

**THE 1994 FLOOD OF THE GIOFYROS BASIN ON THE CRETE ISLAND:  
A CASE STUDY OF RISK-BASED FLOODPLAIN MANAGEMENT**

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**Abstract.** Engineering Risk Analysis and Multi-Objective Decision-Making Under Risk are considered as a general framework for floodplain management and protection from extreme floods. Distinction is made between (a) the *catchment* or *large scale planning* and (b) the *local* or *small scale design* of protective measures. After defining the risk of flooding at different scales and multiple criteria for selecting among alternative measures of floodplain protection and management, the methodology is illustrated using the Giofyros Basin in Crete Island, where a devastating flood occurred in January, 1994. Alternative structural and non-structural solutions, which may protect the inhabited area and important public buildings from future extreme floods, are analyzed.

## **1. INTRODUCTION**

Extreme floods are essentially natural hazards that occur at a relatively low frequency. Excessive precipitation is, in most cases, the main cause of catastrophic floods. However, anthropogenic factors, such as human occupation of floodways, extensive urbanization, and structural measures to mitigate floods (flood levees and walls, cutting of the river meanders, river training) have modified the natural characteristics of extreme floods (Rossi et al., 1994; Gardiner et al., 1995). Recent catastrophic flood events in Europe (Rhine River, 1995) and the USA (Mississippi River, 1993) have shown that human activities and traditional river engineering works may result in an increase in the frequency of extreme floods, of the water stage and, most importantly, of negative impacts and consequences such as the loss of property and human life.

In the Mediterranean area, flooding conditions are unique because of semi-arid climate, geological characteristics, and the socio-economic environment. The main characteristics of floods in the Mediterranean Basin may be described as follows:

- 1) Heavy rainfall in the autumn and winter may produce flash floods in catchments and streams that remain dry throughout much of the year. These flash floods are of short duration (from a few minutes to a few hours) and have high flood peaks (many hundreds of  $\text{m}^3/\text{s}$ ).

- 2) During flash floods, soil erosion and sediment transport are important and may lead to the failure of flood-defensive engineering structures such as reservoirs, spillways, and gates.
- 3) In karstic areas, which make up more than half of the Mediterranean drainage basin, flash floods are more acute and much more violent than in non-karstic areas (Davy, 1989; Ganoulis, 1994b; 1995; Ganoulis and Vafiadis, 1995). Excessive flooding occurs in these areas after the karstic cavities are filled up with huge amounts of rainfall water.
- 4) Heavy concentrations of population in urban and residential areas around the centers of historic cities have resulted, in many cases, in the occupation of beds and floodways of ephemeral streams. This phenomenon has been recorded mainly near the coastal areas, where tourist activity has dramatically increased in recent years. As the existing infrastructure in sewer systems is inadequate and its completion is very expensive, great volumes of storm water cannot be evacuated after heavy rains. As a consequence, the lower areas of cities become flooded and important losses to public and private property occur (Ganoulis, 1994b).

In view of the limited economic means of local authorities, the implementation of expensive traditional engineering measures for flood protection, such as the building of dams and drainage tunnels, is very unlikely. In populated areas, expansion of the existing storm sewer system is difficult, due to the high cost of replacing the existing sewers and the impact of engineering works on urban activities such as trade, tourism, and traffic. A risk-based design of alternative measures may be appropriate to reduce costs and to improve reliability of the design (Ganoulis, 1994a). Floodplain management and flood control involve *alternative measures* (*structural*: levees, dikes, retention basins, channel modifications, or *non-structural*: flood warning, land uses), *different states of nature* (type of climate, socio-economic environments) and *various preferences* (economic, environmental, aesthetics, etc.). For the management of risks related to floods, various uncertainties should be assessed and quantified, such as hydrologic, economic, and environmental uncertainties. A traditional risk-based design of flood reduction structures is the one which has been adopted by the US Army Corps of Engineers. It is based on the selection of the hydrologic risk that maximizes the net economic benefits from the project under various uncertainties (Dotson and Davis, 1995).

