



# A geoprocessing workflow system for environmental monitoring and integrated modelling



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## ABSTRACT

Environmental information infrastructure benefits from mainstream information technologies including workflow and service technologies. These technologies allow distributed geoprocessing algorithms, models, data, and sensors to be accessed through Web Services, which later can be chained together to support environmental monitoring and integrated modelling. Existing approaches on integrated environmental modelling, such as OpenMI, have advantages in enabling interoperability between modelling components. It is possible to integrate both of them to take the best from both approaches. The paper introduces the design and implementation of a geoprocessing workflow tool, named GeoJModelBuilder, which is able to integrate interoperable Sensor Web, geoprocessing services, and OpenMI-compliant model components into workflows. In this way, sensors, data, geoprocessing functions, and models could be integrated in a flexible, reusable, interoperable, and user-friendly way. The system has been published as an open source software and illustrated in cases on environmental monitoring and integrated modelling.

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## 1. Introduction

Integrated environmental modelling (IEM) has been identified as an important discipline to provide approaches and tools to understand the social–economic–environmental systems (Rizzoli and Davis, 1999; Parker et al., 2002; Jakeman and Letcher, 2003; Laniak et al., 2013a). It provides a structural way to develop and organize multidisciplinary knowledge through models. The development of IEM covers issues on applications, science, technology, and community (Laniak et al., 2013b). In the past decades, significant efforts have been devoted towards the technological development of IEM systems (Granell et al., 2013a). With the advancement of Spatial Data Infrastructure (SDI) or Cyberinfrastructure, “Model as a Service” (MaaS) approach is being used in the Model Web initiative to provide an engineering approach towards the implementation of integrated modelling systems layered on environmental information infrastructure (Geller and Turner, 2007; Nativi et al., 2013). In this way, different models could be implemented as services, often accessible through Web Service interfaces, and coupled through service-oriented workflows (Granell et al., 2010; Bastin et al., 2013; Nativi et al., 2013).

Workflows and Web Services are widely employed in environmental information infrastructures (Béjar et al., 2014; Laniak et al., 2013b). These technologies allow distributed models, data, and sensors to be accessed through Web Services, which later can be chained together to support environmental monitoring and integrated modelling. A vision on integrated environmental modelling has shown that interoperability across modelling components and leverage of Web Services for the next generation modelling framework are critical technological drivers (Laniak et al., 2013b). In the geospatial Web Services area, the Open Geospatial Consortium (OGC) is the major organization working on developing interoperable geospatial Web Services standards by adapting or extending the common Web Service standards (OGC, 2015). Examples of OGC Web Service standards include Web Feature Service (WFS), Web Map Service (WMS), Web Coverage Service (WCS), Sensor Observation Service (SOS), Catalogue Services for Web (CSW), and Web Processing Service (WPS). These standards could be used in the software design and implementation of IEM systems (Laniak et al., 2013b). For example, an environmental model could be accessed by WPS (Nativi et al., 2013). Although the geospatial community tends to treat models as any algorithm accessible through the WPS interface, there are still some challenges on adopting WPS for accessing environmental models. The WPS specification has some limitations in dealing with complex semantics and time-step computations of models. However, some proposals have been

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available to address these challenges, such as adding formalized models as the payload in a WPS 2.0 extension (Nativi et al., 2013), profiling of the WPS for models (Bastin et al., 2013), and maintaining state on the WPS server (Castronova et al., 2013a). Therefore, the workflow tool in this paper still adopts the WPS to support its promise for MaaS. In cases where WPS is not adequate for providing complex environmental models, the tool also accommodates the OpenMI, a standard for describing modelling components and runtime data exchange between them (Vanecek and Moore, 2014). Thus the tool will provide a workflow environment to bridge models in the geospatial and environmental communities.

The paper introduces the design and implementation of a geoprocessing workflow tool, named GeoJModelBuilder, for environmental monitoring and integrated modelling. Here the term geoprocessing has a broader meaning than the analysis function in traditional Geographical Information Systems (GIS), and can refer to any sort of geospatial processing, analysis functions, or models. For example, it could include Earth system prediction models or a simple spatial buffer analysis function. Both traditional geospatial analysis algorithms and environmental models are integrated using geoprocessing workflows. Compared to existing scientific workflow tools, the tool is geo-enabled in that it integrates interoperable OGC Sensor Web, geoprocessing services, and OpenMI-compliant model components into workflows. In this way, it addresses the two key topics on the technological development of IEM systems, interoperability and Web, envisioned by Laniak et al. (2013b). The event-driven technologies adopted by Sensor Web are leveraged with geoprocessing workflow to support environmental monitoring. In contrast to “passive” workflow enactment in traditional workflow engines, the advocate of the new “Event” node in the workflow can support “active” environmental monitoring, thus enriching the service-oriented paradigm with events for environmental model software architectures. The system is coupled with virtual globes to allow users to interact with IEM in a user-friendly graphical user interface (GUI). Thus the tool allows models, sensors, computational and data resources distributed on the Web to be integrated in a flexible, reusable, interoperable, and user-friendly way. The result has been published as open source software and illustrated in cases on environmental monitoring and integrated modelling.

