Modelling forest fires hydrological impact using spatio-temporal geographical data.

Soulis Konstantinos[1], Valiantzas John[2], Dercas Nicholas[3]
Agricultural University of Athens, Department of Natural Resources Management and
Agricultural Engineering, Sector of Water Resources Management, Athens, Greece,
([1]soco@aua.gr, [2]ival@aua.gr, [3]ndercas1@aua.gr)

Abstract: In recent years, forest fires frequency and intensity has increased, causing a new awareness about their impact not only on vegetation, but also on hydrological regime. Changes in vegetation influence the processes of interception and evapotranspiration, seriously affecting the hydrological cycle. Forest fires can also affect hydrological processes indirectly, altering the hydraulic properties of the soil. The period needed for the hydrological process recovery is greatly dependent on the rate of vegetation recovery. In dry areas, water shortages can seriously limit this rate. The interaction between hydrological processes and vegetation recovery makes harder the simulation of forest fires hydrological impacts and post-fire recovery with hydrological models, which are not able to consider the significant temporal variability of soil hydraulic properties and vegetation development. This paper presents the modelling of forest fires hydrological impact with a modified hydrological model, using spatio-temporal geographical data. This model can simulate the hydrological balance, taking into account both the spatial and temporal variability of vegetation and soil hydraulic properties. The interactions between hydrological balance, plants water stress, vegetation development, and soil hydraulic properties, can also be simulated within the model. The case study of a Mediterranean experimental watershed in Greece, which was affected by a wildfire in August 2009, is also presented.

Keywords: hydrological model; wildfire; spatio-temporal geographical data; GIS.

1.   INTRODUCTION

Climate change in combination with human intervention and the increment of forest biomass due to the abandonment of agricultural lands and the lack of forest management, significantly increases forest fire hazard. In recent years, especially in northern Mediterranean countries, an important surge in catastrophic forest fire incidents is observed [European Commission 2002]. Thus, wildfires have emerged as increasingly dominant drivers of ecosystem functioning [Pausas and Vallejo 1999]. This has led to a new awareness about forest fires impact, not only on the loss of vegetation, but also on the possible loss of life and property, as well as on changes in the hydrological response and erosion/sedimentation process of the once vegetated areas [Rulli and Rosso 2007].
Several studies have pointed out the effects of forest fires on the hydrological cycle, such as reduced infiltration rates, reduced evapotranspiration rates and increased overland flow. These effects are mainly attributed to the destruction of the vegetation cover and the consequent direct impact on interception, evapotranspiration and overland flow velocity [Robichaud 2000, 2005, Prosser and William 1998, Pierson et al. 2001, 2002, 2008]. Furthermore, forest fires can also affect hydrological processes indirectly, altering the hydraulic properties of the soil [Giovannini and Lucchesi 1983, Gionannini et al. 1988, Lavabre et al. 1993]. Fires destroy the top soil organic mutter destabilizing soil structure, they convert the organic ground cover to soluble ash and give rise to phenomena such as water repellency [Imeson et al. 1992, Neary et al. 1999]. Water repellency is an

abnormality in soils resulting from the coating of soil particles with organic substances, which reduce the affinity shown by the soil for water [DeBano 2000].

Fire effects on hydrological processes are normally apparent for one or two years after the wildfires [Marques and Mora 1992, Cerdà 1998]. However, in dry areas, much higher runoff and erosion rates are being noticed even five to ten years after the fire [Inbar et al. 1998, Robichaud 2000, Mayor et al. 2007]. The period necessary for the hydrological process recovery to the pre-fire conditions is greatly dependent on the rate of vegetation recovery. Inbar et al. [1998] and Vega et al. [2005] show that the period necessary for runoff and soil erosion to return to background levels depends on the type of species existing prior to fire, because each species has its own specific recovery. Cerda [1998], Marcos et al. [2000] and De Luis et al. [2003] found that the amount of litter and vegetation cover is a key factor in reducing post-fire runoff and erosion, and in accelerating the recovery time of burned soils. But in dry areas, water shortages can seriously limit plant growth rate [Mayor et al. 2007]. The plant recovery and the recovery of post-fire hydrological responses may be constrained by common conditions in Mediterranean countries, such as harsh meteorological and hydrological conditions [Inbar et al. 1998, Mayor et al. 2007], plant communities with low regeneration potential that have colonized abandoned fields [Pausas et al. 1999], highly erodible soils, and steep slopes [Yassoglou, 1995]. South-facing slopes have also been reported as particularly sensitive to wildfire impact [Marques and Mora 1992, Andreu et al. 2001] highlighting the vast spatial and temporal variability.