In this paper, the general framework of Engineering Risk Analysis is used to develop a multiobjective risk-based approach to floodplain management. The various steps taken in a comprehensive application of Engineering Risk Analysis to flood control are: (1) identification of hazards, (2) risk quantification, (3) consequences of risk, and (4) risk management. The risk-based floodplain management approach is illustrated in the case of the Giofyros Basin, Crete Island. In this area, near the city of Heraklion, hydro-meteorological data and data from the 1994 flood are available.

## **2. IMPACT OF THE 1994 FLOOD**

### **2.1 GEOLOGICAL AND HYDROLOGICAL CHARACTERISTICS**

As shown in Fig. 1, the hydrologic basin of Giofyros lies in the northern part of Crete Island. The Giofyros Stream outfalls through the western suburbs of the city of Heraklion to the Aegean Sea. According to its catchment area, the Giofyros is one of the largest streams on this

Mediterranean island. It has a constant flow only during the humid part of the year (autumn and winter). The main geomorphological characteristics of the catchment are:

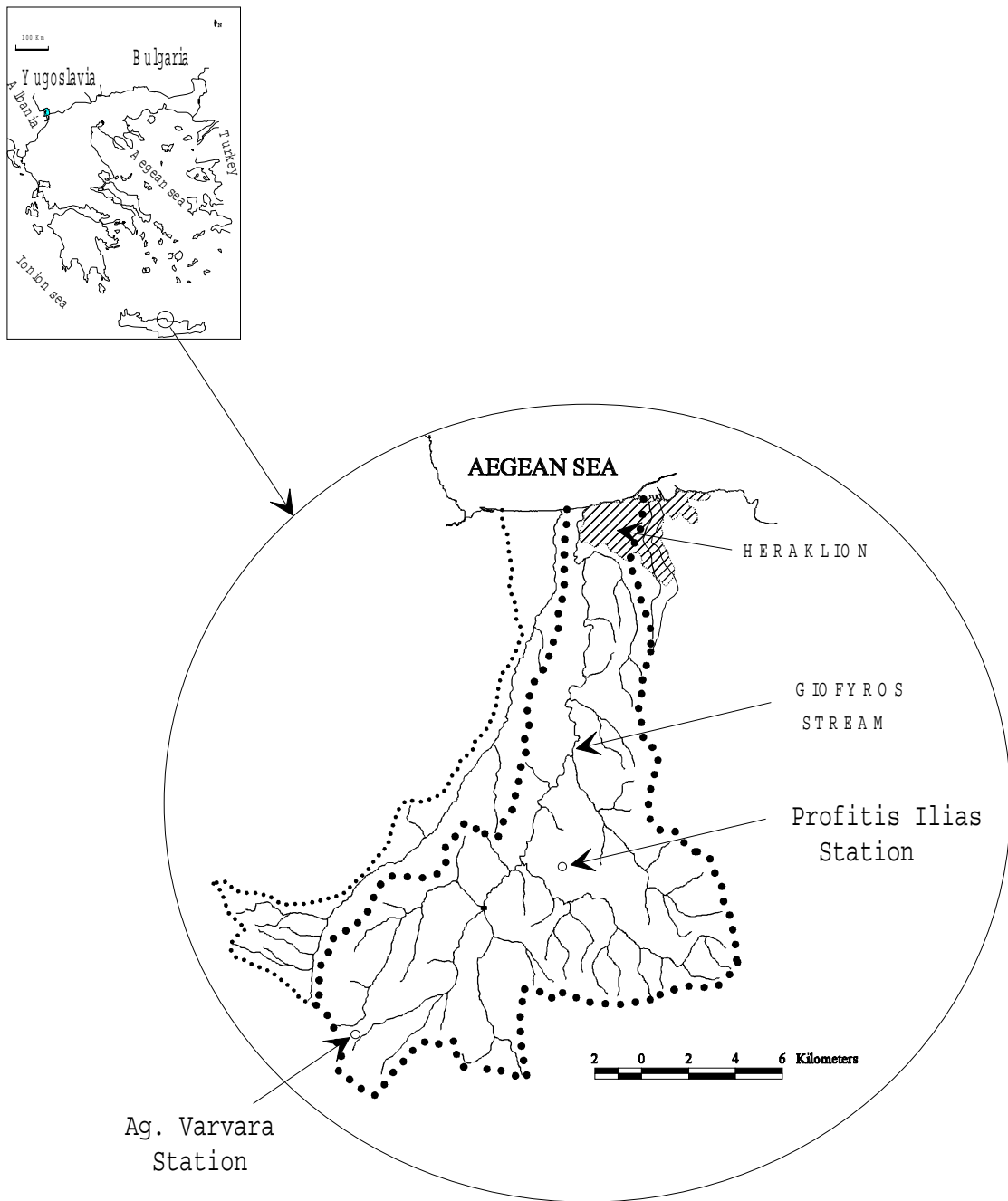


Figure 1. Location of the Giofyros catchment and hydrometeorological stations.

- Total area: 189 km<sup>2</sup>
- Max hydraulic route: 31 km

- Max altitude: 1000 m
- Mean altitude: 353 m
- Mean slope: 0.22

The soil is mainly alluvial and contains a relatively high percentage of clay, and some areas of rock. The area is constantly cultivated and covered mainly by vineyards and olive trees, with some forests. The climate is of the typical Mediterranean type, with hot and dry summers and mild winters. Rainfall is important during the winter period (from October to March). The mean, maximum, and minimum annual precipitations are:

- Mean annual precipitation: 827 mm
- Min annual precipitation: 469 mm
- Max annual precipitation: 1217 mm.