The remainder of the article is organized as follows. Section 2 introduces related work in the literature. Two motivating examples are described in Section 3. Section 4 presents the architectural design of GeoJModelBuilder. Details of software implementation are described in Section 5. Section 6 provides the evaluation. Conclusions and pointers to future work are given in Section 7.

## 2. Related work

Conventional environmental modelling systems include GIS software (Laniak et al., 2013b). Since 2004, the Environmental Systems Research Institute (ESRI) has released a geoprocessing framework in ArcGIS software. The framework includes not only a set of analysis functions but also a geoprocessing ModelBuilder tool (ESRI, 2015). The tool allows users visually combine different analysis model components and generate new geoprocessing models. The spatial modelling tool in the ERDAS IMAGINE software, named Spatial Modeler (Intergraph, 2015), has a similar model chaining function. It can combine GIS analysis components with ERDAS's commercial image processing components to support integrated modelling. These proprietary GIS software systems have limited capabilities in supporting open integrated modelling in the Web environment. The analysis components and the modelling capability are often used in their own proprietary environments. There are also some open source scientific workflow tools, such as Kepler

(Ludäscher et al., 2006), Taverna (Oinn et al., 2004), and Vistrails (Callahan et al., 2006), which have been used for IEM (Bastin et al., 2013; Granell et al., 2013a; van Zyl et al., 2012). Nevertheless, these workflow tools are originally designed to be general or for non-geo domains. For example, Kepler is intended for workflow applications across different domains, Taverna focuses on bioinformatics activities, and VisTrails initially addresses data visualization. Significant efforts have to be devoted to adapt them to distributed geoprocessing service environment (Pratt et al., 2010; de Jesus et al., 2012; McFerren et al., 2012). GeoJModelBuilder is designed in nature for geo-enabled workflows by providing built-in support for open standard-compliant geospatial Web Services and data. In addition, it leverages OGC Sensor Web standards and virtual globes for event-driven workflow enactment in a user-friendly environment, which are not done yet in existing IEM tools.

Component-based modelling has been widely used in existing IEM tools (Granell et al., 2013a). There are already various modelling frameworks available, such as Common Component Architecture (CCA), Earth System Modelling Framework (ESMF), and Open Modelling Interface (OpenMI). Among them, the OpenMI standard aims to be a global framework for coupling diverse models, and has been subjected to extensive studies recently (Laniak et al., 2013b). From the perspective of component-based software engineering (Sommerville, 2004), models (a given functionality, executables, or algorithmic code) could be treated as software components working together using workflows (Bastin et al., 2013; Granell et al., 2013b). Although there are some arguments that model integration is more than software coupling (e.g., data sets should be treated as components on the same level as models) (Voinov and Shugart, 2013), the software module coupling tools such as workflow tools do show promise for right solutions (Voinov and Shugart, 2013; Laniak et al., 2013b; Granell et al., 2013a). From the “Model as a Service” perspective, models could be accessed through Web Services (Nativi et al., 2013). The advancement of service-oriented computing and Web-Service-based implementation follow the component-based software engineering principles by realizing services as reusable, loosely coupled, and independent components. Thus, the vision of Model Web could be implemented by treating models as services and workflows as composition of Web Services (Granell, 2014).

OGC Web Services, W3C SOAP-based Web Services, and RESTful services are available for implementation of services. Some efforts have been devoted to make them work together, such as defining WSDL for OGC services (Sonnet, 2004), and using WSDL 2.0 as the bridge between REST (REpresentational State Transfer) and W3C Web Service (W3C, 2007; Lucchi et al., 2008). Other efforts investigate approaches on service chaining, or service composition, for example, the use of the Web Services Business Process Execution Language (WSBPEL, BPEL for short) (OASIS, 2007) to support geospatial service chains (Friis-Christensen et al., 2009; Yu et al., 2012). Three types of service chaining are defined in the OGC Abstract Service architecture (Percivall, 2002) depending on the level of user control: user-defined (transparent), workflow-managed (translucent), and aggregate (opaque). In transparent chaining, the human user is responsible for invoking service components and controlling the chains such as passing around processing results. Translucent chaining allows a user to define a service chain using a workflow language such as BPEL. The execution of service chains is managed by workflow engines. In opaque chaining, the human user invokes a service that carries out the chain. The user has no awareness of the individual services in the chain. This type of chaining is often addressed by automatic service composition (Yue et al., 2012).

The OGC WPS specification provides an approach to make traditional analysis functions accessible through standard

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