Automated fire and flood danger assessment system

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Abstract

Forecasting is one of the most important elements in fire and flood danger confrontation schemes for wildland and urban interface areas. The difficulty in studying such natural hazards in general, and in the islands of the Aegean Archipelago in particular, includes not only an assessment of their causes, territorial distribution and damage inflicted in time, but also their dependence on human socio-economic activities. In this context, wildfire danger rating systems have been adopted by many developed countries dealing with wildfire prevention, so that civil protection agencies are able to define areas with high probabilities of fire ignition and resort to necessary actions. Focusing also on floods, it is impossible to avoid them; however, an overall understanding of their nature and development may facilitate their quantitative prediction, and therefore may lead towards appropriate management responses as well as in early warning so as to mitigate their catastrophic effects (loss of human lives, resources and property damage). This paper, having a two-prong emphasis, first presents an initial attempt towards a systematically approached Greek fire danger rating system in the study area of Lesvos Island, Greece. The proposed system estimates the spatial fire danger while it has the ability of risk forecasting based on meteorological data. The main output of the system is the Fire Danger Index, which is based on four other indices: the fire weather index, the fire hazard index, the fire risk index and the fire behavior index. These indices are not just a relative probability for fire occurrence but a quantitative rate for fire danger appraisal in a systematic manner. In addition, the incorporated flood analysis and forecasting module may offer considerable services particularly after a devastating flood event. Such an effort points out that there must be a fundamental shift from a prevailing crisis management approach (short-range preoccupation and technological fixes) to a more anticipatory risk management that allows concentrating on contingency planning and reasonably foreseeable futures. The developed short-term dynamic fire and flood danger indices aid in decision support for better and realistic prevention and pre-suppression planning.

Introduction

Wildfire danger rating systems have been adopted by many developed countries dealing with wildfire prevention, so that civil protection agencies are able to define areas with high probabilities of fire ignition and resort to necessary actions. Most of these systems are based on meteorological data collected by weather stations, i.e., temperature humidity and wind speed (Van Wagner 1987, Carrega 1991, Chuvieco 1997), while they follow different methodological approaches relatively to spatial and temporal scale and the relation between parameters. The objective of this research is to develop a new Greek Fire Danger Rating System that is based on parameters that can be defined and measured easily and promptly. This system is considered as an evolution to today's operational one, which is a qualitative approach with a small spatial scale (Figure 1). The proposed methodology is a quantitative approach with spatial scale of 30 m. This system can eventually lead to better planning, management and decision making to proactive activities like:

- Community information regarding forthcoming fire danger and regulation of accessibility and activities
- Force dispatching, manning of lookout towers and patrol preparedness
- Emergency management scenarios for high-risk areas.

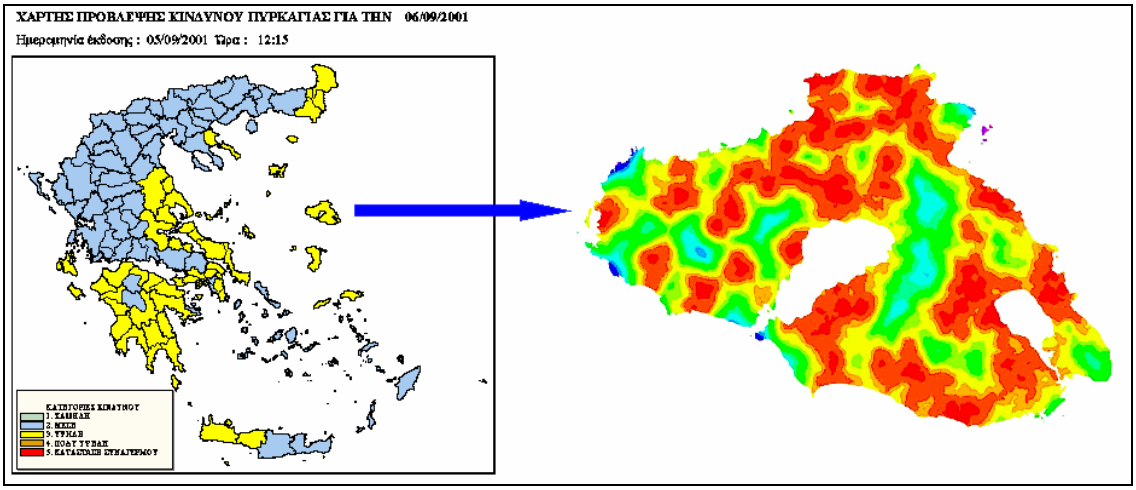

Figure 1: Evolution of current operational Fire Danger Rating System for Greece.

