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AEGIS: a wildfire prevention and management information system

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Abstract

A Web-GIS wildfire prevention and management platform (AEGIS) was developed as an integrated and easy-to-use decision support tool (http://aegis.aegean.gr). The AEGIS platform assists with early fire warning, fire planning, fire control and coordination of firefighting forces by providing access to information that is essential for wildfire management. Databases were created with spatial and non-spatial data to support key system functionalities. Updated land use/land cover maps were produced by combining field inventory data with high resolution multispectral satellite images (RapidEye) to be used as inputs in fire propagation modeling with the Minimum Travel Time algorithm. End users provide a minimum number of inputs such as fire duration, ignition point and weather information to conduct a fire simulation. AEGIS offers three types of simulations; i.e. single-fire propagations, conditional burn probabilities and at the landscape-level, similar to the FlamMap fire behavior modeling software. Artificial neural networks (ANN) were utilized for wildfire ignition risk assessment based on various parameters, training methods, activation functions, pre-processing methods and network structures. The combination of ANNs and expected burned area maps produced an integrated output map for fire danger prediction. The system also incorporates weather measurements from remote automatic weather stations and weather forecast maps. The structure of the algorithms relies on parallel processing techniques (i.e. High Performance Computing and Cloud Computing) that ensure computational power and speed. All AEGIS functionalities are accessible to authorized end users through a web-based graphical user interface. An innovative mobile application, AEGIS App, acts as a complementary tool to the web-based version of the system.

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1 Introduction

Weather, topography and fuel patterns along with socioeconomic conditions are factors that increase the complexity and uncertainty of wildfire management. Expected impacts of climate change, including global increases in wildfire severity and frequency, further complicate the problem of wildfire risk management (Abatzoglou and Kolden, 2013; Kalabokidis et al., 2015). Decision support systems are increasingly being developed and applied in a number of different capacities including protecting firefighters, tactical strategies, landscape fuels planning, and environmental protection (Ager et al., 2011; Kalabokidis, 2004; Miller and Ager, 2013; Noonan-Wright et al., 2011). Acquired knowledge from these information systems enables fire protection agencies to spatially define and identify forecasted high risk areas, in the short- and long-term, and plan the necessary preventive and control actions as part of a wildfire risk governance system (Miller and Ager, 2013; Taylor et al., 1997).

There are many challenges associated with building and deploying wildfire decision support tools. Ideally, an integrated wildfire prevention and management system should provide instant access to functionalities such as fire danger forecasts, fire behavior prediction, active fire detection, access to historical fire data and fire damage assessment. In terms of usability, such a system should be fairly intuitive, so that end users can utilize it without specialized knowledge on performing fire science related modeling. From an implementation standpoint, the system must have the capacity and reliability to meet the demands users pose during the peak of wildfires without excessive requirements for maintenance.

Tailor-made wildfire decision support systems have been developed and used in a number of different wildfire regions, including Spain (Alonso-Betanzos et al., 2003), France (Figueras Jové et al., 2014), Italy (Losso et al., 2012), Turkey (Gumusay and Sahin, 2009), USA (Noonan-Wright et al., 2011), and in the alpine areas of Europe (Corgnati et al., 2008). Despite the large number of systems few of them can be considered fully integrated solutions to the wildfire management problem, and generally

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each of the aforementioned systems has emphasized a specific decision support functionality.

A good example of this lack of integration has been the development of decision support systems in the country of Greece, where the current firefighting strategy does not integrate a holistic system of geospatial and decision support tools, but instead relies on independent software and systems that are used separately to accomplish simple operational needs. These systems include Google Earth for mapping and data handling, the European Forest Fire Information System (EFFIS, San-Miguel-Ayanz et al., 2002) for current situation assessment (especially for post-wildfire burned area estimation), Google Maps on custom made simple web applications for wildfire events registration, and daily fire risk maps from the General Secretariat for Civil Protection (GSCP)[1].

The current wildfire management scheme in Greece evolved from many previous efforts that include both conceptual and applied approaches to the problem. For instance, Iliadis (2005), Kaloudis et al. (2005), and Kaloudis et al. (2008) introduce theoretical approaches regarding wildfire prevention and management systems in Greece, but the ideas were never implemented. On the practical side, applications developed by Caballero (1998), Vakalis et al. (2004), Bonazountas et al. (2007), and Kalabokidis et al. (2012) resulted in standalone systems that were difficult to use due to requirements for local installations of specific software components. These issues were partially overcome when Koubarakis et al. (2013) introduced a web based real-time fire hotspot detection service for effectively monitoring a fire-front, based on the use of acquisitions originating from the SEVIRI (Spinning Enhanced Visible and Infrared Imager) sensor of Meteosat satellites. However, this approach emphasized only real-time wildfire monitoring and thus, it is not an integrated wildfire management system.

The first attempt to develop an integrated and distributed system for Greece was Virtual Fire (Kalabokidis et al., 2013a) that was employed on a web-based Geographic Information System (GIS) platform designed to deliver forest fire related information. It

[1]http://civilprotection.gr/en

provided spatial fire ignition probability estimation (Vasilakos et al., 2007, 2009), visualization of weather forecast maps, access to real time weather data from Remote Automatic Weather Stations (RAWS) and fire management tools (e.g. fleet tracking, routing, closest facilities and RSS feeds). While overcoming many integration and implementation shortcomings of the previous systems, the key functionality of fire behavior simulations could be conducted only with the assistance of a system administrator. The application consisted of two high performance computing (HPC) nodes for the spatial calculations, while dependent on commercial ArcGIS[2] software for spatial data visualization and support of geo-processing tasks. The financial cost to maintain/operate the system on-premises was significant, even though the system had been applied for a relatively small area of about 1600 km^2 (i.e. Lesvos Island, Greece). This platform evolved into the VENUS-C system (Kalabokidis et al., 2014b) consisting of a wildfire risk and wildfire spread simulation service, delivered within a web-based interactive platform to the fire management agencies as Software as a Service (SaaS) in the Cloud Computing platform of Microsoft Azure. The wildfire risk service calculated and provided to the end user daily hourly maps of the forecasted fire risk for the next 112 h in high spatiotemporal resolution, based on forecasted meteorological data. In addition, actual fire risk was calculated hourly, based on meteorological conditions provided by RAWS. Regarding the wildfire behavior simulation service, end users were able to simulate fire spread by simply providing an ignition point and the duration of the simulation, based on the HFire algorithm (Peterson et al., 2009). The instant and prompt availability of processing power, along with the cost effectiveness, reliability and scalability of the Azure Cloud were the main advantages of the VENUS-C system.

Parallel efforts to develop universal fire management decision support tools for application in multiple countries has led to a number of applications. In the European Union (EU), the EFFIS system supports the services in charge of forest protection against wildfires for over 30 countries in the European and Mediterranean regions (San-Miguel-Ayanz et al., 2002). EFFIS is considered a comprehensive system covering the

[2]www.esri.com

full cycle of forest fire management, from forest fire prevention and preparedness to post-fire damage analysis. The services include fire danger forecasts, active fire detection through MODIS satellites, rapid damage assessment and post-fire modules dealing with the analysis of land cover damages, post-fire soil erosion, emissions estimates and dispersion of the smoke plume, and finally the monitoring of vegetation recovery in large burned areas. EFFIS estimates fire danger based on the Canadian Fire Weather Index (FWI) (Van Wagner, 1987), while weather forecast data are provided by Meteo France[3] and DWD (Deutcher Wetterdienst)[4].

Comprehensive systems were also built in the US and Canada. A strategic and tactical suppression system was built in the US (Wildland Fire Decision Support System, WFDSS) (Noonan-Wright et al., 2011) and is widely used for incident support. In Canada, the Canadian Forest Fire Danger Rating System (CFFDRS) (Lee et al., 2002) is used for predictive services. WFDSS assists fire managers and analysts in making strategic and tactical decisions for fire incidents with a system that is easy to use, intuitive, linear, scalable, and progressively responsive to changing fire complexity. WFDSS uses the National Fire Danger Rating System (NFDRS) (Burgan, 1988) for fire danger estimation, while data from RAWS (Zachariassen et al., 2003) are utilized for weather analysis. WFDSS also provides damage assessment for the affected area based on the Rapid Assessment Values at Risk (RAVAR) model (Calkin et al., 2011) and the Stratified Cost Index (Gebert et al., 2007). A variety of fire behavior tools are available for analysis of short- and long-term WFDSS decisions. Short-term wildfire behavior simulations (e.g. up to one week) are based on the Minimum Travel Time (MTT) algorithm (Finney, 2002), while long-term simulations are based on the fire spread probability simulator FSPro (Finney et al., 2011a; McDaniel, 2006).