Consequently, the interaction between hydrological processes and vegetation recovery and the important spatial and temporal variability of soil hydraulic properties and vegetation development makes harder the simulation of forest fires hydrological impacts. While sudden changes, such as wildfires, can be efficiently modeled with discrete model executions, gradual changes and interactions are very difficult to be modeled in the same way. Post-fire environment is characterized by rapid change of vegetation cover (vegetation development and succession of species), soil hydraulic properties and hydrological conditions. Furthermore, the variation of vegetation, soil properties and hydrological conditions is interrelated and also related to the meteorological conditions. Recent modelling efforts to predict forest fire hydrological effects are presented by Johansen et al. [2001], Moffet et al. [2007], Rosso et al. [2007], Hill et al. [2008], Rulli et al. [2005], Lane et al. [2010].

This paper presents a new methodology for the prediction of wildfires hydrological effects and the simulation of the restoration process. Post-fire dynamics of vegetation and hydrological conditions are simulated with a fully spatially distributed hydrological model, using spatio-temporal geographical data. The model is being developed as a modification of AgroHydroLogos model [Soulis 2009, Soulis and Dercas 2010]. With this model, the main hydrological balance components, such as, soil moisture, direct runoff, deep infiltration, actual evapotranspiration, and base flow can be simulated taking into account both the spatial and temporal variability of vegetation cover and soil hydraulic properties. The case study of a Mediterranean experimental watershed in Greece, which was affected by a wildfire in August 2009, is also presented.

2.   METHODOLOGY

The proposed methodology was developed based on AgroHydroLogos model [Soulis 2009, Soulis and Dercas 2010]. AgroHydroLogos is a spatially distributed, continuous hydrological model. It is developed as an extension of ArcGIS 9.2 software based on ArcObjects functionality, in order to facilitate the fully spatially distributed calculation of the hydrological balance components, and to make use of the advanced capabilities of Geographical Information Systems (GIS) in managing, editing, analyzing and visualizing geographical data. The model calculates, on a daily basis, the main hydrological balance components, and other important parameters, including plants water stress and irrigation water needs. Its conceptual scheme is based on simplified but well established methods for the simulation of the various hydrological processes. The hydrological model is developed using Object Oriented Programming (OOP) techniques, thus facilitating future improvements or further development. Its Graphical User Interface (GUI) is very easy to use and it follows the standard ArcGIS software extensions form.

The main objective of the proposed methodology is to efficiently simulate the wildfires hydrological effects and the post-fire restoration process. In order to achieve this objective, AgroHydroLogos model was modified in order to incorporate three main characteristics:

1. A flexible data model for the representation of spatio-temporal geographical data
2. A simplified but efficient conceptual scheme, able to describe the rapid change of vegetation cover (vegetation development and succession of species), soil hydraulic properties and hydrological conditions.
3. A method to dynamically express spatiotemporal relationships between vegetation cover, soil hydraulic properties, and hydrological and meteorological conditions.

2.1 Spatio-temporal Geographical Data Model

The different conceptualization of space and time in GIS and hydrological models is an important obstacle for the integration of hydrological models in GIS. Although time is an explicit element in most hydrological models, current generation of GIS does not incorporate an efficient representation of time. The integration of hydrological modelling with GIS requires the development of a high-level common ontology that is compatible with both GIS and hydrological models. The common ontological framework should incorporate multi-dimensional concepts of space, time, and scale [Sui and Maggio 1999]. Another problem in integrating GIS and hydrological models is the complexity of spatial and time series data access, analysis and visualization which limits the performance of integrated applications [Jagadeesh Babu et al. 2006].