Focusing also on floods, it is impossible to avoid them; however, an overall understanding of their nature and development may facilitate their quantitative prediction, and therefore may lead towards appropriate management responses as well as in early warning so as to mitigate their catastrophic effects (loss of human lives, resources and property damage). Especially the islands have to confront the challenge of surviving in a semiarid environment exacerbated by periodic floods, which propagates a continuous air of crisis. The difficulty in studying water resources in general, and in the islands of the Aegean Archipelago in particular, includes not only an assessment of their natural state, territorial distribution, and fluctuations in time, but also their dependence on human socio-economic activities (Karavitis and Kerkides 2002). In recent decades the intensified exploitation of water resources for urban, agricultural and industrial uses, the population redistribution and growth, as well as alarming indications about climatic shifts (green house effect, droughts, etc.) have started to elicit significant impacts on the state of the available fresh water, despite the ability of stream and groundwater flow for renewal and recharge.

Study Areas

The island of Lesvos covers an area of 1672 km^2 with a variety of geological formations, climatic conditions and vegetation types. The climate is typically Mediterranean, with warm and dry summers and mild and moderately rainy winters. Annual precipitation averages around 670 mm. The average annual air temperature is 18^0 C with high oscillations between maximum and minimum daily temperatures. The terrain is rather hilly and rough, with its highest peak at 960 m a.s.l. Prominent arid lands are mainly found in the western part of the island, in which acid volcanic rocks dominate. Vegetation of the area, defined on the basis of the dominant species, includes phrygana or garrigue-type scrubs in grasslands, evergreen-sclerophylous or maquis-type shrubs, pine forests, deciduous oaks, olive tree orchards and other agricultural lands.

Samos Island is located in the central Aegean Sea and covers an area of about 487 km^2. Geologic structures combined with the overland slopes along with general climatic patterns have led to the creation of an extensive stream network. Samos Island was chosen as a case study to examine the flood hazard in an area that has recently suffered severe forest fires, extreme precipitation events, and thus devastating food episodes (Figure 2).

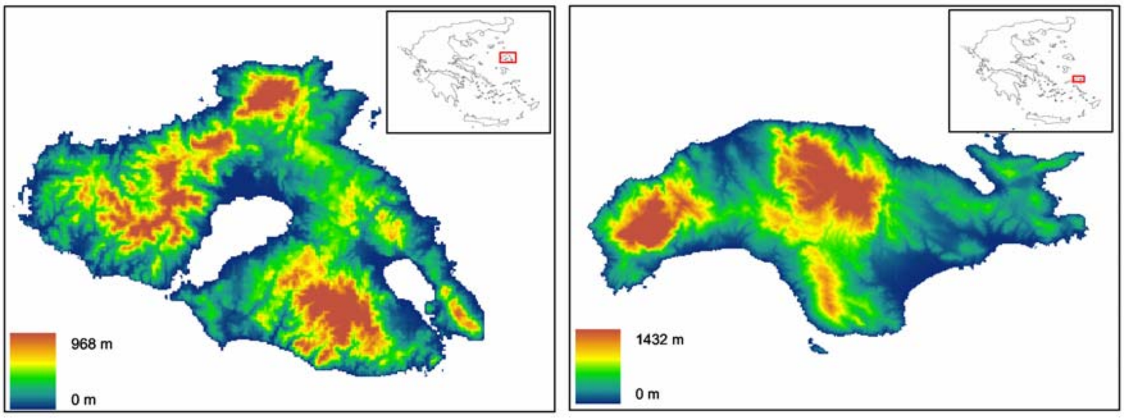

Figure 2: Topography of Lesvos Island (left) and Samos Island (right) in Greece.

Fire Danger Rating System

The main output of the proposed Fire Danger Rating System (FDRS) is the Fire Danger Index which is based on four (4) other indices: the fire weather index (FWI), the fire hazard index (FHI), the fire risk index (FRI) and the fire behavior index (Figure 3). These indices are not just a relative probability for fire occurrence but a quantitative rate for fire danger appraisal in a systematic manner. The parameters have been chosen in a way that is easy to be defined and measured in order to be included in an operational

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system versus basic research methods (Table 1). The parameters are retrieved through the analysis of remote sensing data, namely Landsat TM and Quick-Bird, as well as maps with scale 1:50000 and the operational meteorological model SKIRON. Remote automatic weather stations (RAWS) and the operational weather forecasting system provide real-time and forecasted meteorological data, respectively. Geographic Information Systems have been used for management and spatial analyses of the input parameters, and the relation between wildfire occurrence and the input parameters will be investigated by neural networks whose training is based on historical data.