In Canada, the CFFDRS comprises two primary subsystems or modules: the Canadian Forest FWI System and the Canadian Forest Fire Behavior Prediction (FBP) system (Forestry Canada Fire Danger Group, 1992; Taylor et al., 1997). Fire monitor-

[3]www.meteofrance.com

[4]www.dwd.de

ing, mapping and modeling is achieved based on high-resolution radiometer (AVHRR) satellite data to detect actively burning forest fires. The Canadian Wildland Fire Information System (CWFIS) (Lee et al., 2002) is Canada's national fire management information system, presenting daily information on fire weather, fire behavior potential, and selected upper atmospheric conditions.

In this paper, we describe our efforts to leverage previous work in Greece and other EU efforts as well as US and Canada, to more fully integrate and implement a forest fire management system designed for Mediterranean countries. The goal of this work was to provide access to a large number of information services and use state-of-the-art technologies, all combined into a comprehensive easy-to-use web-based Graphical User Interface (GUI). The result was the Wildfire Prevention and Management Information System (AEGIS), which was developed and tested for seven study areas across Greece (i.e. 10 % of Greek territory). AEGIS incorporates parallel computer processing techniques utilizing HPC and Cloud Computing resources to enable the execution of spatial fire danger rating calculations, and fire behavior modeling with the MTT algorithm. Results are made available to users via a robust web-based GUI and a mobile application (app) that acts as a complementary tool to the web-based version of the system. This article presents the core functionality of the AEGIS platform that resulted from a three-year development and testing period. The scalable implementation of AEGIS guarantees its extensibility to the rest of the country, and other Mediterranean regions.

2 Methodology

The development of AEGIS required the prior development of the web-based GUI and the corresponding mobile application. Initially, an end-user's requirement analysis was conducted to gather information and knowledge from key stakeholders in the wildfire management community. Subsequently, data collection and field inventories were performed on each of the seven study areas further described below. These data were processed and inserted into geographic databases (one database for each study area) containing all available wildfire management spatial information. The data were used as inputs for the wildfire behavior modeling and danger rating components of AEGIS. The above mentioned AEGIS components, along with other relevant information are described in detail below.

2.1 Study areas

AEGIS was developed and tested in seven different fire prone study areas with high socioeconomic values in Greece (Fig. 1). Each area covered a mixture of different conditions, either socioeconomic (i.e. rural/urban interface areas, changes in population size/density, etc.) or environmental (i.e. climate, vegetation, topography, geographical distribution, etc.).

The first study area is Kastoria, located at the northwest inland part of Macedonia region, Greece, with a total area of 1720 km^2 (53 483 permanent residents; i.e. 31 persons km^{-2}). Climate change has led to increased fire activity there, even in high altitude mountainous areas such as Grammos, where fire has always been a low frequency natural disaster.

Chalkidiki, which is a three-pronged peninsula located centrally in the coastline of Macedonia, covers an area of 2886 km^2 (80 000 permanent residents; 28 persons km^{-2}). The region is heavily wooded with pine, oak and beech forests around olive cultivations, vineyards and fertile farmlands inland.

The island of Lesvos (90 000 permanent residents; i.e. 55 persons km^{-2}) is located in the northeastern Aegean Sea and covers an area of 1636 km^2. Lesvos encompasses high fire-prone and fire-risk ecosystems of Greece. Pine forests and olive groves dominate almost half of the island's area, making it one of the most tree-covered islands of Greece.

West Attica, located in central Greece, is close to the metropolitan area of Athens and covers an area of 1060 km^2 (151 038 permanent residents; 143 persons km^{-2}).

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The area is affected by large wildfires and is under continuous urban pressure, industrialization and farming/livestock economic activities.

Messenia is located at the southwest edge of Peloponnesus region with a total area of 2991 km^2 (176 876 permanent residents; i.e. 59 persons km^{-2}). During the summer of 2007, devastating forest fires affected a large portion of Peloponnesus, including Messenia which is a high-hazard area diachronically.

Rhodes Island is located in the southeastern Aegean Sea and covers an area of 1400 km^2 (117 000 permanent residents; i.e. 83 persons km^{-2}). There are intense human pressures on the island's ecosystems due to a developed tourism infrastructure and from urban expansion into the wildland-urban interface to cover housing and recreational needs.

Finally, Chania (156 371 permanent residents; i.e. 66 persons km^{-2}) is located in the western part of Crete Island, covering 2375 km^2 of which 1476 km^2 are mountainous areas. The ever-increasing tourist and human pressure on the area has increased its vulnerability, and recent wildfire events have caused devastating outcomes on biodiversity, social values and economic concerns.

2.2 End-user's requirement analysis

Prior to the system's development, we identified key design and functionality features of the system using a formal information gathering process, plus an analysis of the organizational goals and the corresponding processes that should be followed (Athanasis et al., 2015a). This analysis process started with the most generic goal and concluded in determining concrete objectives, the implementation of which led to achieving the overall objectives set out in the more generic levels. Each final target was associated with one or more processes. The result of this analysis was a Unified Modeling Language (UML) diagram (Fig. 2) that conceptually represented the relationships between the goals and the corresponding processes. Table 1 presents the proposed services, the identified goals and the corresponding processes to be implemented.

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2.3 Architectural components

The architectural components of the AEGIS platform are displayed in Fig. 3. The web-based platform of AEGIS was implemented by utilizing the ESRI ArcGIS Application Programming Interface (API) for Silverlight. The API enables the integration of geo-processing and mapping services provided by the geographical ArcGIS Server. The mobile application AEGIS App (Athanasis et al., 2015b) was implemented by utilizing the ArcGIS Runtime SDK for .NET API.

To utilize the available tools and services of the AEGIS system, users must provide their credentials, stored in a DBMS based on Microsoft SQL Server. The web server hosts the Silverlight application and the weather data management system that is responsible for the automatic retrieval and management of weather forecast data and real-time weather data from several RAWS across the study areas.

The software components of ESRI ArcCatalog and ArcMap are used for the creation and management of all the necessary spatial data and maps. Data are uploaded into spatial databases and published as GIS services through the ArcGIS Server.

On-demand simulations of individual fires and fire danger modeling are conducted inside an on-premises Datacenter (i.e. Aegean University Campus), while seasonal burn probability outputs are initially calculated in Virtual Machines (VMs) in the Cloud infrastructure of Microsoft Azure and then finalized in the on-premises Datacenter. For the creation of the burn probability maps, VMs in the Microsoft Azure infrastructure are allocated on specific time frames (i.e. once per month). After the execution in the Cloud's and/or on-premises VMs, output results are handled by the ArcGIS Server that enables the visualization of the results from the GUI of AEGIS.

2.4 Field Inventories, data collection and geographic databases

One of the main objectives of AEGIS was the collection of spatial and non-spatial data to develop and organize a comprehensive geographic database for each study area to support the various AEGIS functionalities. Data were collected from various agencies from all study areas, including road networks, vegetation types, fuel models, water sources, topographic data, firefighting related data, infrastructure, urban areas, forest management data, historical weather data, etc. Retrieved data were edited, updated or recreated, supplemented by metadata compliant with the INSPIRE Directive[5]. For each geographic database, conceptually similar data were organized in 11 distinct groups (i.e. geophysical, forestry/vegetation, fire history, administration, high risk areas, networks and infrastructure, water sources, high protection sites, annotations, firefighting infrastructure, and raster data and maps) using the ArcGIS software.

Weather forecast maps are prepared daily and stored in geographic databases with the operational use of the SKIRON limited area weather forecasting system, based on the Eta/NCEP model (Janjić, 1994; Kallos et al., 1997). SKIRON covers the entire Greek territory with a high horizontal resolution of 5 km and a forecasting period of five days (120 h). Weather forecast maps of wind speed and direction, humidity, air temperature, cloud cover and precipitation are provided every 3 h for the next 72 h.