According to the data record 1954-1994 of the «Ag. Varvara» hydrometeorological station, the monthly precipitation in December and January has exceeded 550 mm/month at least once during the last 40 years. Many rainfall gauge stations and some full meteorological stations are located in the watershed and in the neighboring basin. Data data from these stations are not easily or fully usable due to errors or missing periods. The best and most reliable rainfall data are available for a period of less than one decade from the official meteorological station at the Heraklion airport. This station is outside the catchment area, on the coast. Analysis of these data showed a good representativity for the catchment.

## 2.2 THE 1994 FLOOD

On the 13th of January, 1994, a devastating flood occurred in the Giofyros Basin. The extreme flood resulted in a series of events, which may be summarized as follows:

a) Heavy rainfall. The total rainfall recorded on the day of the flood was about 185 mm, which is equal to about half of the mean annual precipitation in the region of Heraklion. A maximum rainfall intensity of 37 mm/h was recorded at the hydro-meteorological station of Ag. Varvara (Fig. 2). A total rainfall of 143 mm was recorded in a 6-hour period, which is about the concentration time for the Giofyros Basin.

b) Soil Conditions. Light intensity rainfall had persisted several days before the critical storm of January 13, 1994. The soil was almost completely saturated and runoff was high during the critical storm.

c) Other. Deforestation and removing several hectares of vineyards during the months preceding the storm may have increased the intensity of the flood.

Many houses located downstream, near the coast, were flooded and material damage was estimated at several hundreds of millions of drachmas. The most important flood damage was to the city's wastewater treatment plant, which had been under construction. Many of the plant's concrete reservoirs were disabled or completely destroyed by the force of the incoming water.

