describe the overall process of model building. During this step, different modelling tasks can be apportioned to different experts, and modelling roles can be assigned.

5.3.2 Modelling process design

Because there are currently no unified steps in describing a general integrated modelling process, in this article, we divide the modelling process into conceptual modelling, logical modelling and computational modelling.

Conceptual modelling provides an abstract idea of the integrated geographic models to be developed. Because conceptual models will lay a foundation for model idea communication among the different participants in the integrated modelling process, it is meaningful to develop such concepts and express them in simple, understandable ways to help to reach a consensus on the modelling topics. Clark et al. (2015) summarized the modelling conception of process-based hydrologic models using Structure for Unifying Multiple Modelling Alternatives (SUMMA). In this respect, geographic scenarios, which involve multiple geographic phenomena and processes, can be regarded as suitable media for expressing geographic conceptual models (Lu et al. 2018). Based on geographic scenarios and combined with expression methods (e.g., graphs, script descriptions), geographic conceptual models can be built to match the conceptual scenarios (e.g., Chen et al. 2011). Figure 6 shows an example of a conceptual model based on geographic scenarios to represent a forest fire. But we note that not all conceptual models need to be represented in such a vivid way. Within this possible approach, during the conceptual modelling process, geographic objects and the relationships among these objects should be clarified and expressed. For example, when modelling a forest fire, concepts such as wind (speed and direction), trees (species and density) and air (factors such as humidity) may need to be considered and expressed. Moreover, relationships such as the effects of wind speed and direction and tree density on fire spreading also need to be expressed. In addition to the expression of geographic objects and relationships, constraints are also important for reflecting natural geographical laws and knowledge. For example, trees should generally be planted on the ground, not in the air; thus, when building a conceptual model, constraints based on general geographic knowledge should be included from a knowledge-base to help to guide the building of a realistic conceptual model.

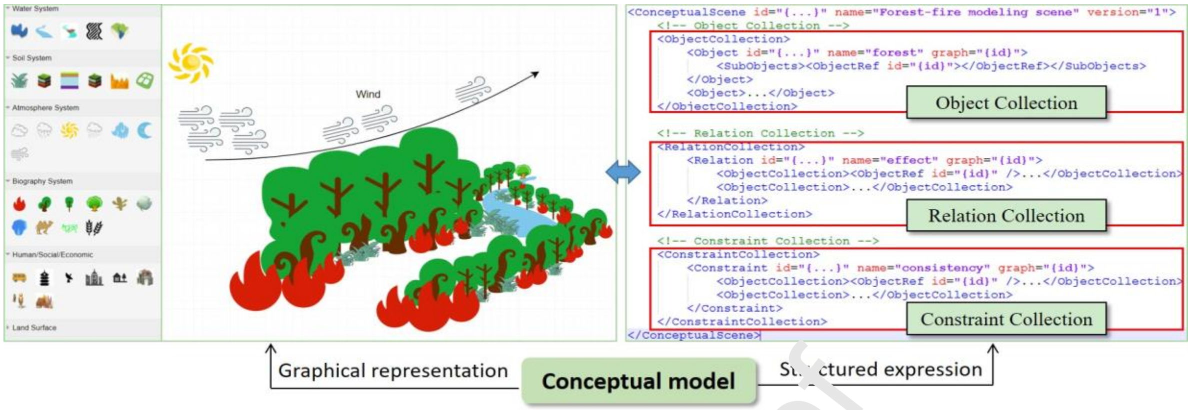

Figure 6. An example of a conceptual model

Logical modelling involves modelling the inner structures (e.g., nested and combined submodel component structures) and behavior (e.g., when to run a submodel) of the integrated models, based on the developed conceptual model. In this stage, first, the geographic processes or subprocesses represented by the geographic conceptual models, need to be mapped to the corresponding logical components. For example, a conceptual model of hydrological processes may include several subprocesses, such as precipitation, evapotranspiration and infiltration. These sub-processes and their relationships need to be expressed by logical components and their associations. GoldSim (https://www.goldsim.com/web/home/) is an example that uses influence diagrams and their links to represent the logical subprocesses and their relationships of an integrated model. Second, these organized specific logic components need to be configured with content, such as declaring which types or classes of models should be used to represent a corresponding process. Finally, the logical model, which is the product of the logical modelling process, needs to be expressed structurally. Thus, it can be associated with the real accessible resources to simulate the represented geographic processes in subsequent steps. Figure 7 is an example of one method to accomplish such logical modelling.