Therefore, a suitable data model for the modelling of forest fires hydrological impact and of the restoration process, should efficiently represent space and time, and at the same time, it should allow the conceptualization of vegetation development and of soil properties annual and interannual variation, which is particularly important in the post fire environment. Furthermore, it must be simple, flexible, and efficient; it must be easy to create, handle and access; and finally it must be based on the core GIS data model.
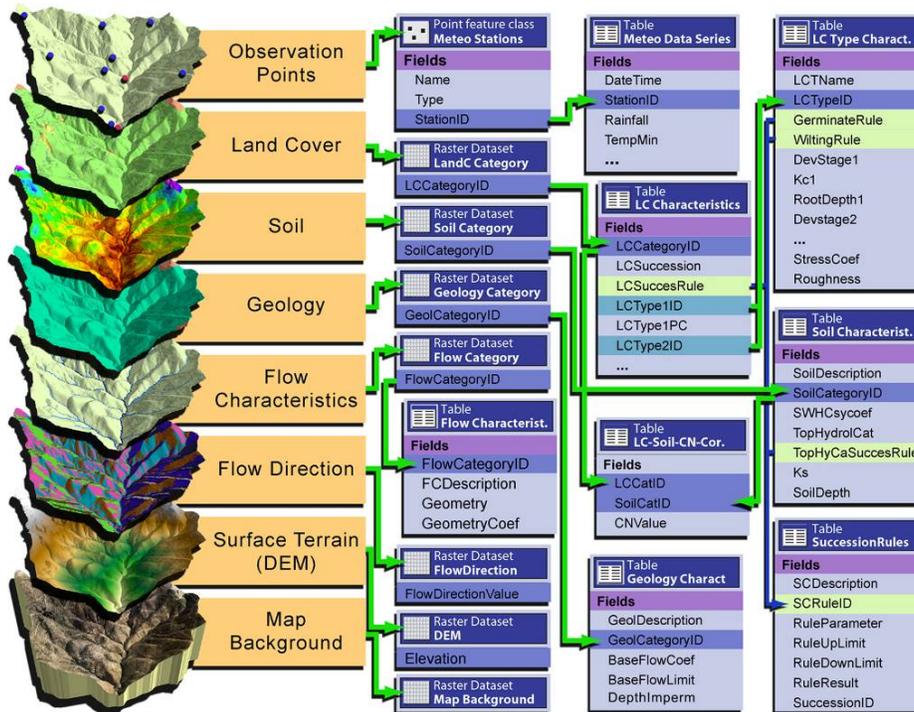

Figure 1. Illustration of the conceptual spatio-temporal geographical data model.

The spatio-temporal geographical data model used by the proposed methodology is illustrated in figure 1. In this data model, the basic concepts of the hydrological basin are

represented by a set of geographical data objects, i.e. map background, surface terrain, flow direction, flow characteristics, geology, soil, and land cover. These data objects consist of raster datasets linked with tables containing the required spatio-temporal data for the simulation of the hydrological cycle (Fig. 1). As an example, the annual temporal variability of each land cover category is described with a set of values for each vegetation development stage. The sequence of the development stages is defined by specific rules. The interannual temporal variability of the land cover characteristics is described by land cover categories succession based on specific succession rules (landscape succession dynamics are described by Millington et al. [2009]). In the same way the temporal variability of soil properties and curve number values is described. The followed approach advantage over time varying surfaces (raster series) as it is much easier to create and handle, it needs much less data storage volume and it has much better data access performance. The meteorological conditions are represented by a point feature class that is linked with tables containing the meteorological data time series.

In the proposed methodology, the hydrological model works as part of the GIS in direct interaction with a geographical database and a knowledge base. The inputs come directly from the geographical database and the resulting outputs are stored in it too. The input data are created and dynamically changed, based on the information and the rules contained in the knowledge base. In this way, the user has access to all the GIS functionality for data preparation, storage, visualization and analysis in a familiar and user-friendly graphical user interface. Moreover, all the advantages of a database management system are provided.
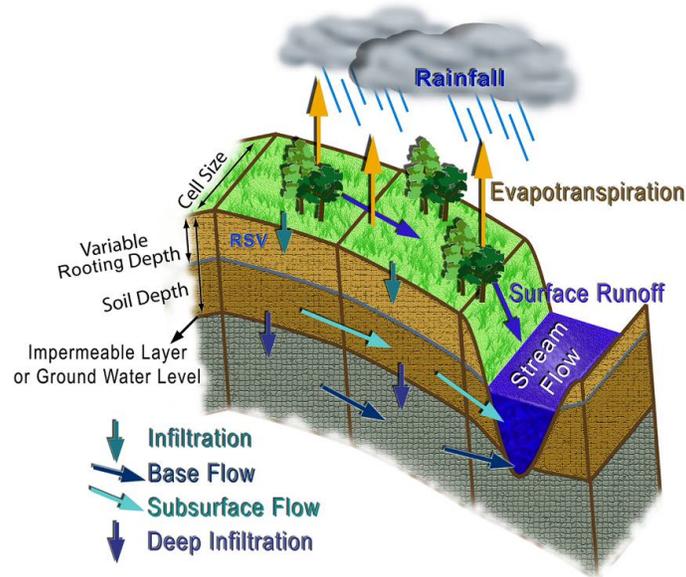
Figure 2. Graphical representation of the modelling conceptual scheme