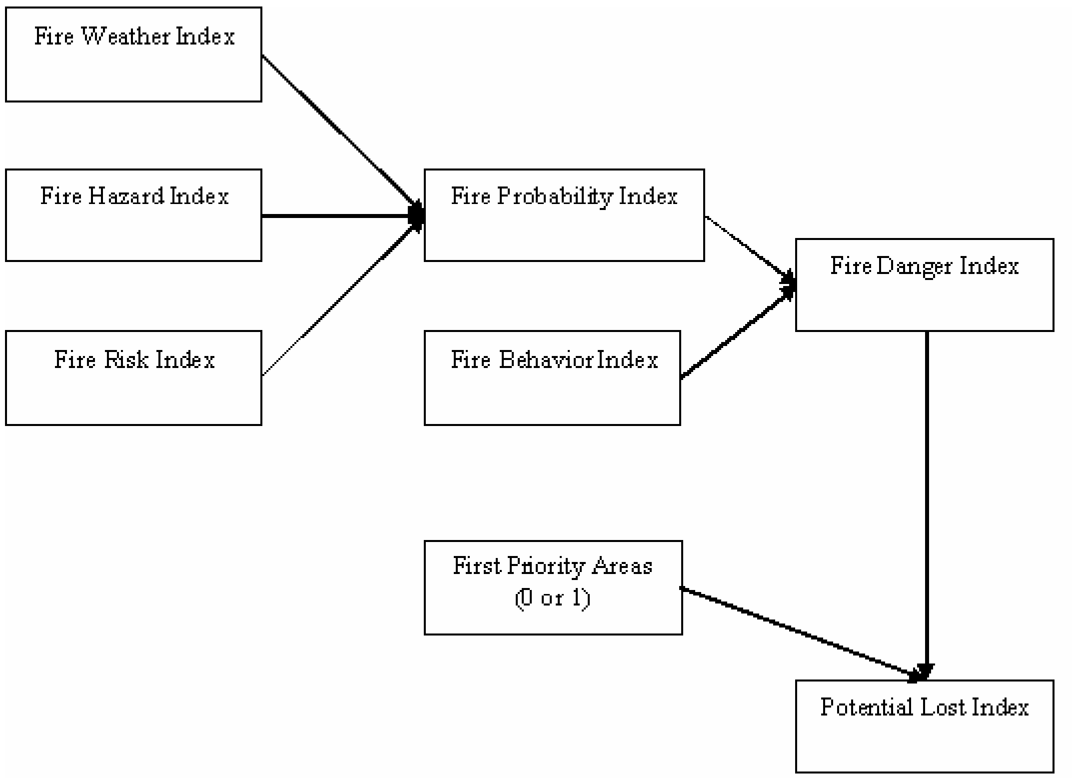

Figure 3: Fire Danger Rating System scheme.

The function mapping of FWI, FHI and FRI will be accomplished with Artificial Neural Network (NN) methodologies. These methodologies have been proved useful for classification and function approximation/ mapping problems, which are tolerant of some imprecision (Sarle 1997) and have been used in spatial prediction of fire ignition probabilities (Vasconcelos et al. 2001). The training of NN will be based on fire history. Thus, 420 historical fire events have been identified and mapped (1970-2001) in Lesvos Island and historical data for the input variables have been collected for each event (Figure 4). This database will be used for training, testing and validation of the NN.

The training of NN will be performed with error back-propagation algorithm (Parker 1982, Rumelhart and McClelland 1986, Werbos 1994). The network starts its training procedure with random weighting values and propagates the errors backwards through the network by changing the weighting values. Let us consider a three-layer network, i.e., an input layer with i nodes, an output layer with k nodes and a hidden layer with j

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nodes; the weights between the input nodes and the hidden nodes are marked with w_{ji}, while the weight between hidden nodes and the output nodes are marked with w_{kj} (Figure 5).

Table 1: Parameters of the proposed FDRS.