Detailed land use and cover type maps were created based on innovative image processing methodologies with high-resolution multispectral RapidEye satellite images (5 m spatial resolution). Field inventories were organized to collect data on vegetation type, stand height, canopy base height and fuel model. The collected information was used in conjunction with auxiliary data, such as vegetation spatial data from the CORINE 2000 vegetation classification system (EEA, 2002) and other forest management data, during the vegetation map creation process. To account for seasonal effects on vegetation, two image mosaics of each study area were used for two time periods of the same reference year. The satellite image processing was conducted in three stages: preprocessing, dividing each study area into homogenous physiographic zones; classification, with a fuzzy set technique and application of a segmentation algorithm; and post-classification, applying convolution filters for image smoothing. Finally, corrections were applied on the results (vector files) by visual interpretation, digitization and cover type characterization over aerial orthophotos.

[5]http://www.ec-gis.org/inspire

2.5 Fire behavior modeling

AEGIS utilizes the MTT algorithm as a cell-based tool for fire behavior predictions and fire danger estimation, in conjunction with FlamMap v.5 modeling capabilities (Finney, 2006). The MTT algorithm is applied in strategic and tactical fire management planning in the US (Ager et al., 2011) and integrated into WFDSS, FlamMap and FSPro. Holding fire weather environmental conditions constant, the MTT algorithm searches for the fastest path of fire spread along straight-line transects connected by nodes (cell corners) (Finney, 2006) and exposes the effects of topography and the arrangement of fuels on fire growth (Ager et al., 2011).

The MTT algorithm can be used to compute potential short-term fire behavior characteristics (rate of spread, fireline intensity, time of arrival, flow paths, etc.) for a single fire or simulate many fires to generate conditional burn probabilities and flame lengths using Monte Carlo stochastic simulations, where fire weather and fuel moisture information varies among the simulated fires (Ager et al., 2007; Finney et al., 2011b). Burn probability is an estimate of the likelihood of a pixel burning given a single random ignition under burn conditions in the simulation. Burn probability modeling represents a major advancement in wildfire behavior modeling and risk assessment compared to previous methods, such as those where fire likelihood was quantified with relatively few predetermined ignition locations (i.e. fewer than 10). As a result, the product of this process is a burn probability map that reveals which areas are more susceptible to encounter a fire event and which are more fireproof. Additional outputs are produced from AEGIS for the entire landscape (flame length, rate of spread, fireline intensity, heat per unit area, crown fire activity, midflame wind speed) using an integrated version of FlamMap.

For individual fire simulations, MTT is implemented within AEGIS in a transparent web-based GUI. When a fire simulation is triggered, a command line execution of MTT starts the simulation inside the HPC cluster. If multiple users begin their simulations simultaneously, each simulation is assigned to one of the available HPC nodes and execution takes place in parallel. Upon the completion of execution, several output files are generated either in GRID ASCII format (arrival time, fireline intensity, ignition point and rate of spread) or vector files with information for regular and major flow paths (Finney, 2006). After output files are created, several ArcGIS Server geo-processing services are executed to convert GRID ASCII outputs to vector format and store them in feature classes inside a geographical database. Finally, ArcGIS Server mapping services retrieves the appropriate information from the feature classes using a filtering process to select the simulation outputs and display map outputs in the AEGIS platform.

In Fig. 4, the information flow for the MTT execution in AEGIS is shown. End users trigger a new simulation (step 1), and the first available machine retrieves the input parameters and starts a new process of MTT execution (step 2). Outputs are stored in a shared repository (step 3) where a geo-processing service retrieves them (step 4), performs the necessary data transformations, stores them in a geo-database (step 5) and, finally, notifies the users that the execution is finished. Visualization of the results is achieved by utilizing mapping services directly over the AEGIS platform (step 6).

Seasonal burn probability and flame length maps are automatically generated periodically (e.g. once per month), by simulating thousands of possible wildfire ignitions across each study area with the Cloud Computing infrastructure of Microsoft Azure. This process is intended to provide regional probabilistic risk-based forecasts of potential fire occurrence and behavior (Kalabokidis et al., 2013b, c, 2014a). During an execution, the VMs in the Microsoft Azure infrastructure are allocated and command line-based executables of MTT ("FConstMTT") are executed simultaneously on each VM.

The phases for conducting seasonal burn probability and flame length maps on Microsoft Azure cloud infrastructure are as follows:

1. *Initialization*: a deployment is uploaded in the Microsoft Azure cloud infrastructure that runs the FConstMTT command line-based executable.

2. *Execution*: parallel execution of the FConstMTT executable is conducted by dividing the overall number of ignition points equally among the available VMs. This partitioning of the ignitions significantly reduces the execution time.

3. *Merging*: the output results are combined into a new ASCII text file to calculate the burn probability and the flame length categories (i.e. 20 categories) for all ignitions.

4. *Extraction*: the burn probability and every flame length category are extracted from the merged output.

5. *Visualization*: the extracted outputs are loaded in a geo-database to be visualized through the AEGIS platform. Furthermore, outputs are available for download from the end users to perform meta-analysis on them (e.g. with ArcFuels).

In Fig. 5, the information flow for the creation of a seasonal burn probability map in AEGIS is presented. The deployment is uploaded from one of the on-premises machines to the Cloud (step 1). Execution starts concurrently at available VMs (step 2). Partial output results are created and a merged file is generated that stores all values for all output categories (step 3). From the merged file, all output categories are extracted in separated output files (step 4), converted to raster files (step 5) and stored in a geo-database (step 6) for visualization purposes (step 7).

2.6 Fire danger

A prototype spatial fire danger estimation system was developed and incorporated into AEGIS, that uses both ignition probability and expected burn area, thus providing an integrated fire danger metric. Initially, artificial neural networks (ANN) were used for the mathematical modeling of conditional probability of ignition (CPI), based on independent variables (i.e. latitude, longitude, altitude, month, day of week, distance from urban areas, distance from power lines, distance from main and secondary roads, distance from landfills, distance from agricultural areas), in conjunction with spatial

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weather forecasts from SKIRON that depict wind speed, rain, relative humidity and temperature. Historical ignitions were used to derive the spatial patterns of wildfire occurrence of each study area, constituting the base of the ANN training procedures.

We experimented with multiple methodologies including the Back Propagation Neural (BPN) Networks (Rumelhart et al., 1986), the Kohonen Networks (Self Organizing Maps) (Kohonen, 1982), and two types of the Radial Basis Function (RBF) Networks (Tsekouras et al., 2015). The back propagation method proved to perform better compared to the other two. As a result, this method was selected and applied for operational use. Development of the final algorithm was based on trial and error techniques. Three different activation functions were tested for transferring the signal between input and hidden nodes; i.e. logistic sigmoid, hyperbolic tangent sigmoid and linear functions. The input parameters were either unprocessed or normalized. Finally, the training process was controlled by the early stopping method, where the number of validation samples and the maximum number of training epochs were monitored (Prechelt, 1998). For each possible combination of the above parameters, a back propagation neural network was developed with one hidden layer of five to 20 processing nodes. Eighty percent of the sample was used for training, while the remainder was utilized during the validation stage. The selection of these samples was randomized during the initialization stage. Each network was trained for ten initializations; therefore, 1008 networks were developed for each study area. Based on the above results, the best performing networks of Root Mean Square Error (RMSE) of the validation dataset were saved for each area and integrated into the graphical interface of AEGIS to be used for the computation and cartographic representation of wildfire ignition risk.

By using FlamMap, the predicted burned area (PBA) is estimated using the elliptical dimensions output grid themes that give the *a*, *b* and *c* dimensions (expressed by rate of spread on meters per minute) for a simple ellipse (Finney, 2001), to derive the burned area per pixel for a time period of three hours. The spatial data of the SKIRON model for wind speed and direction are provided as FlamMap input, while relative humidity and air temperature values are used to estimate fuel moisture values. Finally, CPI is combined with PBA in the matrix of Table 2 to derive the resulting fire danger index in five categories from Low (1) to Extreme (5).