2.2   Conceptual Scheme

The hydrological model calculates, in spatial distributed form and on a daily basis, the main hydrological balance components, such as, soil moisture, direct runoff, deep infiltration, actual evapotranspiration, and base flow, and other important parameters, such as plants water stress. The daily temporal discretezation was chosen in order to describe with satisfactory detail the hydrological processes and at the same time to allow the simulation of long time periods and the utilization of readily available meteorological data and data concerning future climate projections. The conceptual scheme of the model was designed in order to efficiently describe the wildfires hydrological effects and the post-fire restoration process. In order to achieve these targets it must be able:

1. to describe the rapid change of soil hydraulic properties, hydrological conditions, and vegetation cover (vegetation development and succession of species), based on the previously described spatio-temporal geographical data model,

2. to make use of simplified but well established methods for the simulation of the various hydrological processes,
3. to adapt at semi-arid and arid regions,
4. and to efficiently describe vegetation-water dynamics,.

The conceptual scheme and the involved storages and flows are presented in figure 2.

2.3   Water Balance of the reference soil volume (RSV)

Soil moisture of the top soil layer is directly involved in the calculation of most of the water balance components, such as direct runoff, infiltration, deep infiltration, and actual evapotranspiration. Thus, the principal equation of the hydrological model is equation (1) that describes the water balance of the reference soil volume (RSV):

$$SWC_{i-1} - SWC_i = P_i - Q_i - aET_i - DI_i + INF_i - OF_i \qquad (1)$$

where SWC_{i-1} and SWC_i (mm) are the reference soil volume water contents of the day before and the actual day respectively, P_i (mm) is the total rainfall depth the actual day, Q_i (mm) is the direct runoff depth the actual day, αET_i (mm) is the actual evapotranspiration depth the actual day, DI_i (mm) is the deep infiltration depth the actual day, INF_i (mm) is the total inflow from the upstream cells the actual day and OF_i (mm) is the outflow to the downstream cell. As reference soil volume is defined the top soil layer, which is limited to the rooting depth. A schematic representation of the interactions determining the water balance of the reference soil volume is shown in figure 2. The *SWC* can increase up to a maximum, which is equal to the water holding capacity of the reference soil volume (*SWHC*). *SWHC* value for each cell varies according to the annual and interannual variation of the land cover characteristics and it is dynamically evaluated using data from the geographical database and the knowledge base concerning the soil hydraulic properties and the rooting depth.

In the same way the water content of the deep soil layer, which is the remaining soil volume to the soil depth (*DSWC*), is calculated based on equation (2):

$$DSWC_{i-1} - DSWC_i = DI_i + DINF_i - DOF_i - FA_i \qquad (2)$$

where $DSWC_{i-1}$ and $DSWC_i$ (mm) are the *DSWC* values of the day before and the actual day respectively, DI_i (mm) is the deep infiltration depth the actual day, $DINF_i$ (mm) is the total inflow from the deep soil layer of the upstream cells the actual day, DOF_i (mm) is the outflow to the deep soil layer of the downstream cell and FA_i (mm) is the flow to the aquifer.