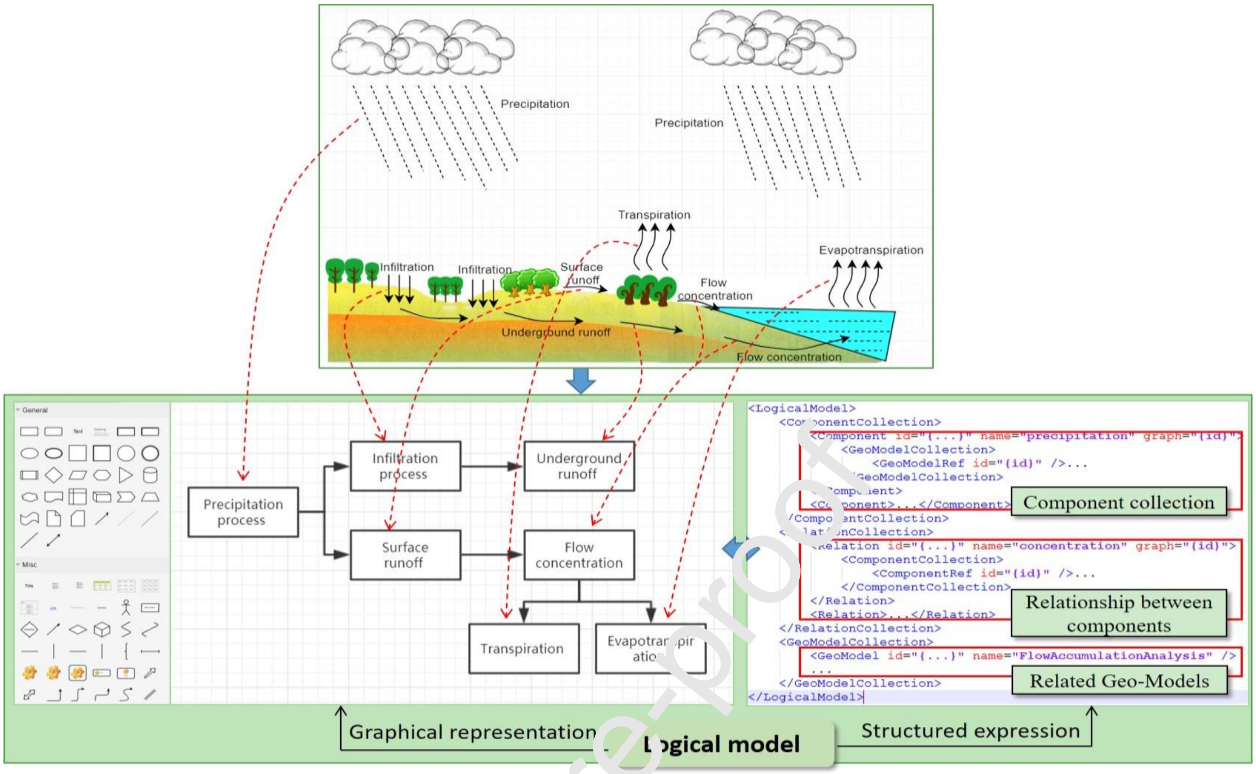

Figure 7. An example of a logical modelling process

Computational modelling can be regarded as the process of configuring distributed resources on the networks to generate an executable integrated model workflow based on the guidance from the designed conceptual models and logical models. In this stage, first, the appropriate model resources on the distributed networks need to be matched and bound to the corresponding logical components. These may be different services that are deployed and published on different server resources. Second, the matched model behaviors and input/output data need to be clarified and configured before their invocation. For example, model data assimilation generally requires external inputs for further computations; thus, such behaviors must be declared so that the model operates correctly. Additionally, the methods for resource coupling also need to be designed to generate a real computational model. Such designs may include methods for model-model coupling (e.g., upscaling and downscaling, spatio-temporal feature type adaptations and transformations), model-data preparation (e.g., model-specific data preprocessing, see Yue et al. 2018 which provides a loose data resource configuration strategy for web-based model services) and model-server compatibility (e.g., server environment selection and configuration to fit the model). Figure 8 shows an example of this type of computational modelling.