3 Results

All services and data provided by AEGIS are accessible through the web-based interface eliminating the need to install specific desktop software. This minimizes the deployment time and eliminates client costs for software, thus enabling any authorized user to immediately access the GUI from anywhere in the world over the Internet. Users have the ability to perform GIS tasks and utilize the resulting products within the GUI (Fig. 6). The mapping schemes of Bing Maps and Open Street Maps provide high resolution satellite images and detailed thematic maps with annotations and road network information, used as the background mapping layers of AEGIS. Land use/land cover types can also be selected and displayed, along with annotations, study area boundaries and urban areas. Apart from background layer selection, users have access to information to support forest fire suppression efforts. This information includes the road network, water sources, fire watch outlooks, monuments, helipads, gas stations, landfills, evacuation sites, and firefighting vehicle patrol sites. Several tools and services such as live camera image streams, geo-processing tools, and elevation profiling of any area of interest are integrated. Spatial queries regarding the drive time distances from a site and the locations of closest water tanks, fire hydrants and pumping stations are also provided, as well as the analysis of the shortest routes among locations on the map based on the Bing Maps routing scheme.

Furthermore, SKIRON weather forecast maps of wind speed and direction, air temperature, cloud cover and precipitation can also be visualized by selecting the date, time and variable of interest. In addition, real time weather data and weather records from RAWS are provided for any desired time period.

End users are able to conduct fire behavior simulations or access and view previously stored simulations. If the user decides to conduct a new simulation, the ignition

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point (by clicking on the map or by providing coordinates) and the duration time (hours and minutes) of the simulation must be specified. The duration time cannot exceed six hours, since MTT provides higher simulation accuracy for short-term time periods. Real-time wind parameters (speed and direction) are retrieved from RAWS (either the closest to the ignition point or one from the available) or can be user-defined to conduct “what if” scenario simulations with an additional specification of a fuel moisture scenario. After providing the required inputs, users can trigger the “Start Simulation” button. When a fire simulation is initiated, MTT is executed and the necessary input parameters are read from a configuration file generated at runtime. Through the GUI, information is steadily provided regarding the simulation status for as long as the execution is in progress (Fig. 7a). At the end of the simulation, all outputs can be directly visualized by enabling a checkbox next to each mapped attribute (Fig. 7b). Individual outputs can also be downloaded as either kml layers or alternatively, in their raw format (GRID ASCII or shapefiles) as a zip file.

Data and services of AEGIS are also accessible through the mobile application AEGIS App (Fig. 8). The AEGIS App provides access to key services of fire management, especially to the operational end users at the front line. In case of a fire emergency, end users in the field can utilize the mobile app, and the location of the fire is directly incorporated in the graphical interface of the web platform of AEGIS. To the best of our knowledge, this is the first wildfire management application for native Windows Phone devices. Upon opening the AEGIS App, the current end-user location is tracked (received from the GPS sensor of the device) and visualized as a fire vehicle symbol on top of the background mapping schemes (Bing Maps or Open Street Maps). Below the map, options and icons exist that provide access to different functionalities. Several tasks can be accomplished from the AEGIS App, such as routing, spatial search for closest facilities and firefighting support infrastructures, access to weather data and visualization of fire management data (water sources, gas refill stations, evacuation sites etc.). An innovative feature of AEGIS App is the support of these tasks by a new digital assistant for artificial intelligence named Cortana (developed by

Microsoft for Windows Phone devices), that allows information utilization through voice commands. The voice commands are executed in an automatic and transparent way and the result is visualized on the screen of the mobile phone without any further user intervention. Especially during a fire emergency, this feature absolves the end users from text typing and filling of forms, which can be a very time consuming task.

Results of wildfire propagation and fire danger rating for six of the larger fire events that actually started and burned in our study areas during the summer of 2015 are presented in Figs. 9 and 10. The propagation simulations were conducted at the beginning of each wildfire through the AEGIS platform by designated trained civil protection officers. West Attica's incident burned 50 ha (Fig. 9a); Chalkidiki's wildfire burned approximately 150 ha (Fig. 9b), while three wildfire outbreaks on Rhodes Island resulted in a total of 450 ha of forest lands burned (Fig. 9c–e). In Lesvos Island, a wildfire burned approximately 550 ha (Fig. 9f). Suppression efforts and major fire runs occurred for up to 3–10 h after ignition in these wildfire events. Three of these wildfires started in moderate danger areas (Fig. 10a–c) and three wildfires started in very high danger areas (Fig. 10d–f) in our spatial fire danger rating, as the summer fire season progressed through June to August 2015.

Wildfire perimeters were initially derived from EFFIS databases[6] whose products are the outcome of remote sensing techniques with low resolution MODIS[7] satellite data (250 m ground spatial resolution). Civil protection agencies were instructed to conduct simulations through the AEGIS platform upon the start of a new fire, by defining five hours of duration and using weather data from the nearest RAWS at the time of ignition. Fine tuning could be made in case of feedback from the field crews, suggesting that wind speed and direction values should be altered. Ignition points were also set by approximation, based on information coming from the field (no GPS signal is taken in Greece at the beginning of each event). Furthermore, the propagation results did not

[6]http://forest.jrc.ec.europa.eu/effis/about-effis/technical-background/rapid-damage-assessment/

[7]http://modis.gsfc.nasa.gov/

consider any firefighting actions and activities taking place during the evolution of the event, thus they represented the uncontained fire growth over a period of five hours.

Results revealed that simulations captured the general shape of fires, while major travel paths were accurate as to where the fastest propagation actually occurred. All simulations over-predicted the actual fire area, with the exception of the Lesvos Island wildfire, an acceptable fact given all the assumptions and considerations of the simulation procedure. The fire on Lesvos Island had the largest actual area and duration (Fig. 9f) compared to all other case fires, exceeding 500 ha of burned forest lands. A clear wind direction shift from NE to N occurred when the fast moving front inside a gully surpassed the mountain ridge after the first five hours of burn time; fuel models and topography also changed for the second five-hour fire run, thus explaining differences between simulated vs. actual wildfire perimeters. To adjust to these changes, we conducted a supplementary simulation for another five hours and results revealed that the wildfire reached its total/actual perimeter at a comparable time to the actual event (Fig. 11). End users may run simulations with trial and error attempts, involving multiple "what if" scenarios within AEGIS. Civil protection agencies found results helpful, promising and very informative on estimating wildfire growth, intensity and propagation speed.

Regarding our spatial fire danger index, it was noticed that relatively moderate danger ratings dominated the study areas early in the fire season (June 2015), while high to very high danger ratings were more common during the latter part of the fire season (July–August 2015). As expected, wildfires occurred throughout the study areas according to the conditional probability of ignition; however, the ignitions in moderate danger areas (West Attica and Chalkidiki) resulted in smaller burned area (i.e. small predicted burned area) than the ignitions in higher danger areas (Rhodes Island and Lesvos Island).

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4 Discussion

The need for more sophisticated approaches to wildfire management is becoming increasingly recognized by fire protection agencies worldwide. Mega fires are a global phenomenon (Attiwill and Binkley, 2013) and routinely overwhelm government capacities for their control and suppression (Cruz et al., 2012; Williams, 2013). Harnessing new technology in computing capabilities, software integration, cloud services, and geospatial processing offers the potential to create next-generation decision support tools to combat the growing incidence of catastrophic fires. Our work on an integrated decision support system for Greece resulted in the AEGIS system, an integrated approach to wildfire decision support that provides a spatial fire danger rating, fire behavior modeling (for both single fire behavior simulations and burn probability maps), visualization of real-time and forecast weather data, access to fire management and historical fire data, and fire management tools (e.g. elevation profile, visualization of the shortest routes to the closest firefighting facilities, and real-time images of high-risk areas through web cameras). The net result is that fire intelligence and resources can be more easily shared among fire agencies, thus reducing costs and enabling efficiency for suppression operations. The distributed architecture of the system eliminates the need for specialized computing and storage capabilities further contributing to efficiencies over standalone and non-integrated systems. From the end-user point of view all that is needed to access the AEGIS platform is a standard computer, laptop, tablet or smartphone with internet connection. Thus, the innovations in AEGIS provide advanced tools for firefighting personnel, emergency crews and other authorities to facilitate operational planning for wildfire incidents. Valuable assistance and decision support tools can be then provided to the local authorities responsible for wildfire management to extract useful information as part of an operational wildfire prevention and management plan. The comparison of AEGIS with previously developed wildfire management systems (Kalabokidis et al., 2013a, 2014b) reveals that AEGIS covers the full range of forest fire management and prevention, except for damage assessment (Table 3).