Direct runoff is calculated with the Soil Conservation Service Curve Number (SCS-CN) method [SCS 1956, 1964, 1971, 1985, 1993]. SCS-CN is one of the most popular techniques among the engineers and the practitioners, mainly for small catchment hydrology (Mishra and Singh [2006]). The main reasons for its success is that it accounts for many of the factors affecting runoff generation including soil type, land use and treatment, surface condition, and antecedent moisture condition, incorporating them in a single CN parameter. CN parameter takes values from 0 to 100. In this application the spatial and temporal variable CN values are dynamically calculated from the soil and land cover data, which are stored in the geographical database and the knowledge base. In the model, CN value is also justified each day, depending on the actual soil moisture.

The determination of horizontal and vertical flows through the soil profile is based on the Brooks and Corey [1964] equation. At bottom of the soil profile is assumed a free drainage (zero pressure head) boundary condition.

Actual Evapotranspiration (*aET*) rate is dependent on weather parameters, land cover and water availability. In this study reference evapotranspiration (*ET_o*) is calculated from weather parameters and then *aET* is determined taking into account the land cover characteristics and the soil moisture. *ET_o* is calculated with the FAO Penman-Monteith [FAO 1998] method or the Hargreaves method [Hargreaves and Samani 1985] according to the data availability. The required plant and stress coefficients are dynamically determined for each grid cell and each day, depending on the vegetation characteristics of each place, based on the knowledge base, which contains information for a wide range of land cover types. Using the above described methodology, the model efficiently describes vegetation-water dynamics and is able to calculate plants water stress.

Finally, daily accumulated runoff is evaluated for each grid cell of the river network, for every time step, by adding the accumulated surface runoff for this time period to the accumulated subsurface flow and base flow. Runoff components routing through overland, subsurface and base flow and through the hydrographical network is performed with a simplified travel time approach.

2.4   Spatiotemporal Relationships

The modelling of wildfires hydrological effects and post-fire restoration process necessitate the use of a method that is able to dynamically express spatiotemporal relationships between vegetation cover development, soil hydraulic properties variation, and hydrological and meteorological conditions, which is particularly important in the post fire environment. In the proposed methodology, this requirement is covered with the utilization of the previously described spatiotemporal geographical data model, and conceptual scheme and the dynamic variation of input parameters, based on information and rules contained in the knowledge base.

The future development of the proposed methodology includes integration of the hydrological model with plant growth and wildfire and Landscape succession –disturbance dynamics models in order to fully describe the above mentioned spatiotemporal relationships. The development of the hydrological model in the framework of a GIS and the use of OOP techniques makes possible the future integration of such modules.

3.   CASE STUDY

As a paradigm for the development of the proposed methodology the small scale experimental watershed of Lykorrema stream (7.84 km^2) is used, which is situated in the east side of Penteli Mountain, Attica, Greece (Coordinates: UL 23°53'33"E-38°04'13"N; LR 23°56'00"E-38°02'28"N) (Fig. 3a). The region is characterized by a Mediterranean semi-arid climate with mild, wet winters and hot, dry summers. Precipitation occurs mostly in the autumn–spring period. A more detailed description of the watershed is presented by Soulis et al. [2009a].
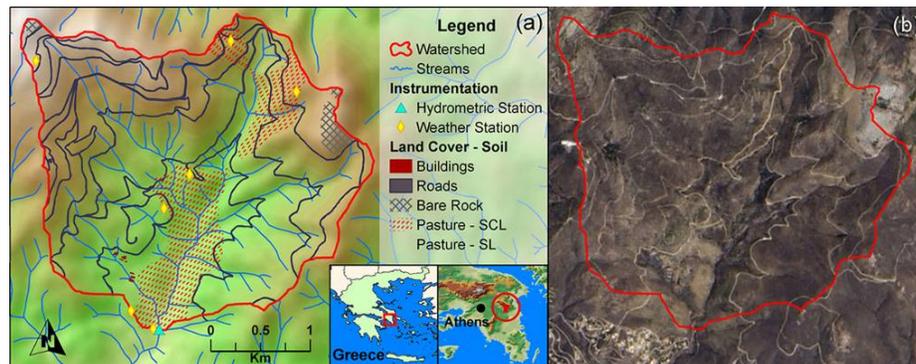
Figure 3. (a) Map of Lykorrema stream experimental watershed. (b) Satellite image of the watershed after the wildfire of August 2009.