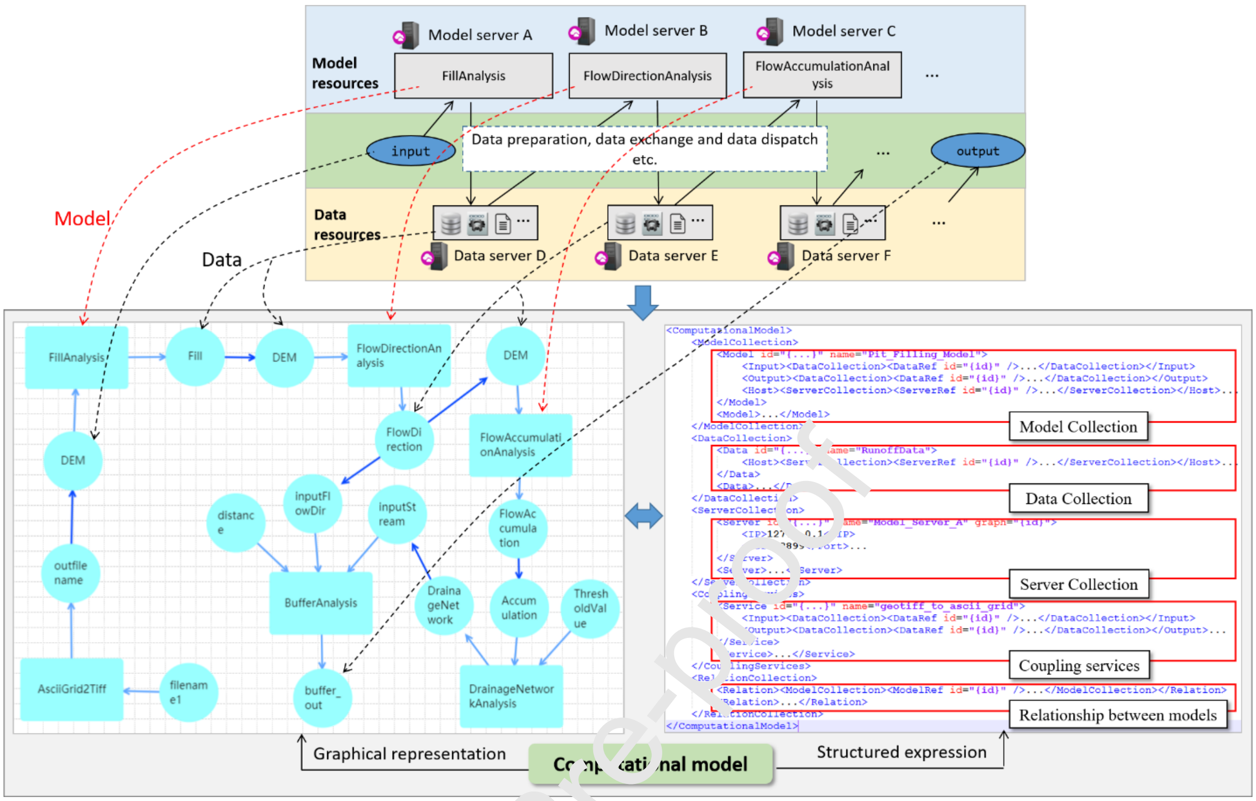

Figure 8. An example of a computational modelling process

5.3.3 Collaborative modelling mode design

Collaborative modelling mode design provides a series of methods and tools that allow a team of researchers to perform modelling tasks together and share their knowledge over a network. This concept may involve several methods, such as task decomposition and flow formulation, role assignment and management, and collaborative process control.

Task decomposition and flow formulation are aimed at dividing the full set of open web-distributed integrated geographic modelling tasks into subtasks and forming a complete modelling workflow. For example, when studying pollution in a specific area, the modelling process can be divided into several tasks, including hydrology process modelling, meteorological process modelling, effects on humans and ecology, their costs and responses, and data preparation or acquisition of server resources. These tasks can be linked to form a modelling workflow. To implement these tasks collaboratively, role assignment and management may require different kinds of roles that must be simultaneously managed. For example, meteorologists, health experts, economists and hydrologists may be assigned different roles when conducting different modelling tasks with which they are familiar. Moreover, the process of modelling may need to be collaboratively controlled (e.g., progress monitoring, task optimization and role scheduling) during the entire geographic modelling process.

5.4 Distributed simulation environment

The distributed simulation environment, which includes distributed execution and control, and collaborative simulation and evaluation, enables integrated computational models to operate in networks and helps users conduct and optimize collaborative simulations (see Figure 9).