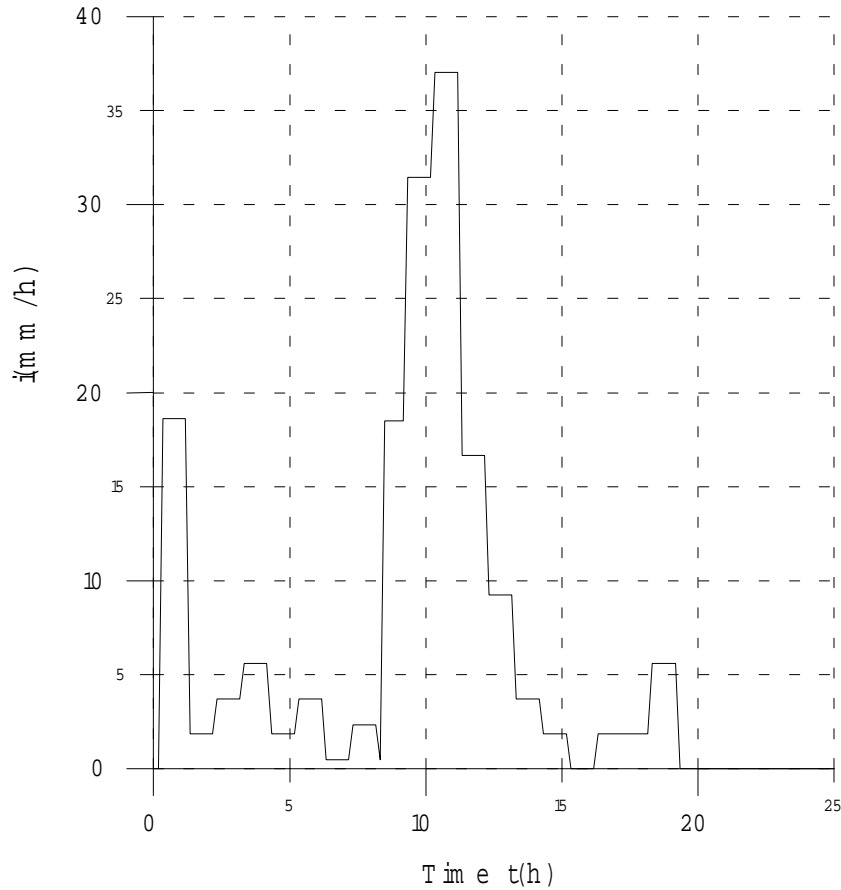


Figure 2. Relationship between rainfall intensity  $i$  (mm/h) and duration  $t$  (h) during 13-14 January 1994 (Ag. Varvara Station).

### 3. RISK-BASED FLOODPLAIN MANAGEMENT

By definition, floodplain management is an integrated consideration of all structural (engineering) and non-structural (administrative) measures to minimize losses due to flooding on the catchment scale. Selection among alternative measures to prevent floods may be made at different scales. It is useful to distinguish between the following design scales:

- (a) *catchment scale planning*: a large scale or regional scale «optimal» selection between various alternative measures, and
- (b) *local scale design*: a small scale area (sub-basin) design of hydraulic structures.

At both scales, the risk of flooding is traditionally related to hydrologic uncertainties (hydrologic risk). If we define the engineering risk as the probability of failure (Ganoulis, 1994a; Ganoulis, 1991), then at the *catchment scale* (regional scale) we have:

$$\text{risk of flooding} = P(Q > Q_T) \quad (1)$$

where  $P(\cdot)$  denotes probability,  $Q$  is the actual flood at the catchment area, and  $Q_T$  is the  $T$ -year flood.

At the local scale of a hydraulic structure, the risk may be defined as the probability of overtopping. As shown in the case of a simple flood levee (Fig. 3), failure occurs if  $h_0 + z > H$ . In this case we have:

$$\text{risk of failure} = P(h_0 + z > H) \quad (2)$$

where  $h_0$  = the mean water level,  $z$  = the surelevation for a given flood, and  $H$  = the height of the levee.