In recent years, the watershed was affected by two wildfires in August 1995 and in August 2009. Before the first wildfire the watershed was mainly covered by a dense pine forest, while a small part of the watershed, around the top of the hills, was covered with shrubs or bare rock. The pine forest was almost totally destroyed by the wildfire in 1995. Before the second fire the watershed had a mixed vegetation cover consisting of pasture, shrublands, and pine forest at the first stages of development (Fig. 3a). The forest fire in August 2009 destroyed most of this vegetation cover as it is shown in figure 3b.

Soulis et al. [2009b] studied the effect of the August 1995 wildfire in peak runoff values. They observed as much as 10 times increment in peak runoff values the period soon after the first wildfire, compared to the period soon before the second wildfire.
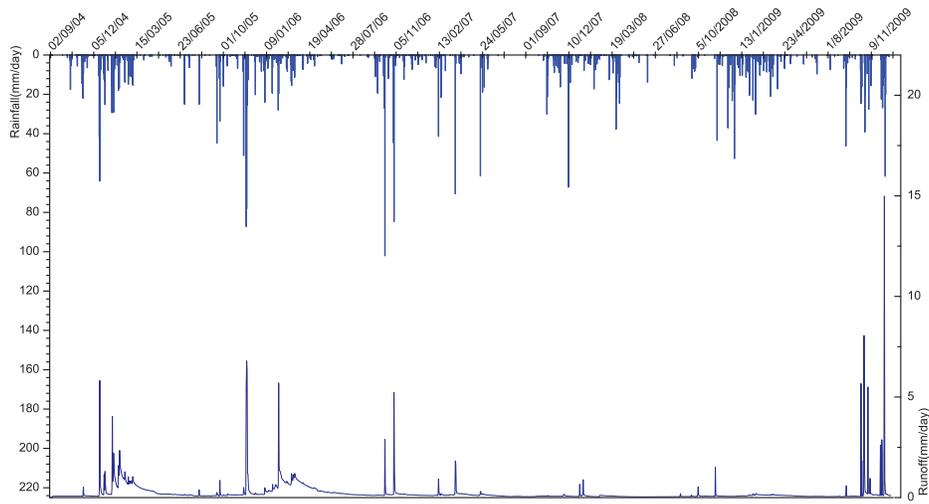
Figure 4. Daily rainfall and runoff values for the period from September 2004 to December 2009.

In figure 4 the daily rainfall and runoff values for the period from September 2004 to December 2009 are presented. In this figure, the great temporal variability of the watershed response is clearly demonstrated. This variability is more clearly depicted the period soon after the wildfire in August 2009. The steep relief of the watershed in accordance with the forest fires effects, resulting in great spatial variability of soil and land cover properties. Furthermore, the rapid change of vegetation cover, soil hydraulic properties and hydrological conditions following the wildfire exhibit the advantages of the proposed methodology in describing the post fire conditions.

4.   SUMMARY AND CONCLUSIONS

The interaction between hydrological processes and vegetation recovery and the important spatial and temporal variability of soil hydraulic properties and vegetation development complicates the simulation of forest fires hydrological impacts. In the proposed methodology post-fire dynamics of vegetation and hydrological conditions are simulated with a fully spatially distributed hydrological model, utilizing spatio-temporal geographical data. In order to do this it incorporates a flexible data model for the representation of spatio-temporal geographical data, a simplified but efficient conceptual scheme, able to describe the rapid change of vegetation cover, soil hydraulic properties and hydrological conditions, and a method to dynamically express spatiotemporal relationships between vegetation cover, soil hydraulic properties, and hydrological and meteorological conditions. The importance of the development of this method is demonstrated in a small scale Mediterranean experimental watershed in Greece, which was severely affected by wildfires. The future development of the proposed methodology will provide a better understanding of the processes taking place in the post-fire environment and will make feasible the thorough study of the relationships and the interactions between them. It will therefore improve the prediction of wildfires impacts under various scenarios and will operate as test-bed for testing new ideas.

REFERENCES

Andreu, V., A.C. Imeson, and J.L. Rubio, Temporal changes in soil aggregates and water erosion after a wildfire in a Mediterranean pine forest, *Catena 44,* 69–84, 2001.

Brooks R. H. and C. T.Corey, Hydraulic properties of porous media, *Hydrol. Paper 3 Colorado State University, Fort Collins, USA*, 1964.

