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A distributed framework for multi-risk assessment of natural hazards used to model the effects of forest fire on hydrology and sediment yield

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Abstract

Within the European Commission-funded MEDIGRID project, Grid computing technology is used to integrate various natural hazard models and data sets, maintained independently at different centres in Europe, into a single system, accessible to users over the internet. Each centre forms a process (application) or data storage node and has been fitted with the Globus toolkit, which provides the distributed computing environment functionality that is required for the system set up. In addition, several Grid data management components were developed to allow the system to operate on different computing platforms. Access to the data and application management services is enabled through a Grid Portal. A series of portlets enable users to access the system, providing a personalised interface to the Grid. Integration of the individual models required them to be modified as web services, so as to be run remotely over the internet. As the models have different data characteristics, a common data format was adopted for creating harmonised data sets and allowing the exchange of data between the models. As an example, the Fire Spread Engine model is used to derive a map of areas that have been burnt by fire. This forms an input to the SHETRAN hydrology, soil erosion and landslide model, which in turn could provide data for other models such as vegetation regeneration. The use of the system is demonstrated for a site in south-west Spain where a large forest fire occurred on 2 August 2003. The MEDIGRID system marks an advance in the integration of independently constructed models to provide improved hazard assessment technology.

Keywords: Integrated modelling; GRID; Soil erosion; SHETRAN; Fire Spread Engine

1. Introduction

It has long been known that forest fires can significantly affect river basin response through their elimination of the hydrological and soil protection functions of the vegetation cover. Impacts can range

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from increased runoff, flashier runoff and accelerated soil erosion in the short term to increased landslide and debris flow incidence in the longer term (e.g. Keller et al., 1997, Prosser & Williams, 1998; Cannon et al., 2001; Conedera et al., 2003). Mediterranean-type environments are especially vulnerable to fire and there is interest therefore in the post-fire management of Mediterranean landscapes. However, while there is an extensive literature on experimental studies of fire impacts, the field of impact modelling is less developed. In particular, models tend to refer to individual components of the overall impact, such as fire propagation, hydrological and erosion response and vegetation regeneration which makes it difficult to make a multi-risk assessment of a particular event. It would, therefore, be beneficial to collate models dealing with the different aspects of fire, fire management and fire-impacts, and make these available via a central access point. Furthermore, if some of these models could then be linked and chained so that the results of one model could feed into another, this would provide the basis of a decision support system. Individuals interested in fire management options could then test out various fire-management scenarios and assess their wide-ranging implications and overall impacts. There are however, many problems with this approach. Models have usually been developed in isolation from each other, so have different software architectures and data needs, and they may apply to different spatial scales or domains, e.g. plots, catchments and regions (e.g. Drossel and Schwabl, 1992; Campolo et al., 1999; Ewen et al., 2000; Kirkby et al., 2002; Bonan et al., 2003; Osborne, 2004). Furthermore, institutions owning different models can be reluctant to allow code to be distributed and may like controls over who has access to the executable. Distribution and use of data also has several restrictions such as licence agreements and different access authorisation requirements. Integration of such models is therefore difficult.

The aims of the European Commission (EC)-funded MEDIGRID project (Mediterranean Grid of Multi-risk Data and Models),[1] running from 1 November 2004 to 30 October 2006, were to try to resolve such issues by using a distributed Grid technology to integrate several of the independent, pre-existing, natural hazard models into one single system. The MEDIGRID project test-case therefore highlights the problems and benefits of implementing such a system and provides valuable experience to others thinking of setting up a similar framework. Models of forest fire behaviour and effects, erosion, floods, landslides and vegetation regeneration, which are individually maintained at centres throughout Europe, have been linked through the internet such that the output of one model forms the input to another where appropriate. Major challenges in integration have included the identification of common data themes and links between the models, conversions between different spatial and temporal resolutions, the identification of a common data format and development of data transformation routines for data exchange so that data can flow between the models. This paper describes the MEDIGRID system and in particular describes two models, the Fire Spread Engine (FSE) (Martínez-Millàn et al., 1991) and the SHETRAN hydrology, soil erosion and landslide model (Ewen et al., 2000), their integration into the MEDIGRID system and how the two models link with the system. SHETRAN can receive output (in the form of a vegetation map of burnt areas and consequential changes in soil properties) from a fire propagation model and although not discussed here, can itself provide input (in terms of soil erosion and landslide data) to other models such as a vegetation regeneration model. An example application of the first part of the exchange is given for the Alburrel River catchment near Valencia de Alcántara in the Extremadura region of Spain, which suffered major forest fires in August 2003.

Integrating FSE, SHETRAN and other hazard assessment models into such a web-based system provides a modular decision support framework for multi-risk assessment of natural disasters, thereby helping users assess the links between, and impacts of, multiple hazards. A full integration was not achieved: the paper therefore also discusses some of the difficulties in building a distributed computing system.

The MEDIGRID partners are ALGOSYSTEMS, Greece; ADAI, Portugal; CEREN, France; TECNOMA, Spain; IISAS, Slovakia and Newcastle University, UK.

2. The MEDIGRID system

2.1. Background

The MEDIGRID project aims to provide a modular decision support framework for assessing multiple natural hazards based on a distributed architecture using Grid computing services. The key

[1] www.eu-medigrid.org.

goals of Grid computing are to enable sharing, selection and aggregation of geographically distributed computational resources (e.g. hardware, software, data and people), and to present them as a single, unified resource for solving internet-scale (Parastatidis et al, 2005) computational and data intensive computing problems. The concept of Grid computing is not new. Several projects currently exist worldwide which deal with the development of Grid infrastructure for scientific applications, e.g. EGEE[2] (an EC project originally conceived for the fields of high-energy physics and the life sciences, but now incorporating other scientific fields such as geology or computational chemistry); OSG[3] (a north American project incorporating fields such as astrophysics, bioinformatics, computer science, medical imaging, nanotechnology and physics); and NAREGI[4] (a Japanese initiative to develop a general science Grid). However, it is only recently that there have been projects dealing specifically with Earth Science applications, for example eMinerals[5] and DEGREE.[6] *Environmental* Grid computing (i.e. the application of Grid computing technologies and principles to environmental and Earth systems engineering problems) is, therefore, a relatively new field.

The MEDIGRID project differs from many other Grid-related projects, in that it aims to integrate any suitably modified application running on any computing platform into the system. In addition, users should be able to access the system in a ubiquitous way and from any operating platform. Issues of security and access to the models are dealt with by allowing model owners to maintain full control over the computing resources they share with the system. Model owners therefore dictate which executable can be run externally and by whom, removing the need to transfer code or executables to the user. The project deals specifically with issues of data availability, security and archiving by providing owners the means to specify who is allowed access to the data and under what circumstances. Although some data may be transferred between certain machines hosting the applications by prior consent, these are not usually transferred to the end-user.

One of the main features of the MEDIGRID project is the concept of model chaining. Although there are many problems to overcome, linking models and running them in sequence can provide the user with a powerful, relatively easy to use, decision support system using models and data they would normally not have access to and which would not, under general circumstances, be run with one other.

The natural hazard models considered within the MEDIGRID project are those based around forest fires and post-fire hazards, i.e. models of forest fire behaviour and effects, soil erosion, flash floods, landslides and vegetation regeneration. The different individual models or ‘‘process nodes’’ are maintained at the different partner sites in Portugal, France, UK, Spain, Slovakia and Greece (see Fig. 1). In addition to the process nodes, the project created a distributed repository of data populated with data from countries that have suffered major forest fires. These ‘‘data storage nodes’’ are located in France, Spain and Portugal. Users will eventually be able to run any of the models set up on the process nodes, in sequence if they wish and if the logical model outputs/inputs allow, using data stored remotely in the data storage nodes. In this way, users will be able to assess the impacts of multiple hazards on an area. Although models can be run in sequence if applicable, certain hazards or models are not relevant or suitable for all sites. In the future, several different models for a variety of hazards could be offered, and the results from each could be compared and chained together to form a computational workflow, thus offering a multi-model, multi-hazard assessment tool.

2.2. Globus toolkit

Middleware[7,8] is the intermediate, connectivity software that mediates between an application program and a network and sits on top of an operating system and communication protocols. It includes web servers, application servers and content management systems.

[2]EGEE II: Enabling Grids for E-sciencE. www.eu-egee.org.

[3]OSG: Open Science Grid. http://www.opensciencegrid.org/.

[4]NAREGI: National Research Grid Initiative. http://www.naregi.org/index_e.html.

[5]http://eminerals.org.

[6]DEGREE: Dissemination and Exploitation of GRids in Earth sciencE. http:/www.eu-degree.eu.

[7]SEI Middleware, 2006, Carnegie Mellon Software Engineering Institute http://www.sei.cmu.edu/str/descriptions/middleware.html (visited October 2006).

[8]Krakowiak S., 2003. What is Middleware? Published on Object Web Open Source Middleware. http://middleware.objectweb.org/ (visited October 2006).