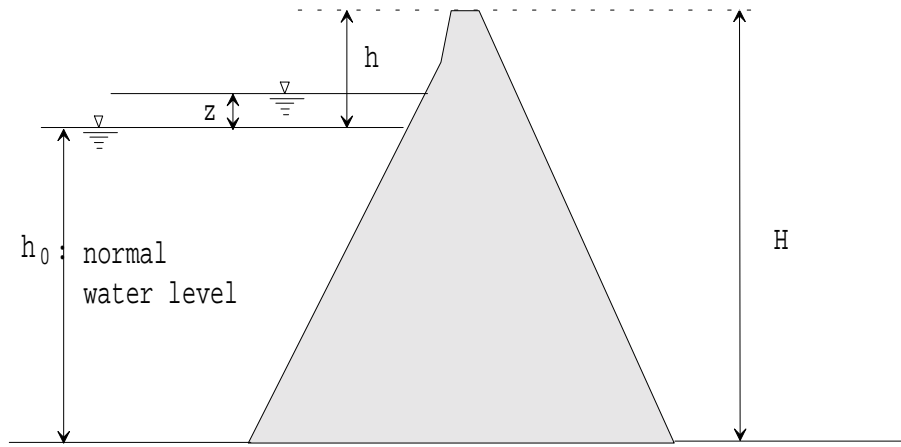


Figure 3. The flood levee problem.

Traditional risk-based design (US Corps of Engineers) incorporates uncertainty analysis under risk into an optimization framework (Dotson and Davis, 1995). The objective is to select the *optimal risk-based design* to maximize the *net economic benefits*.

If  $C_D(x)$  is the expected annual damage cost due to flooding failure,  $C_I(x)$  the annual installation cost and  $x$  a vector of decision variables relating to structural sizes, then the optimal risk-based design may be expressed as

$$\min_x \{C_I(x) + C_D(x)\} \quad (3)$$

under some design specifications  $g(x) = 0$ .

The design level  $x$  is the structural size  $H$  for the flood levee, which may be related to the hydrologic risk  $P_F$  or the hydrologic reliability  $(\ln p_F)$  (Ganoulis, 1995). The result of minimizing expression (3) in a special case (Ganoulis, 1995) is shown in Fig. 4.

This approach has only one objective: the *total cost* or the *total net benefit* of the project, (maximize benefit or minimize cost) as a function of the flooding risk. The procedure is suitable mainly for a small scale design (sizing a flood levee or a hydraulic structure) where a trade-off between costs (or benefits) and risk (reliability) may be obtained through the optimization procedure.

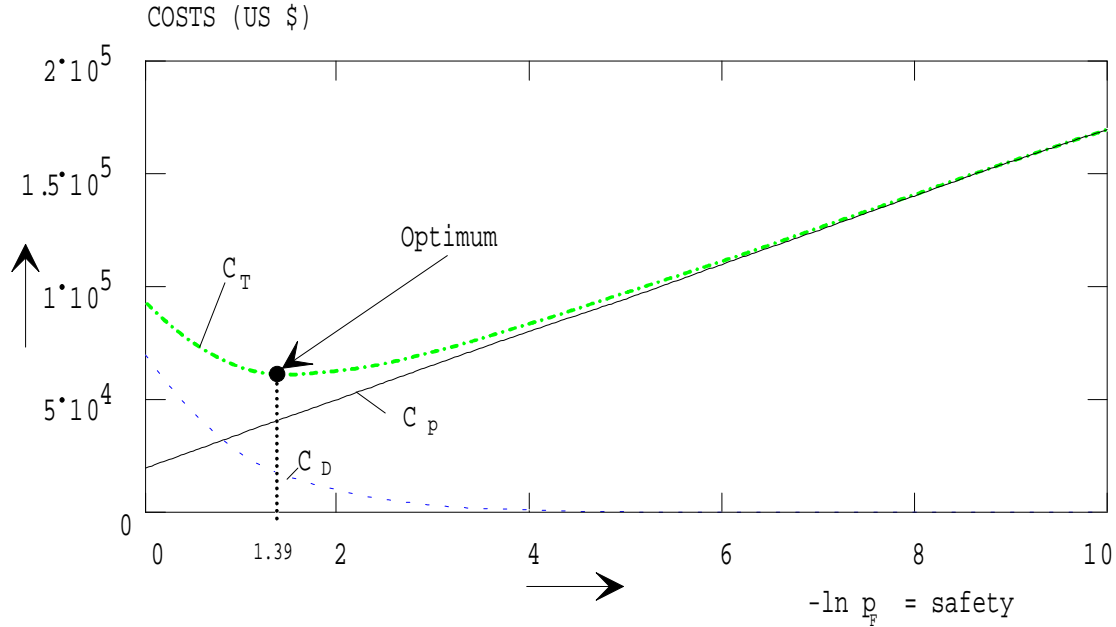


Figure 4. Total cost-reliability relationship for a flood levee.