The AEGIS system was intensively tested during the 2015 fire season. Local fire agencies from the seven study areas utilized the system; their personnel consulted and retrieved information from the AEGIS platform and sometimes adjusted their alertness and emergency levels, especially during days of high fire risk. Several useful conclusions and remarks were received, and several ideas were proposed for a better utilization of the platform's capabilities.

BPN networks used in AEGIS fire danger rating achieved better performance compared to other methodologies; and the BPNs were trained based on different parameters for each study area. In all but one of the study areas (due to the smaller training dataset), the RMSE of the validation datasets was less than 12.1 %, while the correct classification rate of ignition points was more than 80.3 %. Sensitivity analysis of the trained BPNs proved that the initial choice of the study areas was justified because of the different wildfire ignition patterns that were finally identified. Results showed that the distance from urban areas was a critical parameter for wildfire ignition, while air temperature seemed to have the smallest influence compared to the rest of the parameters for all the study areas.

Regarding the fire propagation/behavior scheme, the integration of the MTT algorithm enabled end users to overcome the difficulties that arise from the lack of knowledge or the complexity in usage of fire behavior systems (e.g. BehavePlus, FARSITE, FlamMap). Interconnectivity with Google Earth, the primary GIS application of most Greek civil protection agencies, brings a new perspective on interpreting simulation results from AEGIS by using functionalities such as 3-D visualization (Fig. 12).

Are methods for calculating burn probability and generating maps using parallel processing techniques providing the necessary processing power and computational speed for operational implementation? The instant and prompt availability of processing power along with cost effectiveness, reliability and scalability of the Cloud are benefits of the application. By taking advantage of the Cloud's ability to increase/decrease the

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number of available VMs on demand, end users will be charged only for their consumed processing time and only during the actual wildfire confrontation period. On-demand fire simulations are better suited to run locally rather than in the Cloud. This is because of the significant amount of time overhead (approximately 15 min) required to allocate new VMs in Microsoft Azure. On-demand fire behavior simulations need to be conducted instantly and thus, time overheads should be minimized to achieve a timely and effective response when a wildfire breaks out.

5 Conclusions

The AEGIS system can potentially contribute towards a more sophisticated knowledge transfer among the various entities involved in wildfire suppression activities including operation centers and firefighting units in the field. The system is designed for wide-scale deployment for the different geographical areas of Greece or regional countries with minimal effort and resources, providing the development of the required input databases and services. We demonstrated a highly scalable implementation of the system that leverages Cloud Computing and HPC resources, allowing AEGIS to be applied at the national and regional scale. Moreover the mobile application, which currently is only implemented in Windows Phone devices, will eventually be made available for Android and iPhone devices, as well. Future updates of the AEGIS will provide end users with the ability to perform simulations from their smartphones, and visualize the results of the fire behavior directly in their mobile device. Future work will also include integration of the Fire Ranking and Effects Index (FIRE Index) for the evaluation of fire effects (Kalabokidis et al., 2014c). Further research plans include the utilization of different open source Cloud solutions (e.g. OpenStack, promoted by the OpenStack Foundation) for the calculation of spatial fire danger rating and fire behavior modeling, and the utilization of open-source Web-GIS solutions (e.g. Geoserver) for the manipulation of geo-processing and mapping services.

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Table 1. Proposed services, goals and corresponding processes in the AEGIS platform.

Service	Goal (G)	Process (P)
Visualization of fire risk maps	G1.1	P1, P7
Visualization of burn probability maps	G1.2	P2, P3, P7
Visualization of real time weather data	G2.1	P3
Visualization of forecast weather data	G2.1	P2, P7
Access to fire management data, i.e.: – base maps/satellite maps – road network – water sources – evacuation sites – cover types – high risk areas	G1.3	P1
Exploitation of Google Earth (KML) data Online map creation Map printing	G1.3 G2.3 G2.3	P6
Access to historical fire risk data Access to historical weather data Access to historical burn probability maps	G2.2 G2.2 G2.2	P4
Routing	G2.3	P5, P11
Finding the closest routes to water sources	G2.3	P5, P11
Calculate drive times from a specific location	G2.3	P5, P11
Location tracking of fire vehicles on duty	G2.3	P6, P11
Visualization of new fire spots	G2.3	P6, P11
Access to web cameras	G2.3	P6, P11
Access to the provided information through mobile apps	G5	P12
Fire behavior simulation	G1.2, G1.3, G2.1, G2.2	P1, P2, P3, P11

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Table 2. Union matrix of probability of ignition and burned area.

Conditional Probability of Ignition (CPI)	Predicted Burned Area (PBA)				
	< 1 ha	1–10 ha	10–100 ha	100–1000 ha	> 1000 ha
0–20 %	Low – 1	Low – 1.5	Moderate – 2	Moderate – 2.5	High – 3
20–40 %	Low – 1.5	Moderate – 2	Moderate – 2.5	High – 3	High – 3.5
40–60 %	Moderate – 2	Moderate – 2.5	High – 3	High – 3.5	Very High – 4
60–80 %	Moderate – 2.5	High – 3	High – 3.5	Very High – 4	Very High – 4.5
80–100 %	High – 3	High – 3.5	Very High – 4	Very High – 4.5	Extreme – 5

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Table 3. Analysis of services, goals and processes of the AEGIS platform.

	Fire danger forecast	Fire behavior prediction	Fire management tools and data	Fire database	Active fire detection	Damage assessment
VIRTUAL FIRE	daily creation of fire risk maps	X	√	X	covered by optical camera surveillance	X
VENUS-C	hourly fire risk maps for the next 112 h	√	X	X	X	X
EFFIS	Canadian FWI	X	X	√	√	√
WFDSS	√	√	X	√	by reports from individual users	√
CFFDRS	√	√	by using external components	√	√	X
AEGIS	√	√	√	√	covered by optical camera surveillance	X

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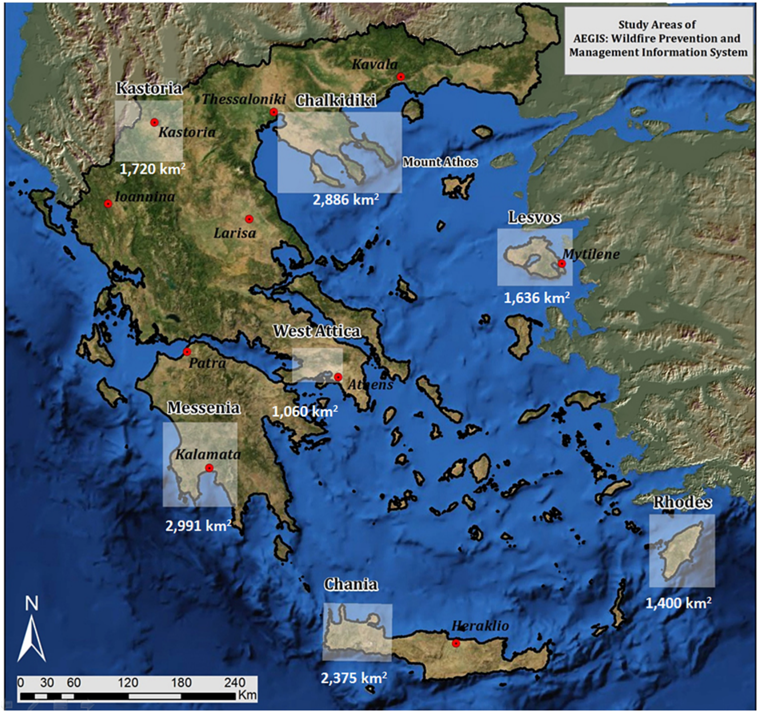

Figure 1. The seven study areas of AEGIS in Greece.