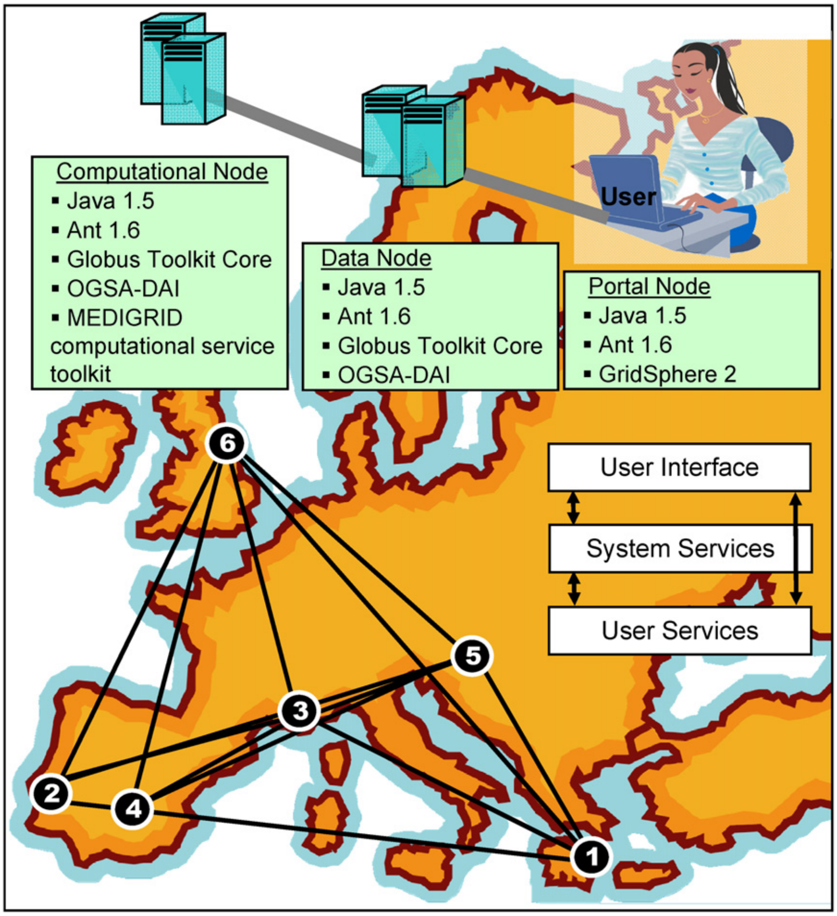

Fig. 1. Required Software for MEDIGRID computational, data and portal nodes; MEDIGRID layers; and partner locations (1) Algosystems, Greece; (2) ADAI, Portugal; (3) CEREN, France; (4) Tecnoma, Spain; (5) IISAS, Slovakia; and (6) Newcastle University, UK.

The MEDIGRID partners (process and data storage nodes) form part of a Virtual Organisation and as such require a shared, specific computing environment. Each node was therefore fitted with Globus Toolkit 4+ (Foster, 2005) (the standard middleware that enables the Grid) because it offers a common Grid technology that provides a secure infrastructure and allows data and computational services to be deployed securely via the internet. This was required because of the multiplatform nature of the individual programs.

The Globus Toolkit 4+ is an open source, open architecture, software project to produce a reference implementation of key Grid standards, specifications and protocols. It provides a comprehensive collection of services, software libraries and documentation for developers to use when building a Grid system. This collection includes tools to support Grid Service resource management (e.g. hardware, software and network), data management, security, communication, fault detection and portability. It is currently being developed by the Globus Alliance[9] community. The project enables the application of Grid technologies and concepts to scientific and engineering computing.

Specifically, the Globus Toolkit is an implementation of the Open Grid Services Architecture (Foster et al., 2005) based on the standards developed by the WS-Resource Framework (WSRF)[10] and the architectural principles as defined by the two Grid

[9]The Globus Alliance. http://www.globus.org (visited May 2006).

[10]Czajkowski, K., Ferguson, D. F. Foster, I., Frey, J., Graham, S., Sedukhin, I., Snelling, D., Tuecke, S., Vambenepe. W., 2004. The WS-Resource Framework. http://www.globus.org/wsrf/specs/ws-wsrf.pdf (visited September 2006).

standards bodies: the Global Grid Forum[11] and OASIS.[12] In addition to the standard web services interface, the Globus Toolkit provides security mechanisms in the form of authentication, message encryption and verification using X.509 certificates.

2.3. System architecture

The overarching role of the MEDIGRID software framework is to manage and support the interaction between a user of the system and the Grid services. The system is then logically divided into three layers: (1) user interfaces (using a portal with series of portlets); (2) system services (which includes security issues, workflow, data exchange and data services); (3) user services (which includes the computational nodes and the hazard assessment applications such as SHETRAN and FSE) (Fig. 1).

2.3.1. User interface

2.3.1.1. Portals and portlets. Users access and use the MEDIGRID system through a Grid Portal and a series of portlets which provide a personalised interface to the Grid. Grid Portals are enhanced versions of Web Portals, themselves being web-based applications. Web Portals, such as those used by Yahoo or Amazon, are in common use on the internet. In much the same way that these Web Portals deliver specific, targeted, mainstream services (e.g. email, calendar, search, mapping, file storage and visualisation) to large numbers of users through a single, integrated user interface, Grid Portals deliver a shared access point to Grid services and resources. A Grid Portal therefore communicates with, integrates and manages Grid-enabled applications, services and resources.

Portlets run within portals. They are reusable web components that display relevant information to portal users. Common web applications include the display of email, weather reports, discussion forums and news. Portlet standards are such that portlets can be plugged into any portal supporting the standards. The portlet specification allows interoperability between portlets and web portals. This specification defines a set of Application Protocol Interfaces for portal computing, addressing the areas of aggregation, personalisation, presentation and security.

To facilitate user interaction and management of the MEDIGRID system, the Grid Portal software, GridSphere[13], has been implemented. GridSphere is an open-source portlet framework that offers many common Grid Portal features and functionality (e.g. single sign-on, credential management, job submission, job monitoring, resources management, file transfer). GridSphere enables developers to quickly develop and package third-party portlet web applications that can be run and administered within the GridSphere portlet container.

2.3.1.2. System operability. All the individual hazard assessment models are controlled via the MEDIGRID portal through a set of configuration portlets. These portlets allow portal users to operate the models remotely and interact with them as if they were actually sitting at the machine on which the application is running. In addition, the portlets allow users to specify model interconnectivities (i.e. how and which models are chained), required outputs and their display properties. Portlets to enable various stages of model setup from input dataset selection to individual configuration parameter adjustment are under development.

Although the initial datasets for the standardised, distributed, data repository are populated with physical, climatic and field measurement data, provided by MEDIGRID partner countries that regularly suffer forest fires, users outside the consortium will eventually also be able to add to the datasets and run the models.

2.3.2. System services

2.3.2.1. Grid services. Current Grid middleware implementations do not have full multiplatform support. In the MEDIGRID project, certain simulation applications are closely bound to the Windows operating system, whilst others can be executed only on a Linux platform. This means that the underlying data Grid infrastructure must be operable on heterogeneous resources. Several standard Grid data management components, however, such as the current implementation of the GridFTP, the basic Grid transportation mechanism, function only on a Linux platform. Grid services for job

[11]Global Grid Forum. http://www.ggf.org/ (visited May 2006).

[12]OASIS, 2006, Organisation for the Advancement of Structured Information Standards, http://www.oasis-open.org/ (visited October 2006).

[13]Gridsphere portal framework project, http://www.gridpshere.org (visited May 2006).

submission and data services have therefore had to be developed and implemented separately[14] (described next). They have been developed using the Globus Toolkit's Java WSRF Core.[15] This is a common set of Web Services specifications for resources, events and management such as communication protocols and formats.[16]

2.3.2.2. Data management

2.3.2.2.1. Requirements. In large distributed computing systems, especially in the scientific or engineering fields, data management poses considerable issues. Firstly, the organisation of data, data security and access policies vary between partner sites. For example, some data sets are freely available but others are proprietary and can be used only by members of certain organisations owing to license agreement issues.

In addition, several input data sources for the applications and many simulation results must be stored, maintained and accessed within the MEDIGRID system. To facilitate use of the data managed in the MEDIGRID, metadata must be kept and made available for the users to search. Moreover, experimental results of a single simulation can be composed of multiple data files and must be locatable as a single result data set. Within the metadata service, it is therefore necessary to exploit the concept of logical file collections.

In order to address these requirements, the MEDIGRID data transfer service (DTS) has been integrated with the Replica Location Service (RLS) and the Metadata Catalogue Service (MCS) (see Fig. 2) (see footnote 14). RLS is a component of the Globus toolkit (Foster and Kesselman, 1997)[17] and MCS[18] is a separate component developed as part of the GriPhyN[19] and NVO[20] projects.

[14]More details at http://ups.savba.sk/medigrid/index.php/Welcome.

[15]Web Service-Resource Framework http://www.globus.org/wrsf/ (visited October 2006).

[16]http://www.globus.org/alliance/news/, http://www-128.ibm.com/developerworks/webservices/library/specification/ws-roadmap/.

[17]http://www.globus.org/toolkit (visited September 2006).

[18]The Metadata Catalog Service, http://www.isi.edu/~deelman/MCS/ (visited January 2006).

[19]GriPhyN 2006, Grid Physics Network, http://www.griphyn.org/ (visited October 2006).

[20]National Virtual Observatory Metadata Working Group, http://www.nvo.ncsa.uiuc.edu/VO/metadata/ (visited October 2006).