Fire Weather Index	**Fire Hazard Index**	**Fire Risk Index**
Next day air temperature at 12.00 or real time air temperature from RAWS	Fuel models	Distance to main roads
Wind velocity	10-hr dead fuel moisture content	Distance to secondary roads
Relative humidity	Elevation	Distance to livestock, and other similar significant buildings
Precipitation	Aspect	Distance to power lines
		Distance to urban areas
		Distance to waste disposal sites
		Distance to railways
		Distance to recreation areas and other similar areas with high population density
		Distance to agricultural works, grazing lands
		Distance to forestry works
		Distance to military fire-grounds
		Month
		Day

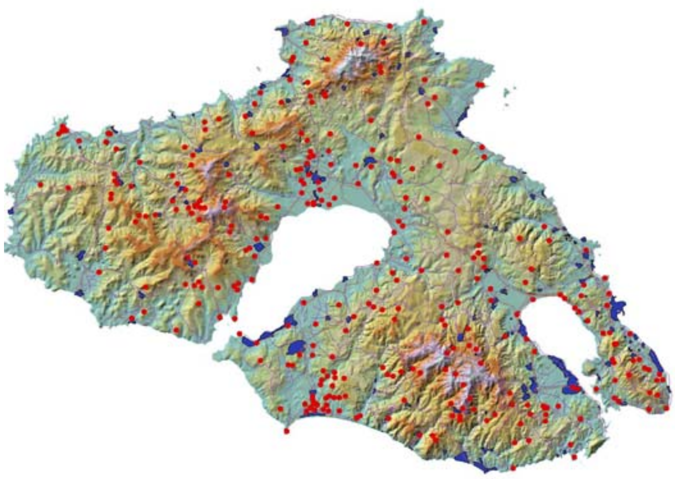

Figure 4: Spatial distribution of fire ignitions points during 1970-2001 in Lesvos, Greece.

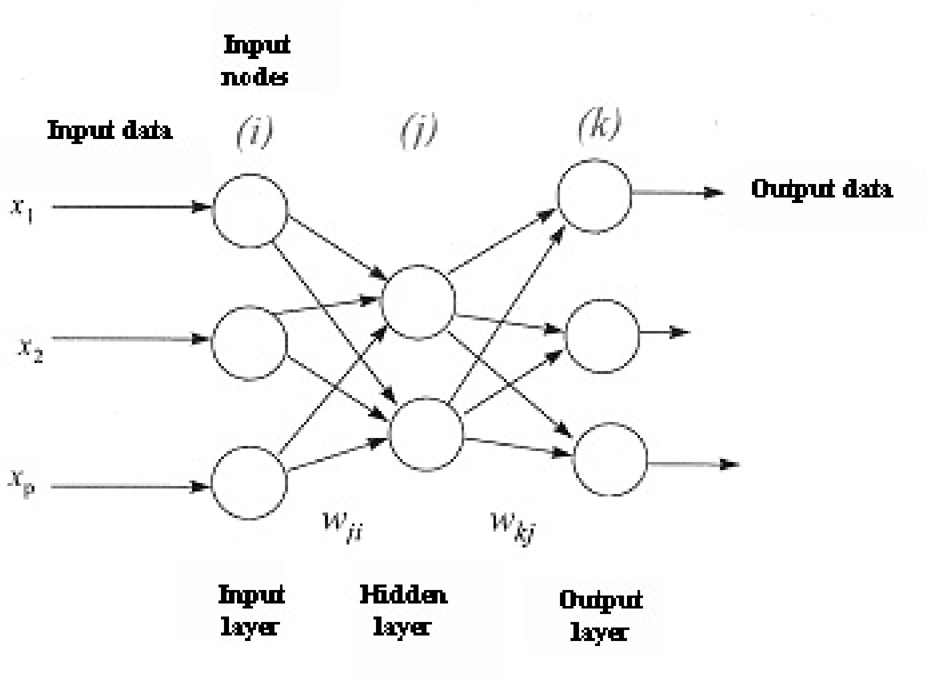

Figure 5: Three-layer neural network.

The input parameters *z* and output *d* in activation function *f(z)* to the layers *j* and *k* are respectively:

$$d_j = f_j(z_j) \text{ where } z_j = w_{1,i}d_1 + \ldots w_{j,i}d_j$$

$$d_k = f_k(z_k) \text{ where } z_k = w_{1,j}d_1 + \ldots w_{k,j}d_k$$

with activation function:

$$f(z) = \frac{1}{1+e^{-z}}$$

This function approximates 1, for high and positive values of *z*, and 0 for high and negatives values of *z,* and is suitable for wildfire occurrence cases because the dependant variable has a binary value (0 or 1) (Jordan 1995, Sarle 1997). Additionally, the use of such an activation function allows the output to be given a probabilistic interpretation (Bishop 1995).