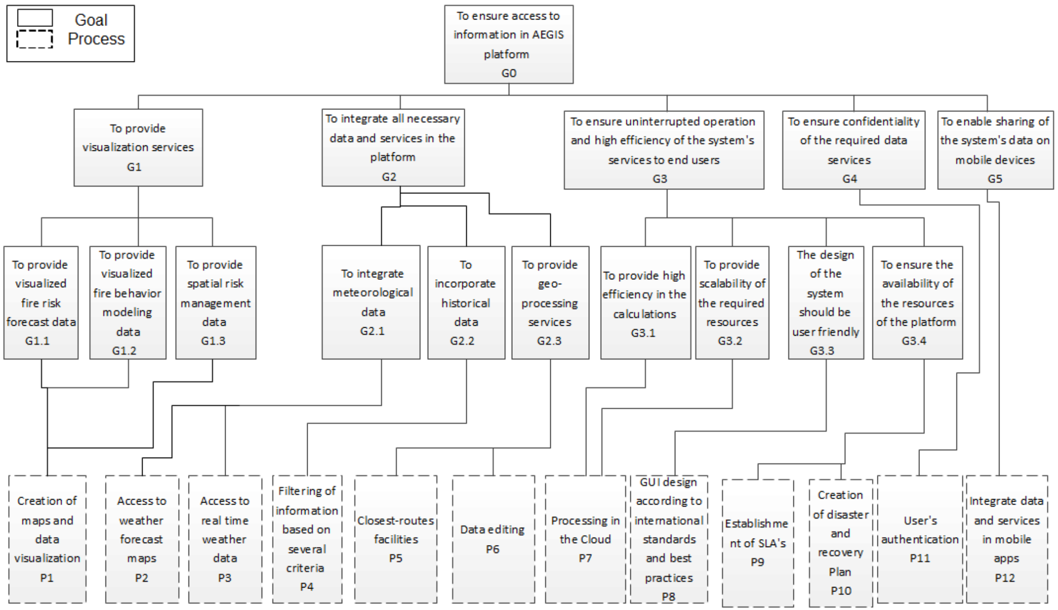

Figure 2. The Goal–Process diagram for development of the AEGIS.

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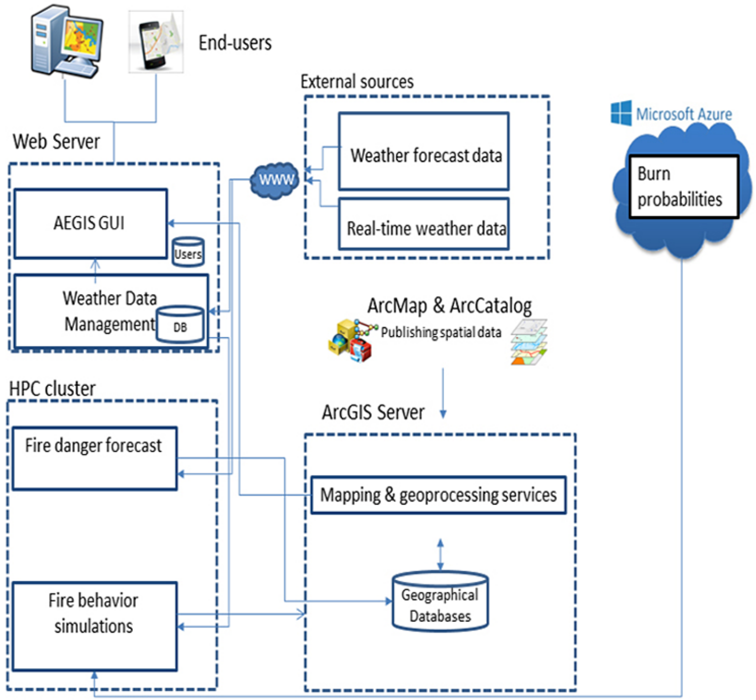

Figure 3. Architectural components of the AEGIS platform showing the linkages among data and computing resources.

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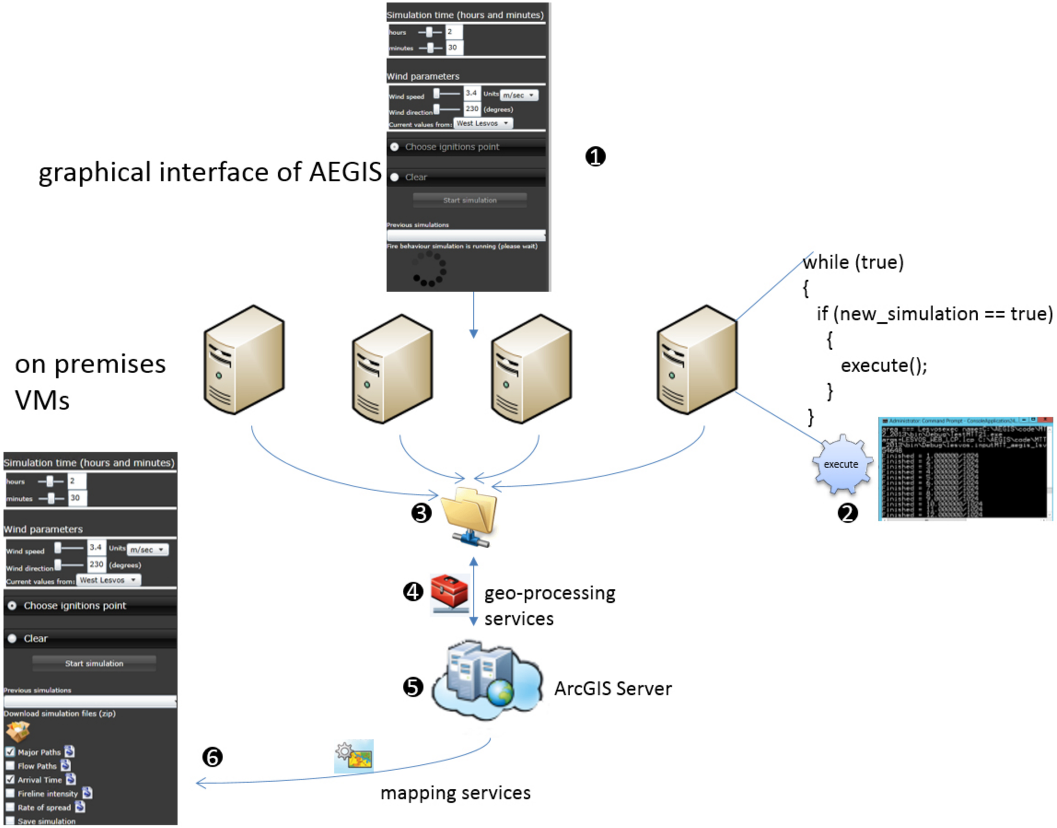

Figure 4. Information flow for on-demand MTT simulations of individual wildfires in AEGIS.

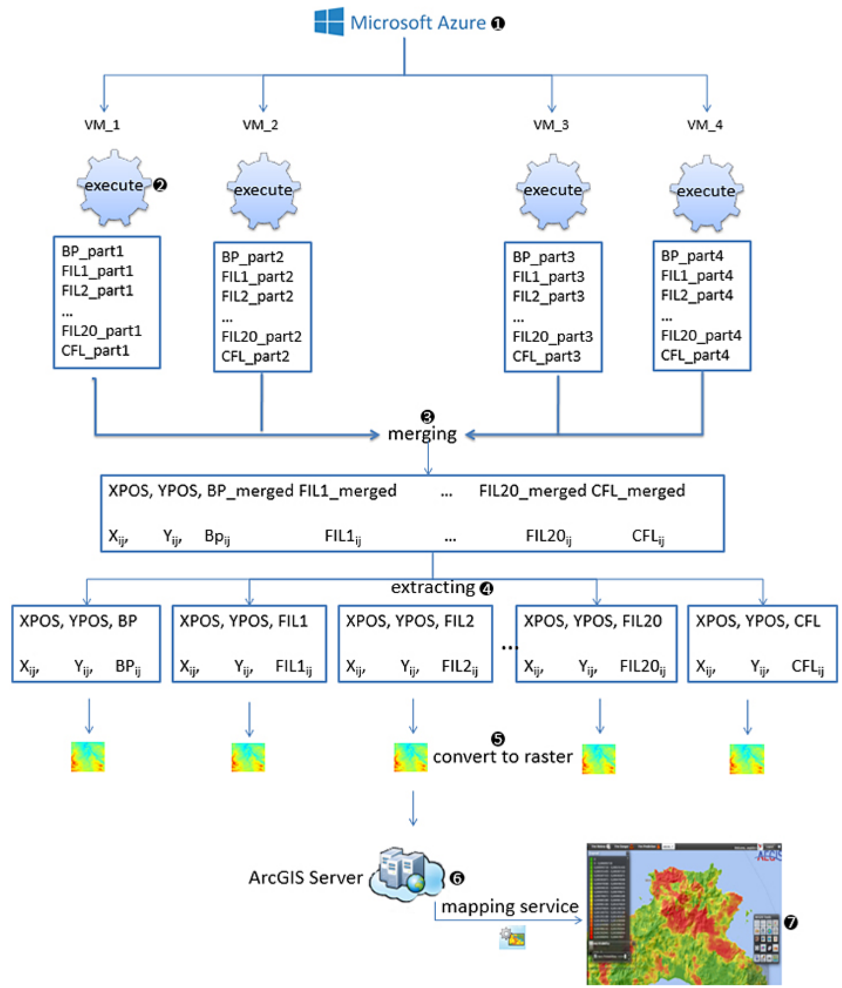

Figure 5. Information flow for the estimation of burn probability maps in AEGIS.