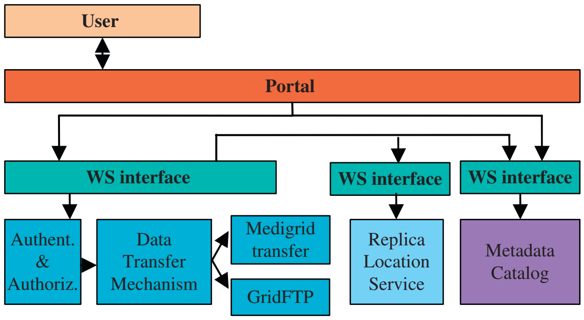

Fig. 2. High-level architecture of MEDIGRID data services layer (WS = web service).

2.3.2.2.2. Data transfer service. Three important features of the DTS are

- integration with the RLS and MCS,
- fine grained data access policies,
- data transfer mechanism for heterogeneous resources.

In a Grid environment, it is necessary to identify files stored anywhere on the system. Within MEDIGRID, two levels of file names are used. A logical file name (LFN) is a unique name and an identifier of the file in the distributed environment, whilst a physical file name specifies the exact location of the file in the system (e.g. protocol, site/service URL, path to file in local file system). By integrating the DTS with RLS and MCS, when a new file replica has been created using the data transfer capability, the replica is automatically registered in the central catalogues (RLS, MCS). Users need to specify only the LFN for data transfer (e.g. Request: 'deliver file with LFN A to the site S1') and the transfer service will automatically determine the exact physical location of the required data sets.

Fine-grained data access policies are dealt with using authorised data resources. Within MEDIGRID the term 'data resource' is used to mean a directory in the file system of a MEDIGRID site, which is registered in the site's DTS and is associated with the resource access list. Each site can contain multiple data resources. A 'resource access list' is taken to be a file containing a list of Grid users (i.e. the names specified in each user's certificate) who are authorised to access the resource. Access privileges are also defined (read only access, read/write access). The users specified in the resource access list are authorised to access all files stored in the data resource. This simplifies the administration of data access rights, compared with resource security models that require an access control list for each distinct file. However, the inability to define non-default access rights to specific files may be restrictive and a potential drawback. To make the system more flexible, the creation of a specialised resource access list for each subdirectory of the data resource is allowed, which overrides the default.

The communication for the data transfer between two Grid nodes happens at two levels. The service information for the transfer (e.g. file name, user credentials, etc.) is exchanged at the web service level, whilst the transfer of the actual data is performed using Java sockets. Each node is capable of both download and upload operations.

2.3.2.2.3. Metadata catalogue and presentation layer. The MCS (see footnote 18) is used in the MEDIGRID project for metadata management. MCS is a Grid-based metadata catalogue that addresses the need of the Grid environment to facilitate data publishing, discovery and access for large-scale data sets. It allows the association of multiple metadata categories and their values with any LFN existing in the catalogue. Different logical files can have different metadata attributes associated with them.

The complexities of the distributed Grid data management system could discourage users wishing to use the MEDIGRID system, so many of these have been hidden away (Fig. 3). The Grid Virtual Directory System (VDS) is an extension of the RLS and MCS. VDS allows the creation of structures of virtual directories for simplifying the logical organisation of the data files distributed across the Grid. VDS hides from the user most of the data management-related operations that must be performed in a Grid environment (e.g. data replication, manipulations with the catalogue services (RLS), metadata catalogues). This concept permits the user to view and manipulate the files in the Grid in much the same way he or she works with the local file system on his or her workstation. VDS is also integrated

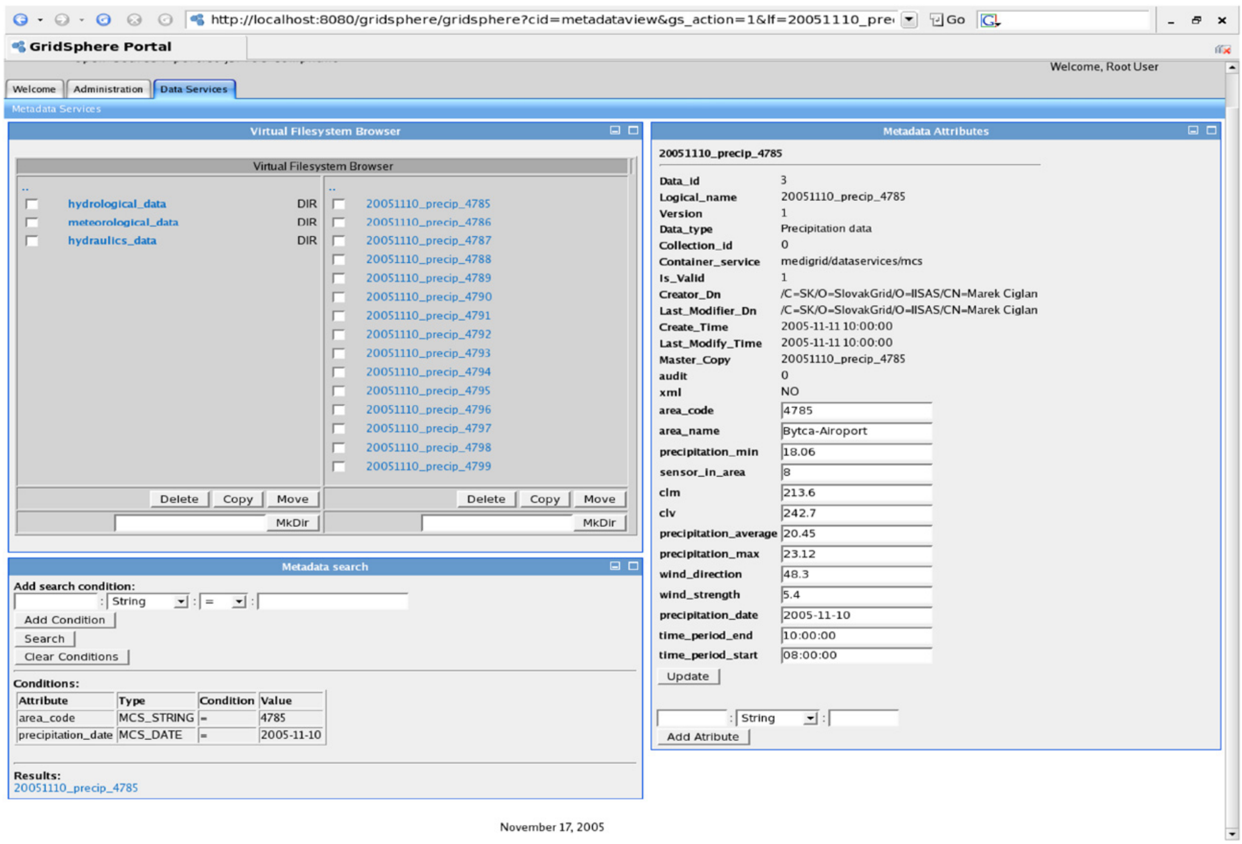

Fig. 3. Presentation layer for metadata service: Grid Virtual Directory Browser (top-left), metadata viewer and editor (top-right), metadata search (bottom-left).

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with the job submission user interfaces, allowing the simplification of the data sets definition for the Grid jobs. Except for metadata viewing, editing and metadata search, the integration of VDS in the user interface provides the users with the capability for browsing the metadata catalogue in a comfortable way. The MCS capability to create and maintain logical aggregations of LFNs allowed the creation of the VDS system. However, additional implementation effort was needed to provide all the necessary functionality.

2.3.2.3. Job management. The main constraint of the DTS, namely the required ability to support applications bound to both Windows and Linux, also applies to job management, thus limiting the choice of available job management Grid tools.

When designing the MEDIGRID job services, an important restriction on the functionality of the service was made so that the specification of the binary file that will be executed as part of the job submission is denied. The executable is always fixed for a specific instance of the service. This constraint has many benefits. It provides fixed application functions, limits security threats by not allowing users to run arbitrary code, makes the application environment easier to maintain and hides platform differences from the job submission process. Although fixed-binary job services were thought to be better suited for the MEDIGRID project, when dealing with computationally demanding jobs (sequential and parallel), an option is also given to configure the service to forward the job submission to a GRAM service of the Globus toolkit (Foster and Kesselman, 1997), thus allowing the exploitation of classical unrestricted computational Grid resources.

The Java WSRF implementation provided by Globus toolkit was chosen as a base for implementing the MEDIGRID platform-independent job submission service. Platform independence is on the level of service interface and its semantics. The actual executable binary must be compiled for the target platform. There is, therefore, a separate deployment of the service for each kind of application that is to be run on the machine. The deployed service instances differ in the names associated with the executable binaries and, possibly, by other parameters like maximum execution time, job manager used and so on.

The job submission service provides the ability to run the executable associated with parameters provided by the job submission request. Currently, two job managers are implemented. The first one is a ‘‘local job manager’’, which starts the jobs locally using the ‘‘fork’’-like mechanism on both Linux and Windows with parameters passed to executables as environment variables. Job requests are queued by the job manager and are run in the ‘‘first come first served’’ manner in order not to overload the host (see Fig. 4). The second job manager is the ‘‘GRAM job manager’’ which forwards the actual job submission to the GRAM submission service of the Globus toolkit and works as a wrapper over it.