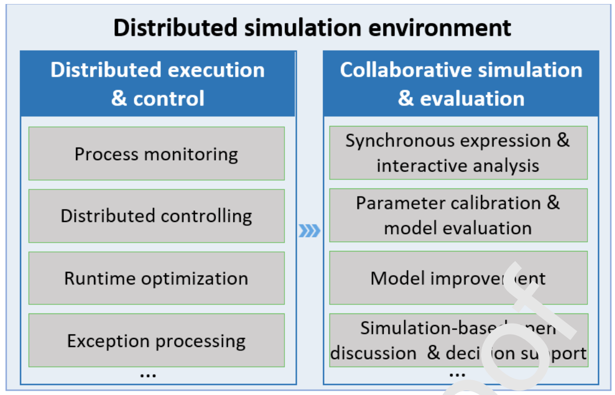

Figure 9 Key points of the distributed simulation environment

5.4.1 Distributed execution and control

The results of integrated geographic modelling are computational models consisting of several submodules that can be invoked through distributed networks. Due to the complexity of the internet, key aspects for model distributed execution and control as indicated below need to be considered.

Process monitoring includes monitoring the operating process of computational models and the corresponding submodules through the web, the model execution status (e.g., the progress of model invocation, log information and exception information), and related server resources (e.g., memory and CPU utilization).

Distributed control involves developing the controlling strategies to handle the entire execution process and interrelated resources in a distributed network, such as invoking each submodule based on the order determined during the modelling process and performing data dispatching among distributed servers.

Runtime optimization provides methods to improve the operating performance of the integrated computational models. This may include methods that optimize the server node selection (e.g., selecting the most suitable server nodes to participate in the collaborative simulation) or optimize the data transmission efficiency (e.g., data compression and block transmission).

Exception processing notifies users of potential mistakes or errors during an interrupted execution process. Error and warning logs provide a direct way of capturing exceptions that occur during computational model invocation. A good logging system can report exceptions in a timely manner. Then, exception-processing solutions can be designed and employed to handle these. For example, if a time-out occurs when requesting certain resources, the logging system may record this exception. Then, corresponding solutions, such as requesting the same model services from another server resource, could be employed to circumvent this exception.

5.4.2 Collaborative simulation and evaluation

Collaborative simulation and evaluation are critical processes when applying the results of integrated geographic modelling in a web-distributed system. In this stage, to achieve comprehensive and collaborative geographic simulations, the following factors should be considered.

First, synchronous expression and interactive analysis are necessary. To evaluate the quality of integrated geographic modelling in the open web-distributed environment, multiple users may need to work interactively and share their knowledge to analyze and optimize the modelling results (e.g., through discussion, comparison validation and visualization) in a distributed manner. In this case, the simulation processes and results need to be expressed synchronously to different experts in the network for exploration. For example, an expert may adjust some parameters before simulation, and another expert may perform some operations (e.g., a cutting analysis of the ground layers) involving the simulation and visualization results. Others may need to be made aware of these changes synchronously, and then provide their comments and suggestions to improve the next round of simulations. Some examples of this can be found in Xu et al. (2011) and Zhu et al. (2016).

Second, parameter calibration and model evaluation is another key part in this aspect. Based on evaluating the model output, the model parameters should be calibrated accordingly to improve the quality of the results. Model evaluation includes uncertainty analyses, model verification and model validation (Matott et al. 2009; Eker et al. 2019). Uncertainty analysis of models is more important in integrated geographic modelling because uncertainty may increase due to model integration (Jakeman et al. 2006; Voinov et al. 2010; Hoo et al. 2020). This might complicate model calibration since the parameters of sub models must be calibrated while comparing data to the output of the integrated model. Model verification focuses on the correctness of model results, while the model validation ensures that the results are as expected. New online tools are needed to support both collaborative calibration and evaluation over the web.

Third, a model might need to be adjusted during simulation. At least two types of adjustments may be considered after initial model execution. First, if the results are not satisfactory, it is necessary to determine how best to adjust the model to improve its results and understand whether certain sub models have to be replaced or fixed, or whether additional sub-models need to be considered and integrated. Tools need to be designed to support the convenient replacement or extension of sub models for further use. Conversely, if the integrated model performs sufficiently well, the simulation process itself can still be improved for the next rounds of simulation by choosing alternative, better performing servers that provide the same sub models as services.