Cerda A., Changes in overland flow and infiltration after a rangeland fire in Mediterranean scrubland. *Hydrological Processes, 12,* 1031–1042, 1998.

De Luis M., J.C. Gonza´lez-Hidalgo, and J. Raventos, Effects of fire and torrential rainfall on erosion in a Mediterranean gorse community, *Land Degradation and Development 14*, 203–213, 2003.

DeBano LF., The role of fire and soil heating on water repellency in wildland environments: a review, *Journal of Hydrology, 231-232*, 195–206, 2000.

European Commission, Forest Fires in Europe: 2001 Fire Campaign, *European Communities, Ispra*, 2002.

FAO, Crop Evapotranspiration, *FAO Irrigation and Drainage Paper No. 56,* 1998.

Giovannini, G., S. Lucchesi, and M. Giachetti, Effect of heating on some physical and chemical parameters related to soil aggregation and erodibility. *Soil Science 146*(4), 255–261, 1988.

Giovannini, G., and S. Lucchesi, Effect of fire on hydrophobic and cementing substances of soil aggregates, *Soil Science 136*(4), 231–236, 1983.

Hargreaves, G.L., and Z.A. Samani, Reference crop évapotranspiration from temperature. *Applied Engineering in Agriculture, ASAE 1*(2),96-99, 1985.

Hill, P.I., A. Mordue, R.J. Nathan, C.C. Daamen, K. Williams, and R.E. Murphy, Spatially explicit modelling of the hydrologic response of bushfires at the catchment scale, *Australian Journal of Water Resources, 12*(3), 281-290, 2008.

Imeson, A.C., J.M. Verstraten, E.J. van Mulligen, J. Sevink, The effects of fire and water repellency on infiltration and runoff under Mediterranean type forest. *Catena, 19*, 345–61, 1992.

Inbar, M., M. Tamir, and L. Wittenberg, Runoff and erosion processes after a forest fire in Mount Carmel, a Mediterranean area, *Geomorphology 24*, 17–33, 1998.

Jagadeesh Babu, A., D. Thirumalaivasan, and K. Venugopal, STAO: a component architecture for raster and time series modelling, *Environmental Modelling & Software, 21,* 653–664, 2006.

Johansen, M.P., T.E. Hakonson, and D.D. Breshears, Post-fire runoff and erosion from rainfall simulation: contrasting forests with shrublands and grasslands. *Hydrological Processes, 15*, 2953–296, 2001.

Lane, P.N.J., P.M. Feikema, C.B. Sherwin, M.C. Peel, and A.C. Freebairn, Modelling the long term water yield impact of wildfire and other forest disturbance in Eucalypt forests, *Environmental Modelling & Software, 25,* 467–478, 2010.

Lavabre, J., D. Sempere, and F. Cernesson, Changes in the hydrological response of a small Mediterranean basin a year after a wildfire, *Journal of Hydrology, 142*, 273–99, 1993.

Marcos E., R. Tarrega, and E. Luis-Calabuig, Comparative analysis of runoff and sediment yield with a rainfall simulator after experimental fire, *Arid Soil Research and Rehabilitation, 14*, 293–307, 2000.

Marques, M.A. and E. Mora, The influence of aspect on runoff and soil loss in a Mediterranean burnt forest (Spain), *Catena 19*, 333–344, 1992..

Mayor, A.G., S. Bautista, J. Llovet, and J. Bellot, Post-fire hydrological and erosional responses of a Mediterranean landscape: Seven years of catchment-scale dynamics, *Catena 71,* 68–75, 2007.

Millington, J.D.A, J. Wainwright, G.L.W. Perry, R. Romero-Calcerrada, and B.D. Malamud, Modelling Mediterranean landscape succession-disturbance dynamics: A landscape fire-succession model, *Environmental Modelling and Software, 24,* 1196-1208, 2009.

Mishra, S.K., and V.P. Singh, A relook at NEH-4 curve number data and antecedent moisture condition criteria, *Hydrological Processes, 20*(13), 2755-2768, 2006.

Moffet, C.A., F.B. Pierson, P.R. Robichaud, K.E. Spaeth, and S.P. Hardegree, Modelling soil erosion on steep sagebrush rangeland before and after prescribed fire, *Catena, 71*, 218-228, 2007.

