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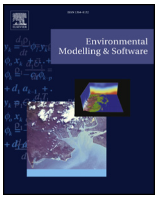

Integrating free and open source tools and distributed modelling codes in GIS environment for data-based groundwater management

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ABSTRACT

Integrating advanced simulation techniques and data analysis tools in a freeware Geographic Information System (GIS) provides a valuable contribution to the management of conjunctive use of groundwater (the world's largest freshwater resource) and surface-water. To this aim, we describe here the FREEWAT (FREE and open source software tools for WATer resource management) platform. FREEWAT is a free and open source, QGIS-integrated interface for planning and management of water resources, with specific attention to groundwater.

The FREEWAT platform couples the power of GIS geo-processing and post-processing tools in spatial data analysis with that of process-based simulation models. The FREEWAT environment allows storage of large spatial datasets, data management and visualization, and running of several distributed modelling codes (mainly belonging to the MODFLOW family). It simulates hydrologic and transport processes, and provides a database framework and visualization capabilities for hydrochemical analysis. Examples of real case study applications are provided.

1. Introduction

Groundwater is the world's largest freshwater resource (Trenberth et al., 2006), life-sustaining at global scale, supplying water to people, irrigated agriculture, industry, energy production and maintaining ecosystems. As such, groundwater exploitation, groundwater sustainability and management, groundwater depletion (Wada et al., 2010; Siebert et al., 2010), groundwater quality deterioration (Menció et al., 2016; Chabukdhara et al., 2017; Werner et al., 2013) and conjunctive use of ground- and surface-water (Li et al., 2016; Singh, 2014) constitute a critical issue worldwide (Foster et al., 2000; Gleeson et al., 2012; Singh, 2014) and need to be carefully addressed.

To manage all these issues, spatial databases for the description of groundwater bodies characteristics (including, i.e., surface and subsurface geology information, aquifer hydrodynamics and hydrodispersive data as a result of direct or indirect site investigations, surface water/groundwater relationships) are available (Schwarz and Alexander, 1995; Refsgaard et al., 2010; Di Luzio et al., 2017; Regione Toscana, 2017; SUPSI, 2017), and extensive monitoring networks are in operation in many areas of the world, as required by groundwater related legislation (CRC, 2004; EU, 2000, 2006; California Department of Water Resources, 2016a, 2016b). Moreover, authorities, in view of improving the management of groundwater abstractions, are increasingly building spatial database where well characteristics and discharge are stored. Such piece of information starts to be available also as open data and standard formats (e.g., Schwarz and Alexander, 1995; Regione Toscana, 2017; ACA, 2000).

As several hydrologic and hydrochemical variables are being monitored, and both satellite and ground-based observation data are collected, there is the opportunity to take advantage of this large mass of data and information to develop dynamically growing and efficient groundwater management plans. While the use of semi-quantitative or analytical approaches is widespread, this type of approach alone does not take advantage of all the information that might be derived by the newly collected data, thus making inconsistent the large economic effort done in data collection and archiving, and potentially leading to

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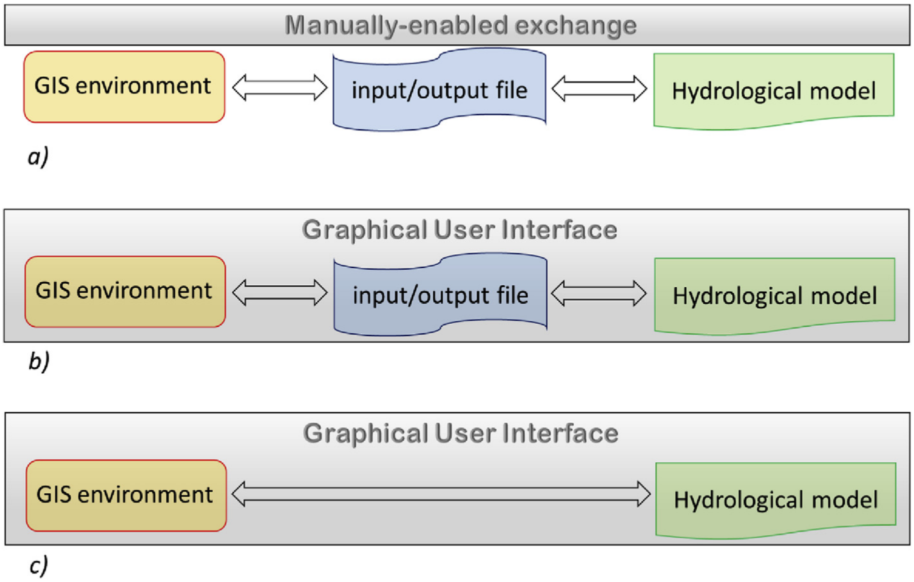

Fig. 1. Coupling strategies between GIS and models: a) loose coupling; b) close/tight coupling; c) embedding. Modified after Carrera-Hernandez and Gaskin (2006).

unsuccessful groundwater management.