Finally, a simulation-based open discussion and decision support will contribute to model application and dissemination. More stakeholders (e.g., the public and decision makers) may become involved in open web-distributed integrated geographic modelling and simulation and provide their own contributions. For example, to create specific simulations requiring real-time environmental data, the public may participate and provide local environmental data to improve the simulation results (crowd-sourcing). Moreover, given different simulation solutions and results, decision makers may perform comparative analyses with modelers and simulators to design better solutions. All these tasks are expected to be supported and online tools (e.g., consultation tools, analysis tools, and report making tools) are needed to facilitate broad participation.

6. Conclusions

Comprehensive geographic exploration and understanding calls for interdisciplinary, multi-scale, and collaborative efforts. Open web-distributed modelling and simulation is an emerging and exciting area of scientific research aimed at supporting such modelling efforts. It can encourage more participants to become active in geographic research by removing obstacles to both resource sharing and collaborative modelling and simulation. It may learn from the experiences of 'big data' to usher in a 'big model' era. This article envisions such an open web-distributed approach to geographic modelling and simulation by drawing on and synthesizing past literature, and by presenting a conceptual framework to organize key research topics in this emerging field. From this perspective, we have arrived at five key conclusions.

First, open web-distributed modelling and simulation will introduce an increasing number of modelling and simulation resources that can contribute to both resource reusability and comprehensive problem-solving. Efforts are still needed to be made to form a limited number of enabling standards and specifications that can be used across topic domains so that this growth in modelling and simulation resources can be effectively inventoried, organized, and integrated for geographic simulations. For example, model document standards and service operation standards for models are still under exploration.

Second, for open research communities, convenience will affect the participation of both resource providers and users in continued exchanges. Designing highly-usable ways to prepare and apply model and data resources is crucial for the long-term success. Recent research has made progress regarding the usability of web-distributed modelling systems with proposed UIs, although most work has focused on model communication standards and semantics. More work that specifically focusses on the user experience is needed to enable broad adoption and participation in these systems.

Third, there is a research gap in enabling a wide variety of potential models to be successfully integrated into compositions caused by a lack of focus on the different conceptualizations and representations of geographic space and time across component standards. For example, the geographic models that could be considered for such integrated systems produce outputs that include a wide variety of spatial feature types, such as grids, points and meshes (Chen et al. 2018). Although the implementations of standards such as OpenMI offers low-level flexibility in interpolating among feature types when implemented in different time-step schemes, and some discrete global grids have been developed to express of grid nodes, edges, and cells in a uniform way to support spatial data organization, pattern simulation, and the visualization of spatial data (e.g., Lin et al. 2018), more work is still required to make this truly generic, practical and efficient.

Fourth, in a web environment, the distributed execution of the sub models within an integrated model calls for safe, secure, and highly-efficient computational and message passing methods. For the servers that provide resource services, safety control is important not only for the server itself, but also for the entire simulation process. Based on multiple servers, execution efficiency must also be addressed through advanced technologies such as parallel-computing, secure message passing, and fault-tolerant model orchestration strategies. Considerable progress has been made regarding these topics, but more work is needed to ensure consistency of reproducibility of model simulations in web-execution environments. Many challenges remain, such as, handling web resources that are upgraded, or deprecated and offline; conducting comprehensive comparisons of software environment and platform dependencies for different servers; and tracking the workflows of the operations in modelling and simulation processes to enable reproducible research.

Finally, beyond geography, this paper also provides a framework to structure the necessary activities required to support general web modelling activities. This framework can combine various existing integrated modelling tools and systems (e.g. CSDMS, OpenMI, and OpenGMS). We argue that having such a framework for organizing and focusing current efforts in the community, as well as identifying research gaps that must be overcome to implement the web-based modelling vision discussed, is needed to advance the field. To this end, an Open Modelling Foundation (OMF, https://openmodelingfoundation.org/) has been established to actively promote international standards and best practices to improve the modelling culture, and make models more accessible, reliable and reproducible. We expect that broad community involvement will help demonstrate the benefits of the framework to providers and users and encourage these stakeholders to incorporate their innovations and offerings. In this paper we have focused on the technical aspects of the framework to demonstrate that it is possible and practical, and that it can advance the science and practices of open web-distributed integrated modelling and the corresponding practices. This is not to discount the equally challenging social and cultural aspects of changing the practice of modelling and facilitate the adoption of open web-distributed integrated modelling principles. Many future developments will be required from both the technical and social perspectives to implement this vision and we anticipate that research outputs in this area will continue to grow exponentially. We hope that the implementation roadmap presented in this paper can serve the community as an organizational structure to motivate and drive future research and development in this field.

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