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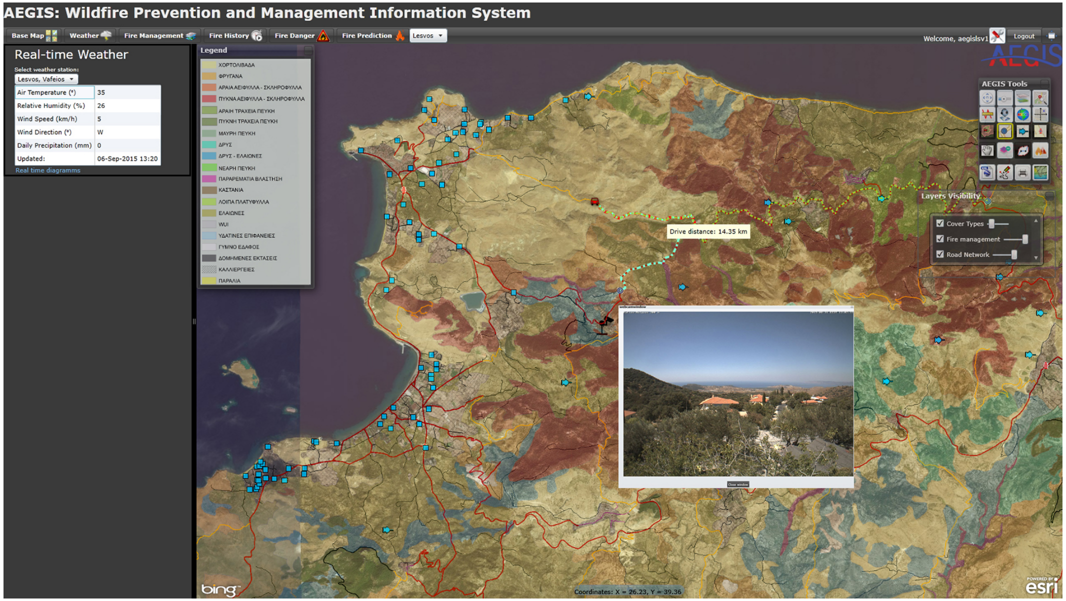

Figure 6. Optical camera surveillance combined with visualization of the road network, the pumping stations, the cover types and real-time weather records from the closest RAWS within the AEGIS graphical interface.

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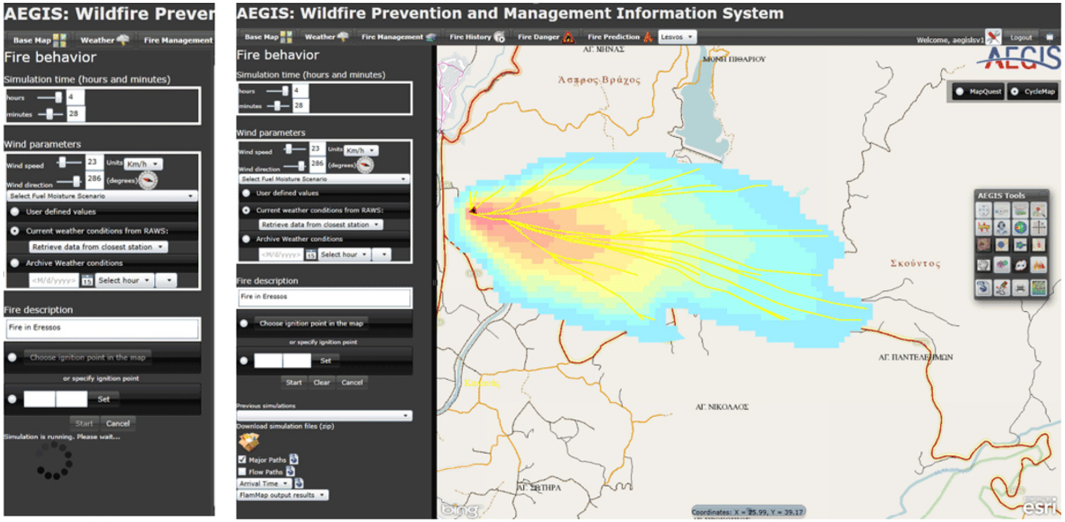

(A) (B)

Figure 7. Visualization of a single fire simulation within the AEGIS graphical interface.

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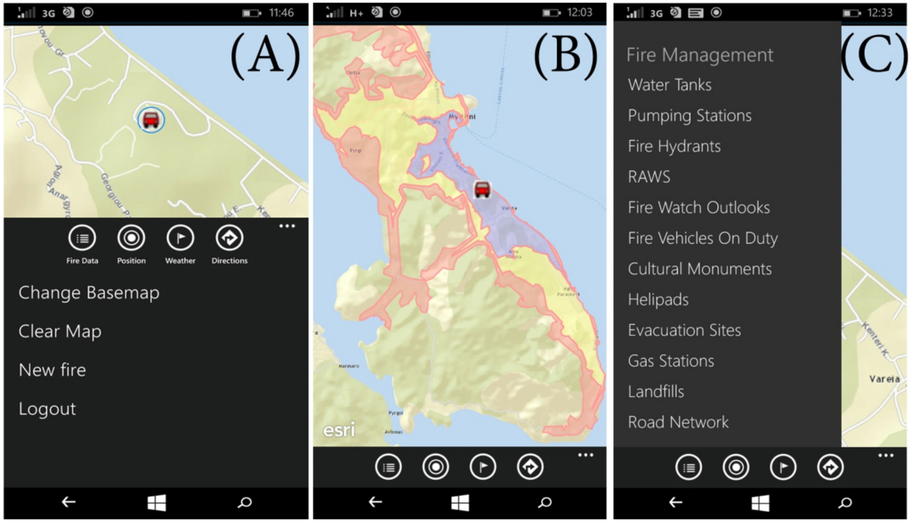

Figure 8. (a) Basic screen of AEGIS App; **(b)** calculation of the areas that the user can access by driving a regular firefighting truck in 3, 5 and 10 min; and **(c)** accessing fire management data through the AEGIS App.