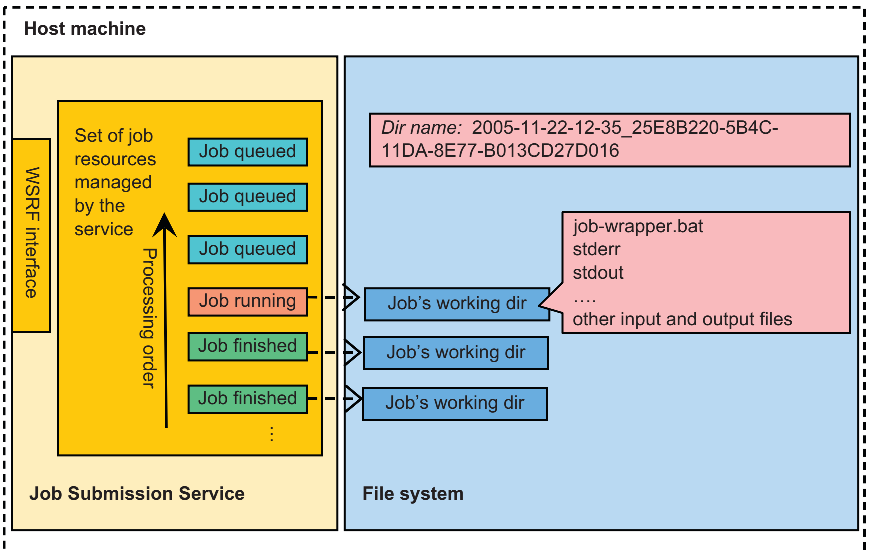

Fig. 4. Schematic of job submission service and its associated resources on a host machine.

The jobs are internally implemented as WSRF (see footnote 10) resources and their status data are exposed as resource properties, thus allowing queries in a standard manner and supporting change notification.

2.3.3. User services

The MEDIGRID user services are the computational nodes which host the natural hazard models based around the forest fire hazards. These are (1) models of pre-fire management such as fire risk mapping for prevention planning; (2) models of fire behaviour such as simulations of fire propagation to aid management of fire containment and suppression; and (3) models of post-fire management and effects, such as flooding, erosion and landslide risk and regeneration.

All six project partners act as computational (or process) nodes. A fire risk assessment model is provided by ALGOSYSTEMS and is based on two commonly used indices, the Canadian (Van Wagner, 1987; Lee et al., 2002) and Portuguese (Gonçalves and Lourenço, 1990) indices. These assess the impact of meteorological factors on vegetation by means of a modified ignition–propagation probability based on the vegetation moisture content. Fire propagation models are provided by several partners. ALGOSYSTEMS provided the FMIS fire simulator (Sphyris, 2001), a model based on the USDA BEHAVE fire behaviour assessment system (Andrews, 1986) and the NUATMOS (Ross et al., 1988) model for simulating wind field, ADAI provided the FireStation system, aimed at simulating fire spread over complex topography (Lopez et al., 2002), and TECNOMA provided the FSE model which is described below. Post-fire effects are simulated using a variety of different hazard assessment tools. A flood forecasting system is provided by IISAS, an erosion model is provided by CEREN, the SHETRAN hydrology, erosion and landslide model is provided by Newcastle University, and a post-fire vegetation regeneration growth model (part of the PROMETHEUS[21] system) is provided by ALGOSYSTEMS.

Each computational node has been fitted with various key services which perform different functions (see also Fig. 1); the service core component is the simulation program itself, whilst the job management service, apart from monitoring the service core, queues and schedules jobs for execution, passes textual configuration parameters to each job and informs the notification management module about any job state change. The notification management component provides the job status in terms of 'queued', 'scheduled', 'running', 'finished' or 'aborted', whilst the interface component provides functionality of service to the other services. The data access layer wraps the metadata catalogue, RLS and data services.

Other auxiliary services do not involve the computations themselves. These include data transformation tools to help the computational services cooperate, and services that present the results of the simulations in a user-friendly manner. The visualisation service, however, will not be discussed here.

3. Integration of the models into the MEDIGRID system

Within the MEDIGRID system, the user should be able to configure, chain and run each model as a single step process. There are, however, several barriers to integrating models which have been developed in isolation from each other, have been written in different programming languages, for different operating systems and which require different input and output data formats, structures and contents including varying spatial and temporal resolutions. Integrating such models has required work by all partners to identify common links between model inputs and outputs and where necessary to develop pre- and post-processing tools to translate data from and into a common format (chosen to be GRASS[22] ASCII) so that information can be shared between the models.

The aim of both pre- and post-processing is to enable models to be chained together so that outputs from one model can flow as input into another model. In this way, the models work together as a single multi-risk assessment process, as opposed to in isolation from one another.

Certain models share a common natural link in terms of input/output components. In particular, forest fire simulation models can easily be chained with models of other natural risks, more particularly those dealing with soil and vegetation properties. Erosion, landslides and flash-floods are of primary importance for land managers whose territories are affected by fires. A recent and dramatic example of multiple natural disasters

[21] EC/DG XII, Contract n. ENV4-CT98-0716.

[22] http://grass.itc.it/devel/index.php.

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occurring after forest fire is highlighted by events in the province of Galicia (northwest Spain) during the summer of 2006. Galicia suffered hundreds of fires followed by extensive flooding and erosion. The floodwaters also transported debris and ashes from the burnt areas to the coast, resulting in damage to Europe's richest shellfish beds.

The following section discusses the integration of the FSE and SHETRAN models into the MEDIGRID system. Model adaptations and linkages between the two models are also described. Changes in vegetation cover resulting from forest fires are output in the form of a map by the forest fire model and are input to the SHETRAN model, which in turn generates amongst other products, landslide, soil erosion and hydrological outputs, appropriate as input to the post-fire vegetation regeneration model. A user can therefore investigate the effect of different intensities and spatial occurrences of forest fire on hydrological, soil erosion and landslide response (for present and future climates) and can plan different strategies for vegetation regeneration accordingly.

3.1. The Fire Spread Engine (FSE) model

The FSE, adapted from the CARDIN simulation system (Martínez-Millàn et al., 1991), has been developed within several EC-funded projects (FOMFIS,[23] E-FIS,[24] FORFAIT,[25] AUTOHAZARD[26] and WARM[27]). It is a semi-empirical model that estimates surface fire propagation in the initial stages of a wildfire. It is designed primarily to compute fire behaviour along the flaming front, i.e. the area of fire at its leading edge. The main output is a prediction of the time at which the fire front reaches a particular point, which is an important aspect of fire management.

Surface fire spread is computed using Frandsen's (1971) and Rothermel's (1972) equations in a similar manner to the BEHAVE fire prediction and fuel modelling system (Andrews, 1986). The spread of fire is simulated as a discrete process of ignitions across a regular grid using cellular-automata algorithms. These compute the time the fire needs for travelling from one cell to the surrounding eight as a function of the cell node distance and the fire propagation speed. The fire spread algorithms use values of slope, aspect, fuel model, fuel moisture and wind vector corresponding to each cell. Multiple and simultaneous ignitions can be applied by giving the cell co-ordinates and ignition time. Each ignition point will then generate a different spread pattern and eventually some of the flame fronts would merge.

Fires can spread through ground, surface or crown fuels, or a combination of them. FSE simulates fires that spread due to surface fuels only. Canopy fires are not modelled specifically. However, the model can be used to forecast the appearance of some canopy effects such as crowning and spotting, even if not the effects of fire twirls and firebrand. The fine fuel size (i.e. fuel particles less than 6 mm in size) drives the spread of the fire and is considered to have constant moisture content.

The model has previously been implemented in several applications at the national level in Spain, and it was also used at the regional scale during the 2004 and 2005 forest fire campaigns.

3.2. The SHETRAN hydrology, soil erosion and landslide model

SHETRAN is a general, physically based, spatially distributed modelling system that can be used to run models of all or any part of the land phase of the hydrological cycle (including soil erosion and sediment transport) (Ewen et al., 2000). Through its integrated surface and subsurface representation of river basins, SHETRAN provides not only the overland and channel flows needed for modelling the transport of eroded soil but also soil moisture conditions. It is therefore a basis for simulating rain- and snowmelt-triggered landslides. The landslide component also models the erosion and sediment yield associated with shallow landslides at the basin scale (Burton and Bathurst, 1998). The occurrence of shallow landslides is determined as a function of the time- and space-varying soil saturation conditions simulated by SHETRAN, using standard geotechnical infinite-slope, factor-of-safety analysis. Depending on conditions, the eroded material is routed down the hillslope as a debris flow. If the debris flow reaches the channel network,

[23]FOMFIS: FOrest fire Management and FIre prevention System (ENV4-CT96-0335) http://www.gnomusy.com/publications/19981121_Caballero_FOMFIS.pdf.

[24]E-FIS: Electronic On-line Decision Support System for Forest Fire (C26789).

[25]FORFAIT: Forest Fire Risk Hazard Assessment: A Holistic Approach (IST-1999-10649).

[26]AUTOHAZARD: Automated Fire And Flood Hazard Protection System (EVG1-CT-2001-00057).

[27]WARM: Wildland-Urban Area Fire Risk Management (EVG1-CT-2001-00044).

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the material is injected directly into the channel. In addition, the material deposited along the track of the debris flow may subsequently be washed into the channel by overland flow. The material that enters the channel network is routed to the catchment outlet by the SHETRAN sediment transport component.