The aim of the training is the minimization of the error function with the corrections of weights *w*. Two error functions will be evaluated during training procedure: The sum-of squares-error function:

$$SSE = E_k = \frac{1}{2}\sum_k (t_k - d_k)^2$$

and the root mean square (RMS) function:

$$RMS = \sqrt{\frac{1}{n}\sum_k (t_k - d_k)^2}$$

where, t_k the desired output, d_k the actual output at the output layer and *n* the number of patterns.

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The training procedure can be described in the steps below (Masters 1993, Fausett 1994, Bishop 1995):

- Selection of the training data with known output values.
- Selection of the random values for weights *w*.
- Feed of network with training vectors $x = (x_1, x_2, ..., x_p)^T$.
- Comparison of output values d_k with the desired output values t_k and calculation of:

$$\delta_k = (t_k - d_k)(1 - d_k)d_k$$

- Correction of output weights according to relation:

$$w_{k,j} \leftarrow w_{k,j} + \Delta w_{k,j}$$

with

$$\Delta w_{k,j} = \rho(t_k - d_k)(1 - d_k)d_k d_j = \rho\delta_k d_j$$

- where coefficient ρ is the learning rate and controls the rate and the speed of the training. Next step is the correction of weights to previous processing layers according to the new values of δ_K and $w_{k,j}$ with the relations:

$$\delta_j = (1 - d_j)d_j \sum_{k=1}^{k} (t_k - d_k)(1 - d_k)d_k w_{k,j} = (1 - d_j)d_j \sum_{k=1}^{k} \delta_k w_{k,j}$$

and

$$\Delta w_{j,i} = \rho\delta_j d_i$$

Afterwards, the neural network is fed with new training data and the above procedure is replied until the desired minimum value of the error functions is reached.

Flood Danger Assessment System

Ideally a flood danger assessment system should have two major components, i.e., a flood warning forecasting system and a flood management plan based on which the proper responses should be initiated (UNESCO 1995). However, the overall management scheme is comprised of both the pertinent elements, which are described in the following sections.

Flood Forecasting System

Flood forecasting systems are not able to prevent the floods, but they may offer on time warnings to minimize the impacts (human losses, financial and social disruptions and environmental catastrophes). Forecasting extreme discharges in real time is an also extremely difficult task and in order to meet the requirements of an operational forecasting system in an accurate enough way, “tailor made” exact river basin models are need to be developed. The accuracy of flood forecasts often depends on the hydrological knowledge about the watershed under consideration, on the experience of local expert hydrologists as well as on the availability and quality of data from field stations (Yen 1986).

Efficiently operating flood-warning systems are more than the sum of their individual components involving a great array of people. Therefore a strict organization and clear definition of duties are essential, as well as timely operation. Flood warning systems ideally consist of the following components (Karavitis 2002, Yen 1986):

- *Precipitation forecasts*

  Specific meteorological situations, which create floods in large river basins, may be analyzed and identified by meteorologists up to 72 hours ahead. Precipitation data for at least the next 24 hours derived from these forecasting models are very helpful in oncoming flood situations as well as during the flood per se. The larger the scale of the rainfall area is, the better it may be forecasted, whereas weather radar data can be used to predict local rainfall up to a few hours.

- *Monitoring network*

  Every forecasting method needs on-line information of different meteorological and hydrological parameters. Representative data from spatially well-distributed gauges should be transmitted in short regular intervals to a central data bank in order to operate forecasting models. Different methods of data transmission (radio equipment, telephone, glass fiber cables etc.) are in use. Regular testing and checking of the whole signal path in non-flood periods is essential.

- *Flood forecasts*

  The mountainous areas have relatively short concentration times on small and mediums sized rivers and often leave only a few hours for operational runoff forecasts as well as preparations on the arriving flood. Forecasts for periods longer than 3 to 6 hours can only be achieved by using pertinent precipitation forecasts, but certainly human experience is needed for dependable results.

- *Communication system*

  In flood crisis situations, communication systems tend to collapse due to overload or technical faults. Reliable connections between responsible authorities and operational hydrological services should therefore be developed in time and also be frequently tested.

- *Headquarters*

  Headquarters are necessary to co-ordinate activities during flood periods, provide flood forecasts as well as flood reports, and need to be well equipped with the ad-hoc communication systems.