Geographic Information Systems (GISs) have been applied to support environmental modelling and, being able to store, manage/analyse and visualize large temporal, spatial and non-spatial datasets, they are the most efficient tools to deal with geometric and alphanumerical data. This makes GIS a perfect candidate for advancing and facilitating the use of tools to manage large set of data and complex modelling environments (Kresic and Mikszewski, 2012). Traditionally, GIS has been used in groundwater studies for producing groundwater head contour or contaminant plume spread maps (making use of GIS-integrated interpolation methods) or to perform groundwater vulnerability analysis (i.e., using the DRASTIC method, Neh et al., 2015; Shrestha et al., 2017). On the other hand, in the last 15 years, several authors have been integrating basic tools for facilitating groundwater management in GIS environment, with increasing production since 2010. Maidment (2002) developed a dedicated data model for water resource; Gogu et al. (2001), Martin et al. (2005), Strassberg et al. (2005), de Dreuzy et al. (2006), Chesnaux et al. (2011) and Strassberg et al. (2011) focused the data model on groundwater related applications. As further examples, Akbar et al. (2011) presented a GIS-based modelling system called ArcPRZM-3 for spatial modelling of pesticide leaching potential from soil towards groundwater; Rios et al. (2013) programmed a GIS-based software to simulate groundwater nitrate load from septic systems to surface water bodies; Ajami et al. (2012) describe the RIPGIS-NET, a GIS tool for riparian groundwater evapotranspiration in MODFLOW; Toews and Gusyev (2013) describe a GIS tool to delineate groundwater capture zone; Velasco et al. (2014) developed QUIMET, a GIS-based hydrogeochemical analysis tools; Criollo et al. (2016) developed an integrated GIS-based tool for aquifer test analysis. However, all these efforts are sparse and non-coordinated, and almost all of them are developed within commercial, not-open GIS software.

Among the available ICTs (Information and Communication Technologies), physically-based and distributed groundwater numerical models (coupling ground- and surface-water and unsaturated zone processes and incorporating climate, land use, morphological, hydrological and hydrogeological data) may represent comprehensive and dynamic tools to target water resource management issues (Refsgaard et al., 2010; Cao et al., 2013; Singh, 2014). These tools allow simulating the distribution of the water resource in space and time, taking into account anthropogenic stresses and providing readily usable information to decision makers (Pullar and Springer, 2000). They may support the development of highly informative representations of hydrological systems by: i) combining all the available spatial and non-spatial data in a single framework; ii) allowing update and improvement as new data are gathered; iii) providing information in space and time to water managers; iv) offering relevant predictive functions, thus allowing evaluation on how a hydrological system might behave under different scenarios of natural and anthropogenic constraints. Anderson et al. (2015) discuss in detail the potential applications of such tools, while Singh (2014) presents a review on the use of numerical groundwater models for managing the groundwater resource. Examples of applications to fulfill water regulation requirements may be found in Vázquez-Suñé et al. (2006), Shepley et al. (2012), Moran (2016).

Modelers may take advantage of integrating advanced hydrological modelling codes within a GIS environment, thus reducing model setup and analysis time, and avoiding data isolation, data integrity problems and broken data flows between model implementation and pre- and post-processing steps (Alcaraz et al., 2017; Bhatt et al., 2008, 2014; Pullar and Springer, 2000).

Since 2000, researchers have been devoted to design the integration of modelling codes within a GIS environment (Alcaraz et al., 2017; Bhatt et al., 2014; Carrera-Hernandez and Gaskin, 2006; Crestaz et al., 2012; Dile et al., 2016; Rossetto et al., 2013; Strassberg et al., 2005; Wang et al., 2016; Lei et al., 2011).

The coupling strategy between the hydrological model and the GIS framework is a core issue in the integration of the two components. Three different approaches are presented in the literature (Brimicombe, 2003; Goodchild, 1992; Nyerges, 1991) (Fig. 1): i) loose coupling; ii) close/tight coupling; iii) embedding. The simplest approach is the loose coupling (Fig. 1a), which treats the two components independently and allows interaction through manually-enabled file exchange only. In the close/tight coupling strategy (Fig. 1b), GIS and hydrological model engines work separately, but the first provides the interface where data are pre-processed, run and then visualized. As such, direct communication between the two components occurs during program execution, when the GIS-integrated Graphical User Interface (GUI) allows to generate input text files, which are then read by the program executable for running and producing output files. Full integration at programming language level is required in the third approach (also called seamless integration; Fig. 1c), where new models using GIS data format are embedded as full component of the host GIS application (Pullar and Springer, 2000; Wang et al., 2016).

Nowadays, GIS is a well-consolidated technology among water authorities/utilities and consultant companies. GISs are commonly used to