Within SHETRAN the spatial distribution of catchment properties, rainfall input and hydrological response is achieved in the horizontal direction through the representation of the catchment and the channel system by an orthogonal grid network and in the vertical direction by a column of horizontal layers at each grid square. The central feature of the landslide model is the use of derived relationships (based on a topographic index) to link the SHETRAN grid resolution (which may be as large as 1 or 2 km), at which the basin hydrology and sediment yield are modelled, to a subgrid resolution (typically around 10–100 m) at which landslide occurrence and erosion is modelled. That is, using the topographic index, the SHETRAN grid saturated zone thickness is distributed spatially at the subgrid resolution. Through this dual resolution design, the model is able to represent landsliding at a physically realistic scale while remaining applicable at basin scales (up to 500 km^2) likely to be of interest, for example feeding a reservoir.

SHETRAN data needs include rainfall and evaporation time series, a digital terrain model and soil and vegetation property maps. Examples of SHETRAN applications are given by Lukey et al. (2000) and Bathurst et al. (2005).

3.2.1. Conversion to web-service

For the models to be fully integrated into the MEDIGRID system, they needed to be network enabled and accessible. Initially, therefore, all the models, including SHETRAN and FSE, had to be modified so that they could be run remotely over the internet as web services. This required that each application be adapted to run as a standalone executable without the use of any graphical user interface.

Unlike some of the other MEDIGRID models, both SHETRAN and FSE were developed as standalone programs and neither has a significant graphical user interface, so only minor modifications to the code were required in order to enable the programs to run as web services. Development work was carried out to alter the arguments that the executables accept at the command line level, in order to allow more fine-grained specification of configuration files and input data sources.

Although all the fire behaviour models of MEDIGRID use input and output files in GRASS ASCII format, SHETRAN uses a set of proprietary format text files as input to the model, so some data transformation routines had to be developed to convert data into and out of the common format. Since SHETRAN requires a large amount of input data in addition to prior knowledge of the physical meaning of the parameters and of their plausible ranges, many of the files for the initial test cases were set up by hand. Users of the system, however, are able to select from various pre-defined SHETRAN configuration input files and customise the SHETRAN configuration parameters (in particular vegetation type and precipitation/evapotranspiration inputs). Advanced users can also alter any input parameter. In addition, users can select which outputs are required, submit a job to SHETRAN, monitor the progress and status of a submitted job and list, view and download model outputs.

Conversions were carried out so that model outputs are in a format suitable for visualisation and analysis through the MEDIGRID portal. For example, within SHETRAN, spatial data in the form of maps (e.g. landslide incidence, catchment properties) are visualised in image (.jpg) formats, whilst other outputs (e.g. time varying river discharge, debris flow volumes) are available to the user to view or download either as ASCII text or as HDF5 (Hierarchical data format) files. Free HDF5 viewers are available as web applets for the user to download and use them independently of the Grid system.

4. Example application

The following is an example application and demonstrates the use of the system and some potential outcomes.

4.1. Spanish test site and forest fire event

The pilot site, consisting of the Sever and Alburrel catchments (Fig. 5), is located within the municipality of Valencia de Alcántara, in the Extremadura region of Spain, close to the Portuguese border. The area is affected by frequent forest fires and as a consequence suffers significant erosion, especially in areas of rougher topography with steeper slopes and shallow soils.

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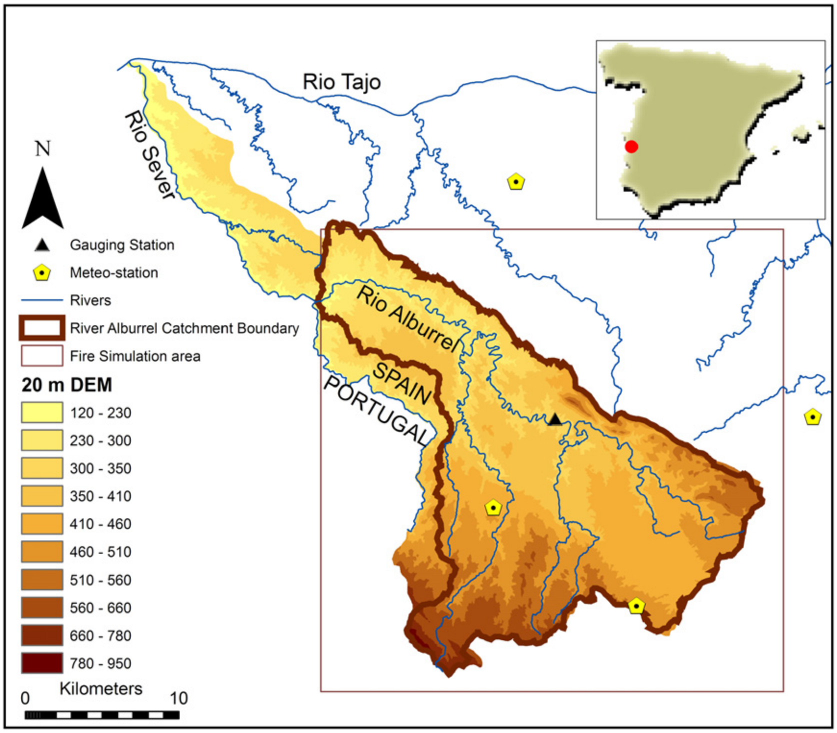

Fig. 5. Location and Digital Elevation Model (DEM) (20×20 m grid) of the study area. FSE is applied to boxed area right of Sever River (shown by DEM), whilst SHETRAN is applied to River Alburrel catchment only. Positions of rivers longer than 10 km, one river gauging station and four rain gauges are also shown.

Extremadura has a rich landscape ranging from plains and mountains to pastures and Mediterranean woodland. An integrated system of landuse called dehesa, maintains agriculture, livestock grazing and forestry in equilibrium and is characterised by savanna-like vegetation. Areas such as acorn and cork oak forests, characterised by dehesa practice are present throughout the catchment. Cultivation is possible only on the more fertile sites located in the lower regions, whilst mature pine stands are present only in the upper reaches of the catchment.

The area is dominated by residual soils that derive from two main lithologies: granites and claystones. The two main soil types in Valencia de Alcántara[28] are Xerochrept (class 95, USDA, 1987), a loamy, deeper soil present in the valleys and Xerorthent (class 45 m USDA, 1987), a shallow, skeletal, silty-clay soil present on steeper ground. A third type, a mix of xerorthent and xerumbrept (class 52E USDA, 1987) is also present over a small area of the catchment.

Extremadura is a semi-arid region with typical Mediterranean climatic conditions. Most of the region receives less than 600 mm rainfall a year. Data from rain gauges (four of which are positioned in and around the pilot site, see Fig. 5) show that inter-annual rainfall is highly irregular, with most rain occurring in spring and autumn. July and August can be particularly dry and hot, whilst winters are cold and relatively wet. The average temperature is about 13 °C with only 10–20 days below 0 °C. Owing to the warm climate and sporadic rainfall, there is a negative hydrological balance in the area, with a sharp minimum in summer followed by a long recharge period, which does not guarantee total recovery of the aquifers in years of drought. The region therefore depends on water from nearby mountains and the large Tajo and Sever rivers.

Only one gauging station exists in the area, station 3-278 (14-76A) on the Alburrel River in Valencia de Alcántara. Data for 1986–2003, from the Confederación Hidrográfica del Tajo, show that

[28] Soil Information is from Cosejo Superior de Investigaciones Cientificas http://leu.irnase.csic.es/mimam/mapa.php3?comarca=CC10&pais=espana&comunid=extremadura&provincia=caceres and http://leu.irnase.csic.es/images/leyendaSUE.gif.

average monthly discharges are less than $6.5\,hm^3$, but can range from 0 to $45.55\,hm^3$ in winter. Average annual discharge ranges from 0.7 to $127.6\,hm^3$ (4–755 mm).

The selected forest fire event was caused by lightning on 2 August 2003. The fire started in Portugal and then crossed the border into Spain from two distinct points. The fire burned actively for 4 days. Although it was controlled on 5 August, a series of secondary fires continued burning until 12 August. A total of 13,692 ha was burned, out of which 5260 ha was forest, 4489 ha was shrubland and the remaining area was a mix of agricultural and other land use. Six villages had to be evacuated (250 people) during the fire management operations.

In addition to the impact on the forest, pasture and crops, the fire caused damage to livestock installations, power and water infrastructures and burned heavy machinery and vehicles. A total of five homes were destroyed completely and a 1000 person working days were lost.

Although the fire affected a large area of Portugal, only the Spanish area affected by the fire is considered here. The selected burnt area lies mainly to the South of the Tajo River where it crosses the Spanish–Portuguese borders.

4.2. Method and input data

For the first stage of the simulation procedure, FSE was used to model the Spanish half of the Sever River catchment (within a square area of $900\,km^2$) using a 20 m digital elevation model (DEM) (see Fig. 5). Four FSE simulations were carried out for the pilot area starting from different ignition points. The simulations were run for 20 model hours of fire propagation (simulation execution time was 14 s), with a simulation time-step of 60 min, dead fuel moisture of 3%, live fuel moisture of 60%, the wind vector azimuth set to 340° and the average wind speed to 22 km/h. The fuel map was determined from a standard fuel classification based on the BEHAVE (Andrews 1986) system.

One of the resulting maps of burned areas was then used as input to the SHETRAN model. This map was chosen to be the one that gave the closest match to the spatial distribution of the selected fire event of 2002. For comparison purposes, two other independent SHETRAN simulations were made, one using the pre-fire vegetation and soil conditions and another using the real spatial extent of the 2002 fire.