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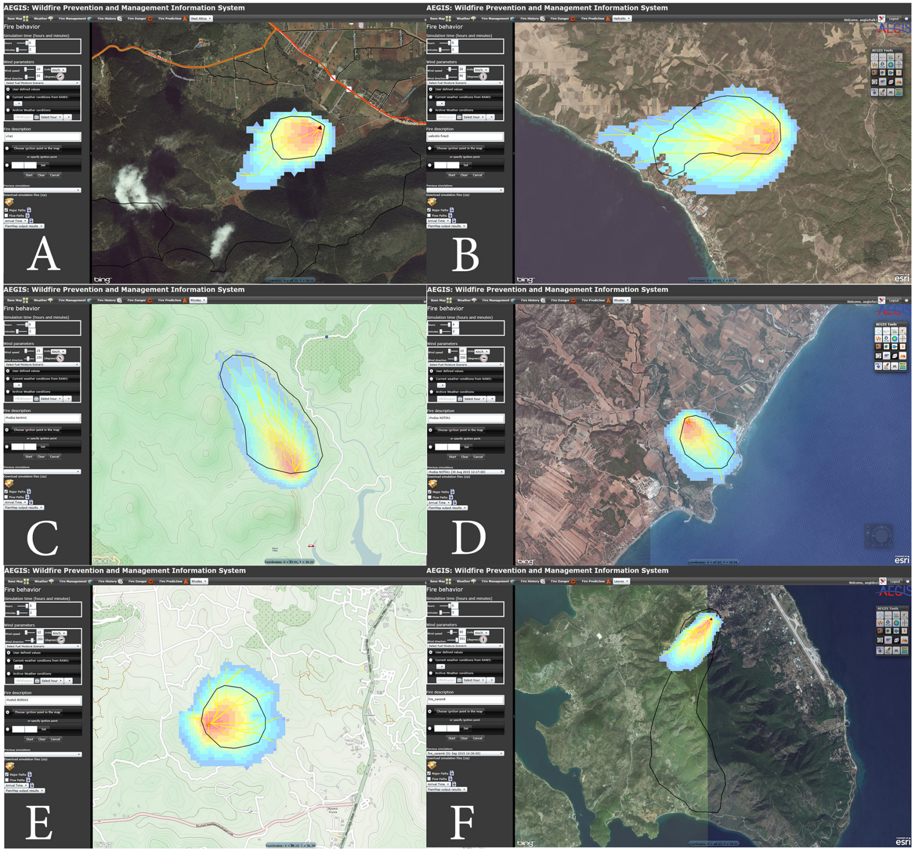

Figure 9. Simulation results of the six actual wildfires that occurred during the summer of 2015 in four of our study areas (**a**: West Attica, 13 June 2015; **b**: Chalkidiki, 16 June 2015; **c**: Rhodes Island, 23 July 2015; **d**: Rhodes Island, 31 July 2015; **e**: Rhodes Island, 23 August 2015; and **f**: Lesvos Island, 30 August 2015) – black polygons delimit the actually burned areas, while colored areas and lines map times of arrival and major travel paths in AEGIS.

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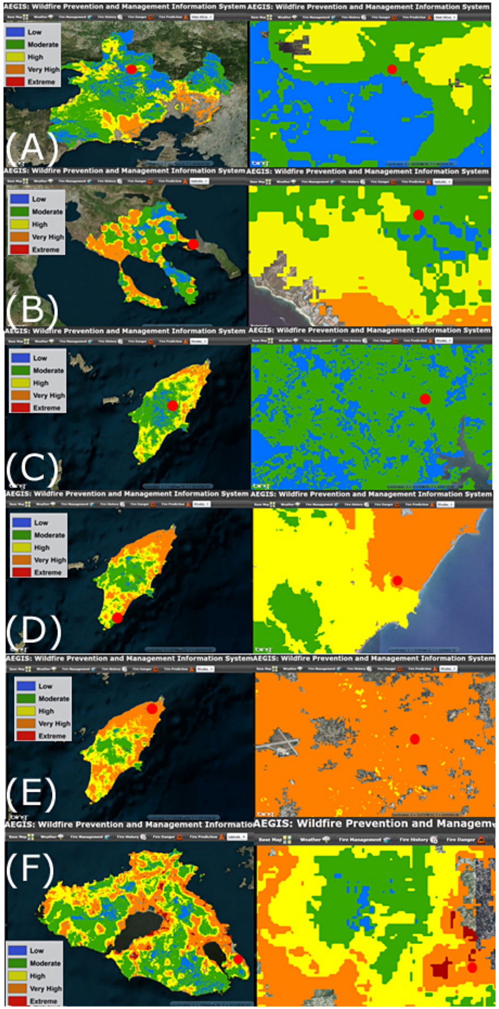

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Figure 10. Spatial fire danger results (left column panels) of the six actual wildfires (right column panels with zoom-in of the starting points in red dots) that occurred during the summer of 2015 in four of our study areas (**a**: West Attica, 13 June 2015; **b**: Chalkidiki, 16 June 2015; **c**: Rhodes Island, 23 July 2015; **d**: Rhodes Island, 31 July 2015; **e**: Rhodes Island, 23 August 2015; and **f**: Lesvos Island, 30 August 2015).

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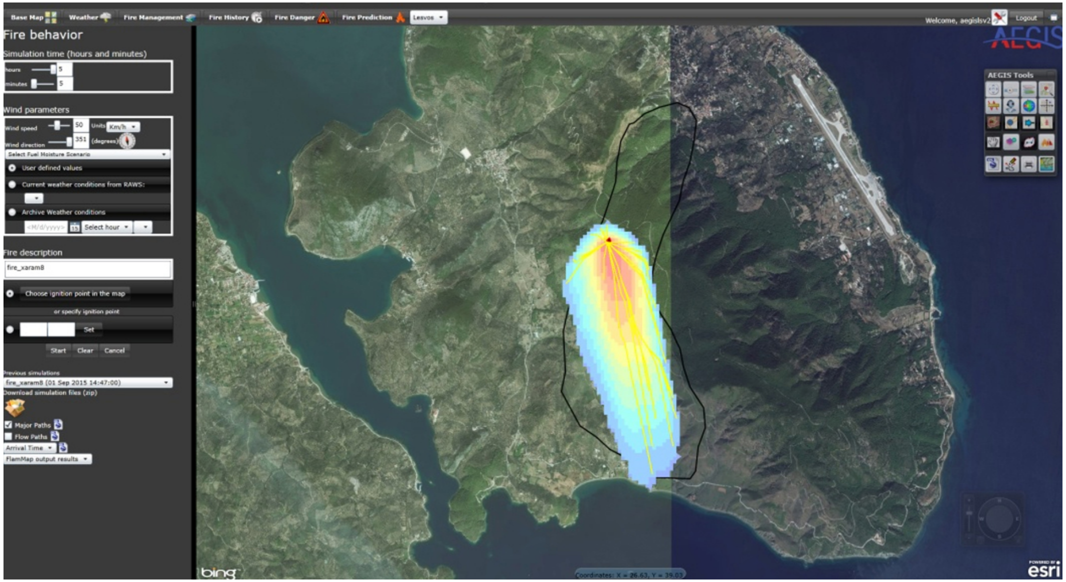

Figure 11. Second simulation run of Lesvos Island 2015 wildfire from the site where the first simulation ended (Fig. 9f). Black polygon delimits the actually burned area, while the colored area and lines map times of arrival and major travel paths in AEGIS.

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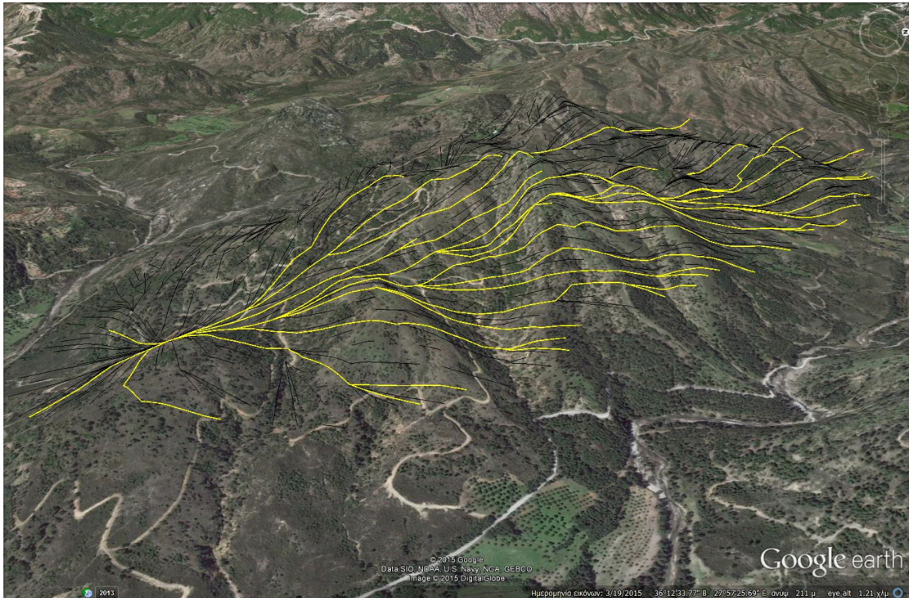

Figure 12. Visualization of travel paths from a wildfire simulation through the AEGIS platform over Google Earth.

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