- *Alarm plans*

  Endangered people need to be warned or evacuated in time, organizations (army, fire brigade, red cross, etc.) dealing with flood situations have to be informed in time. Nevertheless operation rules for power stations and reservoirs have to be put into action in time. All the necessary phone numbers, check lists and other important information compiled in alarm plans should be updated frequently.

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- *Reports and information*

  Flood reports (with a general description of the floodwater situation at present, a precise short time forecast (quantitative information) and a long-time forecast (tendencies, qualitative information) play an important role on the information line during flooding situations. Therefore they need to be clearly structured and easily readable without a chance of misinterpretation by local authorities and involved organizations as well as endangered people and media

Management Options

The existing ideal management practices as well as the overall responses to the floods following the above-mentioned forecasting argumentation were analyzed and presented. In Table 2 there is a classification of the categories of applied flood management responses in a typical Greek island case (Karavitis 2002, Karavitis and Kerkides 2002). In this context, the islands are areas with a high coastal concentration of population and activities, haphazard urban and water related systems development, characterized by almost the absence of maintenance capital of marginal and decaying infrastructure. The existing databases are incomplete and conflicting. Water resources planning and management efforts seem not to be conducted in a sustained and comprehensive fashion. Flood control operation and maintenance practices also seem to be inefficient and the existing water law is inadequate for the insular and urban environments (Karavitis 2002).

The information technology seems not to be incorporated in water resources management practices. However, given the presented existing uncertainties in the insular environment, and the limited meteorological data series, such a fact needs to be further investigated. It would also seem that flood crisis management approaches were prevailing. The decision making process may be characterized by marginal integration among experts, administrators, managers and politicians (Vlachos and Braga 2001).

Table 2: Categories of concern with responses to the Greek island floods.

Resources	**Data**	**Organizational**	**Policy**
Topographic and geographic limitations. Decaying and inefficiently maintained water infrastructure. Limited regulation measures (short- and long-range).	Collection problems. Validity questions. Absence of reliable databases. Lack of information technology usage.	Lack of coordination. Lack of a flood control authority. Spasmodic and untimely responses. Fragmentation of water resources management.	Lack of effective water resources legislation. Centralized decision making. Absence of a flood-contingency plan. Systems engineering approach not applied. Crisis management.

Conclusion

There is a number of fire danger rating systems in use around the world that utilize point-stations to measure all their variables, and the danger degree is calculated for these stations; for spatial distribution of the danger rate, an interpolation method is then applied. Within this research, not only the variables of fire danger index are spatially calculated *a priori*, but also the Neural Network methodology has the ability to be validated daily. For example, if for a certain area the system calculates high danger while there is no fire event, or vice versa, then new data will feed the NN in order to be trained again. The potentiality of NN to be trained continuously makes the system applicable for any geographical area as long as a specific fire history and geographical database is developed.

In terms of the flooding danger, the following recommendations are drawn concerning both tactical and strategic criteria:

- Establishment/ completion of an integrated meteorological stations network for the monitoring of the rainfall-runoff phenomena.
- Usage of the information technology for the rainfall-runoff transformation in area-wide simulation.
- Development of a flood risk area map (GIS, etc.).
- Design and implementation of flood control works using criteria of environmental sustainability and the preservation of the natural collectors' properties. Practices such as covering of the natural streams should be avoided at all cost.
- Synergistic efforts with the overall urban planning framework so as to avoid over urbanization. Areas such as park and open natural spaces should be incorporated in the scheme.
- Establishment of a flood prediction – flood early waning system.
- Implementation of coherent flood management responses in a timely and well-organized manner, so as to avoid the prevailing crisis management attitude.

The synthesis of the overall effort with the recently adopted Water Framework Directive by EC is considered essential. The WFD has far-reaching provisions for the protection of quantity and quality of surface and ground water, integrated planning and the strengthening of public participation (Decleris 2000).

The incorporated fire and flood analysis and forecasting modules may offer considerable services before, during and after devastating fire and flood events. Such an effort points out also that there must be a fundamental shift from a prevailing crisis management approach (short-range preoccupation and technological fixes) to a more anticipatory risk management that allows concentrating on contingency planning and reasonably foreseeable futures. Thus, the approach of policy formulation, management and implementation, entails fundamental changes in outlook, visionary and goal-oriented commitment, as well as acceptance of the central premise that social, technical, economic and environmental problems are intertwined and must be resolved together.

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