Only part of the area modelled by FSE was used as input to the SHETRAN model: the $383.5\,km^2$ Alburrel river catchment area (see Fig. 5). A 20 m DEM was used as input to the SHETRAN landslide component model, whereas a 500 m DEM was used as input to the main SHETRAN hydrology, sediment yield and erosion model (see Fig. 5 and 6a). Other input data included vegetation and soil data, which are given in Fig. 6b and 6c. No soil depth information was available, so soil depths for the deeper xerochrept soil were set to 1 m, whilst the depth for the shallower xerorthent soil was set to 0.3 m based on knowledge of soils from other nearby catchments. The mixed xerorthent and xerumbrept soil type was assumed to be xerorthent only.

Values of soil infiltration rates were taken from a study performed by TECNOMA in 2003 for soils in the Madrid region, which have similar properties to those in the Extremadura pilot site. Infiltration rates for soils under four different vegetation types were examined: a mature pine stand, a young pine stand, shrub land and acorn oak forest. A number of soil samples were taken from both burned and unburned areas for each vegetation cover type and were analysed. The results showed that owing to the effects of fire and the consequential high temperatures in the soil, a significant reduction of the infiltration rate occurred after the fire (see Table 1). This is in accordance with previous studies (e.g. González-Pelayo et al., 2006). In the young pine stands, the reduction in infiltration rate was attributed to poor edaphic structure in the plantation terraces, whilst in the acorn oak stands the lower reduction was attributed to the lower intensity of fire.

For this example application, the mature pine, acorn oak and shrubland infiltration rates were applied directly. However, due to the lack of data regarding the infiltration rates of soils under eucalyptus, the young pine stand results were applied to the eucalyptus vegetation areas instead. No data were available for cultivations and dehesa vegetation types, but very little post-fire change in infiltration rates is expected because of the much lower intensity of the fire in these vegetation structures compared with forested areas. The infiltration rates for unburned areas were then applied in the SHETRAN simulations of the pre-fire catchment condition. For the post-fire simulations, the rates were changed to the values for burned areas for those parts of the catchment

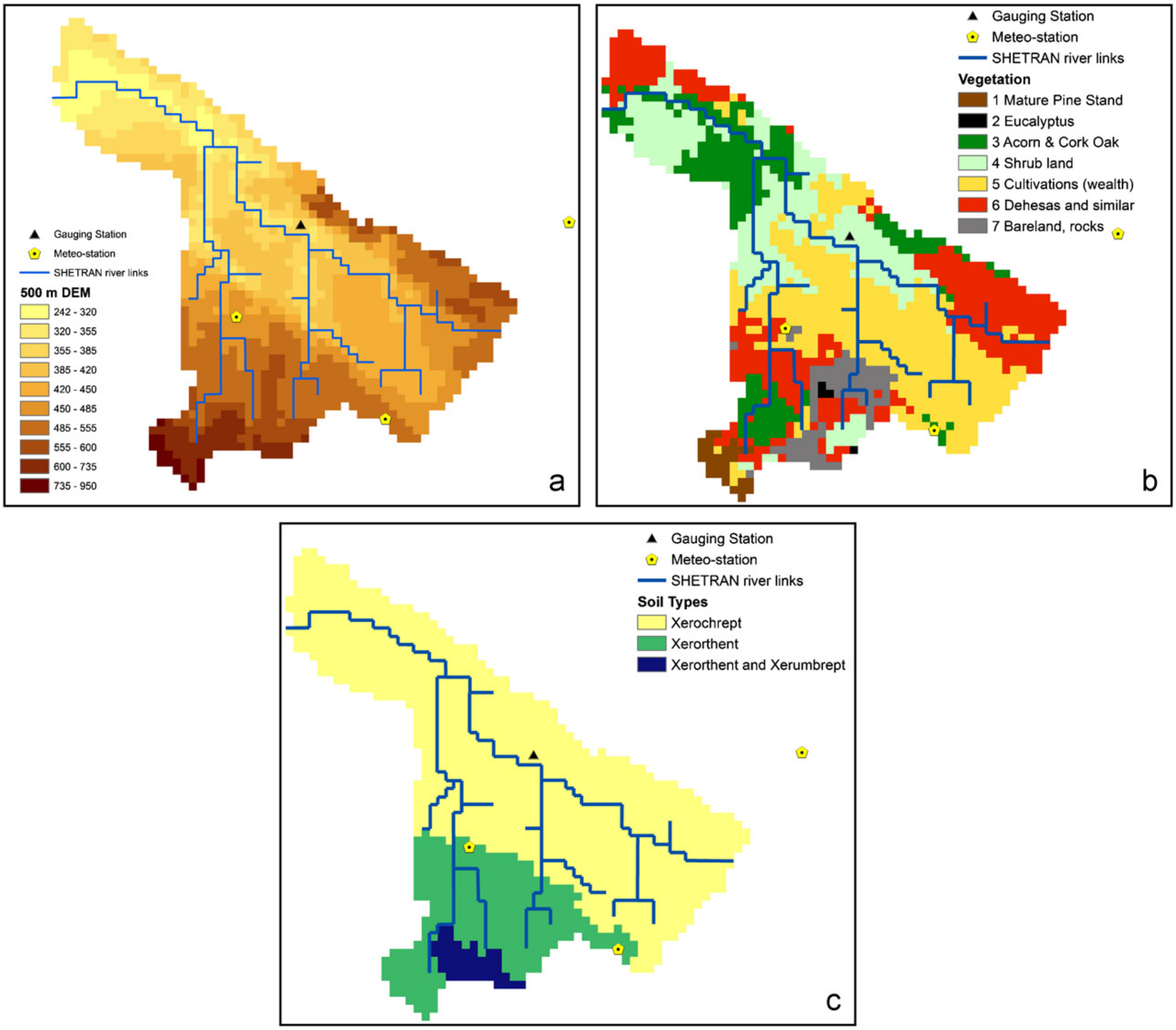

Fig. 6. (a) SHETRAN 500 m DEM grid showing river network, (b) vegetation categories and (c) soil types.

affected by fire. That is to say, SHETRAN received as input maps of the spatial extent of the fire from FSE, which also dictated the new soil properties of the affected soils.

No hourly rainfall or monthly evapotranspiration data were available at the time of writing; therefore, rainfall data available for August 1978–August 1983 from the nearby Cobres catchment, in the Alentejo region of Portugal, (<200 km distance) was used for demonstration purposes (Bathurst et al., 1996).

Although not all the SHETRAN parameter values were based on measurements or observations, as these were not available, and the results have therefore not been validated, the outcomes show the potential use of the system and some tentative results.

Table 1
Average values of infiltration rates for soils under various types of vegetation as measured by TECNOMA for soils in MADRID

	Infiltration rate (mm/h)	
Vegetation type	Unburned area	Burned area
Mature pine stand	716.5	267.0
Young pine stand	215.5	132.6
Shrub land	812.9	179.6
Acorn oak stand	413.5	310.4

5. Results

The results of four FSE simulations, each using a different ignition point, are shown in Fig. 7a and b. The simulation that produced the closest match to the extent of the 2002 fire, assuming just one ignition point, was chosen as input to SHETRAN (labelled 0 in Fig. 7a). A simulation with two separate origins, however, would have resulted in a better match to the 2002 fire because the fire originated in Portugal and entered Spain with two separate strands.

The actual extent of the 2002 fire is shown in Fig. 7c. Both the simulated and real extents of the fire within the Alburrel River catchment were converted into a 500 m grid suitable for input to the main SHETRAN model (Fig. 7d and e). SHETRAN simulations of the catchment in its pre-fire state and with the real extent of the fire were then made for comparison purposes.

Although no discharge data are available for validation purposes, results for the SHETRAN hydrology simulations show that compared with the pre-fire situation, discharges at the Alburrel river outlet in the North-West of the catchment generally increased after fire (see Table 2). This was due in part to the removal of the vegetation layers, and also due to the reduction of infiltration rates in the soil which provided for increased overland flow. It is interesting to note that the discharge simulated at the gauging station was not affected much by the fire simulated by the FSE model. This is because the simulated burned area affected tributary streams joining the main river link downstream of the gauging station. In the simulation using the real extent of the fire, however, a substantial increase in the discharge at the gauging station is seen, as more of the upstream area is affected by the fire.

Sediment yield amounts reflect the river discharge quantities (Table 3). In years with only a small amount of rainfall (e.g. 1979–1980), less erosion of the soil due to the raindrop impact, leaf drip impact and overland flow is simulated, so there is less sediment in the river. Like discharge, sediment yields also increase after fire.

Time varying soil erosion rates over all of the catchment can be calculated by the SHETRAN model. An example of erosion rates for day 179 of the simulation is shown in Fig. 8. Cumulative erosion maps can be used as input to other models, such as a post-fire vegetation recovery model.

It is generally accepted that shallow landslides and debris flows in many soils start on slopes in excess of 25°, in areas with a suitable regolith (non-frictional or weakly cohesive material) and high pore pressures. To reflect this, within the SHETRAN landslide component, landslides are allowed to occur only on slopes greater than 25°. As most of the catchment area has a slope of 25° or less, no landslides were therefore simulated in the pilot area. This is in accordance with no landslides having been recorded in the area.

Once validated, results such as these could help assess potential hazards in an area and could therefore aid decision-making and disaster mitigation policies.