Neary, D.G, C.C. Klopatek, L.F. DeBano, and P.F. Folliott, Fire effects on belowground sustainability: a review and synthesis. *Forest Ecology and Management 122*, 51–71, 1999.

Pausas, J.G., E. Carbó, R. Neus Caturla, J.M. Gil, and R. Vallejo, Postfire regeneration patterns in the eastern Iberian Peninsula, *Acta Oecologica, 20,* 499–508, 1999.

Pierson, F.B, D.H. Carlson, and K.E. Spaeth. Hydrologic impacts of fire on steep intermountain sagebrush–steppe rangeland, *International Journal of Wildland Fire, 11,* 145–151, 2002.

Pierson, F.B, P.R. Robichaud, and K.E. Spaeth, Spatial and temporal effects of wildfire on the hydrology of a steep rangeland watershed, *Hydrological Processes, 15*, 2905–2916, 2001.

Pierson, F.B., P.R. Robichaud, C.A. Moffet, K.E. Spaeth, S.P. Hardegree, P.E. Clark, and C.J. Williams, Fire effects on rangeland hydrology and erosion in a steep sagebrush dominated landscape, *Hydrological Processes, 22,* 2916-2929, 2008.

Prosser, I.P., L. Williams, The effect of wildfire on runoff and erosion in native Eucalyptus forest, *Hydrological Processes, 12*, 251–265, 1998.

Robichaud, P.R., Measurement of post-fire hillslope erosion to evaluate and model rehabilitation treatment effectiveness and recovery, *International Journal of Wildland Fire, 14,* 475–485, 2005.

Robichaud, PR., Fire effects on infiltration rates after prescribed fire in Northern Rocky Mountain forests, USA, *Journal of Hydrology, 231–232*, 220–229, 2000.

Rosso, R., M.C. Rulli, and D. Bocchiola, Transient catchment hydrology after wildfires in a Mediterranean basin: Runoff, sediment and woody debris, *Hydrology and Earth System Sciences, 11* (1), 125-140, 2007.

Rulli M.C. and R. Rosso, Hydrologic response of upland catchments to wildfires, *Advances in Water Resources 30*, 2072–2086, 2007.

Rulli, M.C., M. Spada, S. Bozzi, D. Bocchiola, and R. Rosso, Modelling sediment yield in burned areas, *IAHS-AISH Publication, 292*, 162-170, 2005.

SCS National Engineering Handbook, Section 4: Hydrology, *Soil Conservation Service, USDA, Washington, D.C*, 1956, 1964, 1971, 1985, 1993.

Soulis, K., N. Dercas, AgroHydroLogos: development and testing of a spatially distributed agro-hydrological model on the basis of ArcGIS, *International Congress on Environmental Modelling and Software Modelling for Environment's Sake, Fifth Biennial Meeting (iEMSs), Ottawa, Canada*, 2010.

Soulis, K.X., J.D. Valiantzas, N. Dercas, and P.A. Londra, Analysis of the runoff generation mechanism for the investigation of the SCS-CN method applicability to a partial area experimental watershed, *Hydrology and Earth System Sciences*, 13, 605-615, 2009a.

Soulis, K., P. Londra, D. Alonistioti, E. Pollalis, and J.D. Valiantzas, Investigation of wildfires effect on flood runoff, *6th National Congress of the Hellenic Society of Agricultural Engineers, October 8-10, Thessaloniki, Greece*, 2009b.

Soulis, K.X., Water Resources Management: Development of a hydrological model using Geographical Information Systems, *Ph.D. thesis, Agricultural University of Athens, Greece*, 2009.

Sui, D.Z. and R.C. Maggio, Integrating GIS with hydrological modeling: practices, problems, and prospects, *Computers, Environment and Urban Systems, 23,* 33-51, 1999.

Vega, J.A., C. Fernandez, and T. Fonturbel, Throughfall runoff and soil erosion after prescribed burning in gorse shrubland in Galicia (NW Spain). *Land Degradation and Development, 16*,37–51, 2005.

Yassoglou, N., Land and desertification. In: Fantechi, R., D. Peter, P. Balabanis, and J.L. Rubio, (Eds.), *Desertification in a European context: physical and socio-economic aspects. European Commission, Brussels- Luxembourg,* 35–55. EUR 15415 EN, 1995.