6. Summary and discussion

In summary, the MEDIGRID project offers a unique platform for integrating distributed computer resources. This platform allows a user to access, and use, several completely independent but related models. These can be linked and used in sequence as appropriate. Specifically, the models offered are related to the field of forest-fire hazard and related impacts and can be used to test and assess a range of fire-management scenarios. For instance, a simulation mapping the extent of a particular fire event can be linked with a simulation showing the impact that the fire has on erosion, sediment yield and landsliding. Thus the impacts of alternative scenarios can be assessed and compared. These could include changes in weather conditions (such as wind speed and direction, air humidity, rainfall, etc.) or changes in soil and vegetation properties (such as antecedent soil moisture conditions, land-use and hence surface fuel changes, etc.). The system thus forms the basis for a decision support system.

MEDIGRID differs from other GRID systems, in that the MEDIGRID framework was designed to work with models or applications running on any operating system. Grid services for job submission and data services had to be developed and implemented within the project in order to allow this full multiplatform support. In particular, special attention has been given to the problems of access and security of resources. These components have been designed with the data and model owners in mind. By allowing only specified executables to be run on the system, the system is easier to maintain and security threats are reduced. In addition, owners maintain full control over the

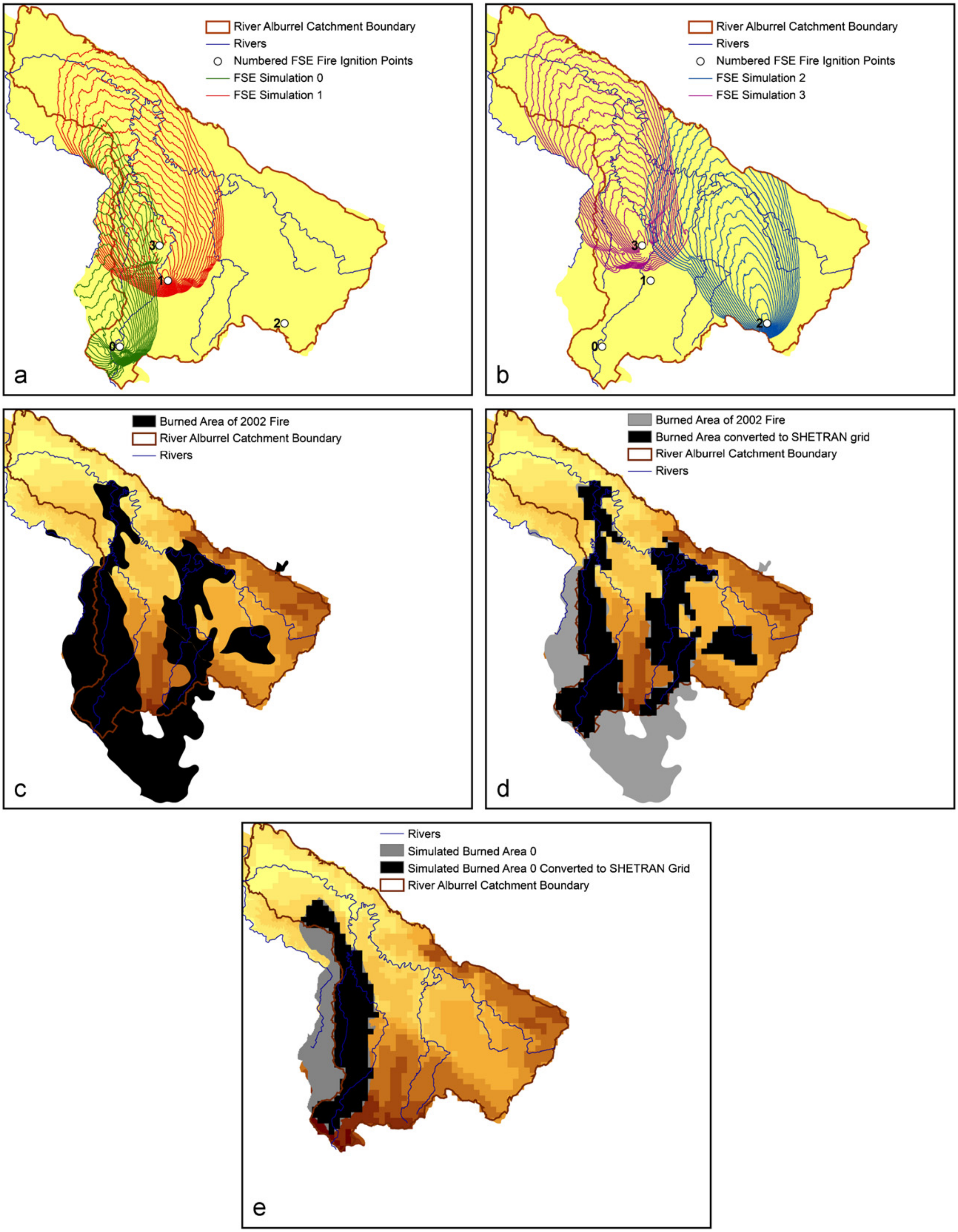

Fig. 7. Four FSE simulation outputs for fires with various origins (a) simulations labelled 0 and 1, and (b) simulations labelled 2 and 3. All simulations ran for 20 model hours. (c) Real extent of 2002 fire, and (d) transformed into SHETRAN input grid. (e) SHETRAN input grid based on FSE simulation labelled 0.

Table 2
SHETRAN simulated discharge for Alburrel River in hm^3/yr for river outlet and gauging station site

	Precipitation (mm)	Pre-fire simulation	Post-fire simulation using FSE simulated output	Post-fire simulation using real extent of fire
August–September		Alburrel River catchment outlet		
1978–1979	813.42	212.42	235.58	268.53
1979–1980	317.75	1.27	1.45	1.72
1980–1981	493.50	12.42	14.63	19.19
1981–1982	628.15	33.29	43.18	56.48
1982–1983	574.85	17.42	26.15	36.52
August–September		Gauging station site		
1978–1979		94.60	94.50	126.01
1979–1980		0.85	0.68	1.03
1980–1981		7.13	6.89	10.34
1981–1982		13.30	13.33	24.48
1982–1983		9.55	9.67	18.61

Precipitation values apply over whole catchment.

Table 3
SHETRAN simulated discharge for sediment yield for Alburrel River in tonne/yr for river outlet and the gauging station site

	Precipitation (mm)	Pre-fire simulation	Post-fire simulation using FSE simulated output	Post-fire simulation using real extent of fire
August–September		Alburrel River catchment outlet		
1978–1979	813.42	28,831.09	33,530.53	34,083.93
1979–1980	317.75	15.49	15.41	10.87
1980–1981	493.50	825.50	1089.97	1363.37
1981–1982	628.15	5430.66	7316.26	9395.02
1982–1983	574.85	1258.58	2183.87	3016.69
August–September		Gauging station site		
1978–1979		12,407.67	12,600.13	14,447.53
1979–1980		15.48	15.37	10.77
1980–1981		553.83	568.97	733.29
1981–1982		1444.21	1503.53	2550.58
1982–1983		594.42	648.80	1068.82

Precipitation values apply over whole catchment.

shared resources they provide by setting access privileges for each user or group of users. Because the data and models are not generally transferred to the user, this makes it possible to share items not usually available due to licensing restrictions. Such arrangements benefit both users and providers. Users can access programs and data to which they may not previously have had access and providers can release their software for use without having problems of compilation of programs on different platforms or issues of security and licensing.

The system itself is relatively user-friendly, providing a personalised interface to the system. General users can either run simulations using existing data, or provide new data sets themselves. During a simulation, the user is kept informed of the status of the job execution by means of error or status messages provided via the portlets. The jobs run at their normal speed on the machines provided by the partners, and data transferred between models (nodes) are dependent upon internet upload and download speeds. Observed data sets are kept separate from simulation results which are stored as a single data set and are available for others to access. This means that simulations do not have to be repeated for different users. Metadata of stored simulation results are searched before a new simulation starts. MEDIGRID also offers generic

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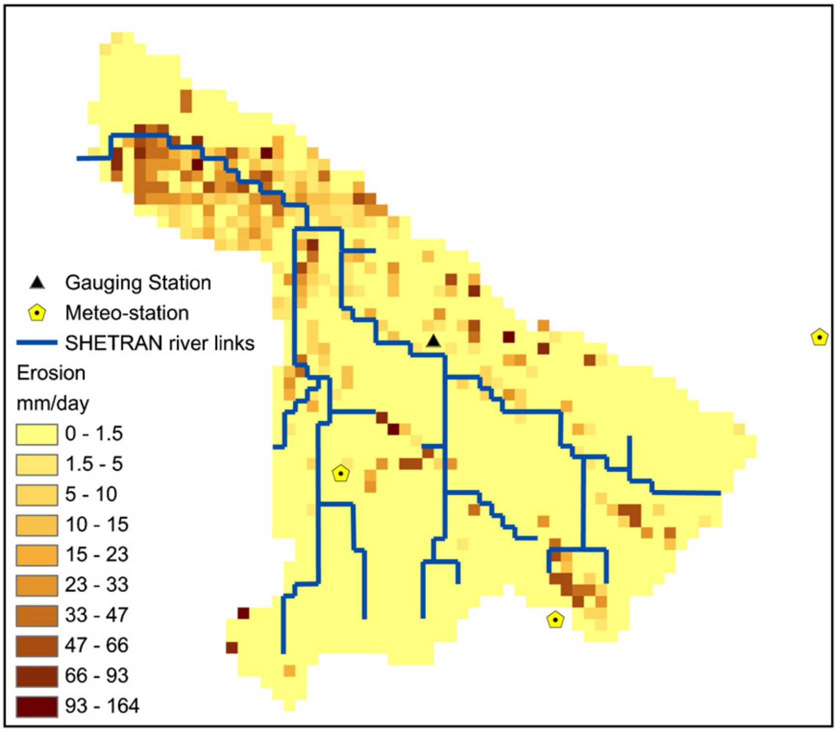

Fig. 8. Example of soil erosion rates over catchment for day 179 of SHETRAN simulation (mm/day).

tools for the visualisation of results. There are therefore many benefits to the MEDIGRID system.

The data and process nodes (i.e. the MEDIGRID partners) provide the necessary computing resources for storing data and for running a particular application. The MEDIGRID nodes are therefore responsible for the upkeep and maintenance of their own computing hardware. The idea is that software providers are willing to share their model and provide applicable hardware in order to gain access to other interesting, independent models that could also be linked with theirs. Although the system is currently set up for fixed-binary jobs, an option also exists to run computationally demanding jobs in a parallel fashion. This option is an obvious additional benefit. Similarly, data providers can benefit from being able to complement their data set with others.

To contribute a new model, several steps are required. Initially, it is necessary for a provider to set up dedicated hardware installed with the Globus Toolkit and the other Grid services. Since good documentation is available, installing these systems is relatively easy for the technically minded. A provider must also have access to the internet and be able to solve issues relating to security. One partner had to re-build their system several times following attacks by hackers, whilst restrictive fire walls, such as those in place by universities, impose access problems. Once these issues are solved, the provider must register with the MEDIGRID certificate authority for authentication purposes. Activating the certificate enables access to MEDIGRID resources.

The model provided must be a standalone executable that can run in command-line mode. With the code of many older models, this could already be the case. However, if an application has a built-in front-end, this has to be removed because the environment does not allow for direct user interaction through a portlet. This may require considerable re-writing of the code to allow for command-line arguments. These arguments can then easily be built into a portlet (following the site's documentation), allowing a user to enter, for example, either alpha-numeric variables or select variables or files from a drop-down box. These can either be used to run the model directly, or used for building input files. If the provider wishes, a model's use can be restricted by setting default values for certain parameters. Once the model is registered with the MEDIGRID services, it is available for use. At this stage, if the model has not required substantial modifications, relatively little time has been required by the provider to set up a working system. However, to make full use of the system, the provider should also aim to modify all data and the inputs and outputs of the model so that they can be transformed from and to GRASS ASCII, the MEDIGRID common format, so as to enable data to be transferred between models. This requires further development time.

The MEDIGRID system has been built as a test case and has been limited in development time by the life span of the project (2 years). This means of course that although there are many benefits to the system, it is not yet perfect. One aspect that is not yet fully functioning concerns data transformation tools which allow data to be used by several models. Owing to time constraints, some partners did not fully develop and implement these, and some of the data were provided in a variety of GIS formats. This is not necessarily a problem as partners can work within the virtual organisation to overcome such data-related issues. In addition, although generic aggregation or disaggregation tools for dealing with differences in spatial resolution have not yet been fully implemented, they could be planned for future use. The actual issue of linking models together, however, requires insight into model functionality and data needs and outputs. Considerable time was spent within the project identifying potential linkages between the models in terms of usefulness, feasibility and potential model-parameter exchanges. Differences in spatial and temporal resolution between the models had to be taken into account and it was found that not all models were able to be linked. Problems due to differences in temporal resolution relate to lack of data availability and contrasts in simulation times. For instance, fire simulations, taking seconds to run, are appropriate for simulating scenarios of a few hours to a few days using input data at the minutes-scale, whereas hydrology models such as SHETRAN, which can take several hours to run, can simulate several hundred years, but require inputs at least at the hourly time-scale. Despite differences in temporal resolutions, these models can be quite compatible as shown by the example above. It is therefore the issues of spatial resolution and spatial extent which have proved to be the most restrictive factor when linking models. It is essential when linking models, that all models simulate roughly the same area, and are at least somewhat compatible in spatial resolution (i.e. work on a similar grid scale). For example, a small, fine, high-resolution grid such as that necessary for the flooding model or a fire propagation model may not be compatible with the larger grid size used by a catchment-scale model such as SHETRAN. Likewise, although certain pilot sites within the MEDIGRID project suffered extensive forest fires, these sites did not necessarily contain streams or rivers, or even steep slopes suitable for modelling with the SHETRAN hydrology or landslide components. A certain degree of judgement on the part of the user is therefore required to identify compatible models and test sites.

The issue of model linkages then leads to questions regarding implementation of the models on a real site. The data required by each model can be rather substantial and lists of these, including the essential items, are available for each model. It is difficult enough to assemble the varied data sets required for running one model, let alone several. However, some models fortunately share inputs based on the same data (such as a DEM). Other data (such as soil porosity) may be gathered by organisations interested in applying the models to a particular site whilst collecting related data (such as soil sand/silt/clay proportions or soil type). In the example shown above, the area chosen for simulation was limited by data availability influenced by political boundaries (i.e. although the fire started in Portugal and crossed into Spain in two locations, fire data were available only for Spain), as well as model requirements. The fire model simulated a larger spatial extent than that modelled by SHETRAN, which owing to lack of boundary condition data was limited to simulating not the whole fire simulation area, but a catchment within it. The example worked well enough in this case, but if several models were to be linked or even looped, the final output would be limited to the smallest area. Multiple feedback loops are not necessarily advised, though, owing to issues of uncertainty. Each model has its own associated uncertainties and, although using outputs, such as maps, as inputs to other models does not increase individual model uncertainty substantially, swapping other parameters may do. The user of the system is therefore expected to have at least some basic understanding of the models and their potential use.

This leads to the question of for whom is the MEDIGRID system intended. Currently, the system is relevant to users who have a good knowledge of models and their potential use. This does not mean that end-users need a high level of programming skills, however, as these aspects have been relatively well hidden. Nevertheless, users should be aware of the limitations of the models and not treat them as a black box. Extensive documentation regarding the models and user-support from the model contributors should ensure this. Although the current end-users are model developers, future users can, and should, include decision makers and those interested in impact studies, particularly those working in the environmental sector. The system, in fact, through the MEDIGRID virtual organisation, unites developers and end-users and helps to promote cooperation. Although at this stage the system has not been tailored for use with disaster management organisations, this is certainly a potential use.

The question of whether a model is worth integrating into the system is therefore dependent on whether the model is relatively easy to convert to a command-line executable, and whether the MEDIGRID system promises enough reward for the effort involved. Any model should, in theory, be able to be incorporated into the system, given enough time and effort, including advanced, simple or legacy software. It is of benefit to the user if the model is easy to use, has available documentation and is relatively robust. The model, however, will work as normal, giving any error messages in the standard way. Although the system was designed for existing models, there should be no problems integrating new models.

The choice of whether to invest in a system such as MEDIGRID rather than working directly with independent data and model providers depends on the model providers' requirements. The choice is similar to that of working independently or within a team. Working independently with other organisations has its own advantages. However, the disadvantages can include the time taken to locate compatible models, enter into negotiations about model use and licensing requirements and getting suitable data. In addition, working with several models can require building different data transformation tools for each model rather than just building one generic set. The MEDIGRID system provides many benefits as stated above, including the use of shared data resources, plus the support of other partners within the virtual organisation. However, a system such as this works only if there are sufficient related models and organisations already involved in the project to make investing in such a system attractive to others. MEDIGRID is very much a team effort and, as such, no one partner could have built the system alone. Likewise, each partner was dependent on the actions of others. The success of the project was therefore dependent on all those involved.

As the project has come to an end, the system continues to work on a voluntary basis. Its continued use will therefore depend on whether the system proves to be useful enough for further investment. The MEDIGRID test case has shown that Grid technology, implemented in the appropriate way, can offer significant benefits to the environmental community. As the system is designed to be able to incorporate any model, in the future, a range of codes could be offered so that the user can choose the best models for their purpose, and outputs from related codes can be compared. Also, the continued development of data management and transformation tools will enhance the use of the system. In addition, the system would benefit greatly from the application of the OGC/ISO/INSPIRE specifications for harmonising spatial data in a standardised way.

7. Conclusion

The prototype MEDIGRID system test-bed provides the natural hazard impact assessment community with a functional distributed computing platform capable of exploiting Grid computing standards and technologies. This is intended to support improvement in impact assessment and decision making focussing on the consequences of forest fires. In addition, as an early, real world example of a large-scale environmental Grid computing system, the MEDIGRID project provides concepts, advice and philosophy on the challenges encountered whilst setting up the system, relevant to other scientific communities who may be thinking of implementing similar systems in the future. The complete MEDIGRID system will also serve as a platform for future research and development into how members of both the academic and industrial environmental hazard/risk impact assessment communities can better collaborate through the sharing of vital (hardware/software/data) resources to improve the decision-making processes and outcomes of environmental impact assessment.

The MEDIGRID portal implementation serves as a demonstration access point for users to interact with the MEDIGRID system. Virtual organisations, like the one formed by the MEDIGRID

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project partners, can improve collaboration and knowledge through the sharing of resources essential to providing accurate assessments of environmental hazard impacts.

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