On the catchment or regional scale planning process, a multi-objective approach to flood control alternatives is recommended (Bogardi and Nachtnebel, 1994). The main *objectives* or *criteria* to be taken into consideration are:

- 1) *Economic Objectives*: Consideration of costs and benefits including project costs, operation and maintenance costs, external costs, reduction of flood damages benefits, land enhancement benefits, and other indirect benefits.
- 2) *Environmental Objectives*: These may be positive or negative environmental impacts, such as increase or decrease in the number of species, flora and fauna modifications, losses of wetlands, and landscape modification.
- 3) *Social Objectives*: Consideration of the risk of extreme flooding, duration of structure construction, employment increases, and impacts on transportation.

After the definition of the objectives, the steps to be undertaken for the multi-objective planning of flood control alternatives are (Ganoulis, 1994a):

- a) Define a set of alternative actions, including structural and non-structural measures of flood protection.
- b) Evaluate the outcome or impact matrix, i.e. assign rates to each specific objective, corresponding to each particular action.
- c) Rank the alternative actions using an appropriate multi-objective analysis technique.

Different techniques are available for multi-criteria decision-making (Goigoechea et al., 1982; Vincke, 1989; Fraser and Hipel, 1984.) Distance-based techniques such as the following have been most developed:

- ELECTRE I to III
- Compromise Programming
- Goal Programming
- Sequential Multiobjective Optimization
- Game Theory.

In selecting the most appropriate method, important criteria are the type of objectives (quantitative or qualitative), the number of decision-makers (one or a group), and whether objectives are involved a priori, a posteriori, or interactively. ELECTRE I to III techniques are more suitable for qualitatively expressed criteria (Bogardi and Nachtnebel, 1994). Game and team theories (Fang et al., 1993) are mainly interactive techniques. Uncertainties and risk may be quantified by using probabilities or fuzzy sets, and can be better handled by Compromise Programming techniques (Ganoulis et al., 1996). Multi-criteria decision-making analysis is currently under investigation for the catchment scale planning of flood defense measures in the Giofyros Stream.

## 4. APPLICATION TO THE GIOFYROS BASIN

### 4.1 LARGE SCALE PLANNING

A distinction should be made between (a) the downstream plain area of the Giofyros Stream and (b) the upstream catchment area. The downstream plain area represents about 20% of the total area of the basin and has a mean hydraulic length of 11 km. This is about 1/3 of the mean hydraulic length of the basin (~30 km). Aside from some minor hydraulic works in the plain area, no other structural measures (reservoirs, regulation structures, etc.) have been implemented in the entire basin.

The hydraulic risk of flooding was first evaluated for the entire catchment area. As no gauged data are available for flowrates, the discharge-frequency relationship was estimated by analyzing the maximum rainfall-frequency data. Then, the HEC-1rainfall-runoff model was used to estimate runoff.

The relationship between the maximum rainfall height (mm) and the return period T(yr) is shown in Fig. 5 for a 2-hour rainfall duration. In order to evaluate different uncertainties which influence the extrapolation results over 50- and 100-year return periods, three different methods have been applied (Ganoulis, 1994b): (a) fitting a Gumbel distribution, (b) fitting the data, and (c) fitting the A and B coefficients. These coefficients appear in the following relation:

$$h(t, T) = A(T) t^{1-B(T)} \quad (4)$$

where t is the rainfall duration (min), h the rainfall height(mm), and T the return period (yr).

The maximum rainfall height and the peak flood discharge corresponding to 30, 50, and 100 years return periods are summarized in Table 1 below.



Table 1. Estimated maximum rainfall height  $h_{\max}$ (mm) and peak flood discharge  $Q_{\max}$ (m<sup>3</sup>/s) for return period T=30, 50 and 100 years.

T	h (max) (mm)	Q max (m <sup>3</sup> /s)
30	125	450
50	152	580
100	193	900

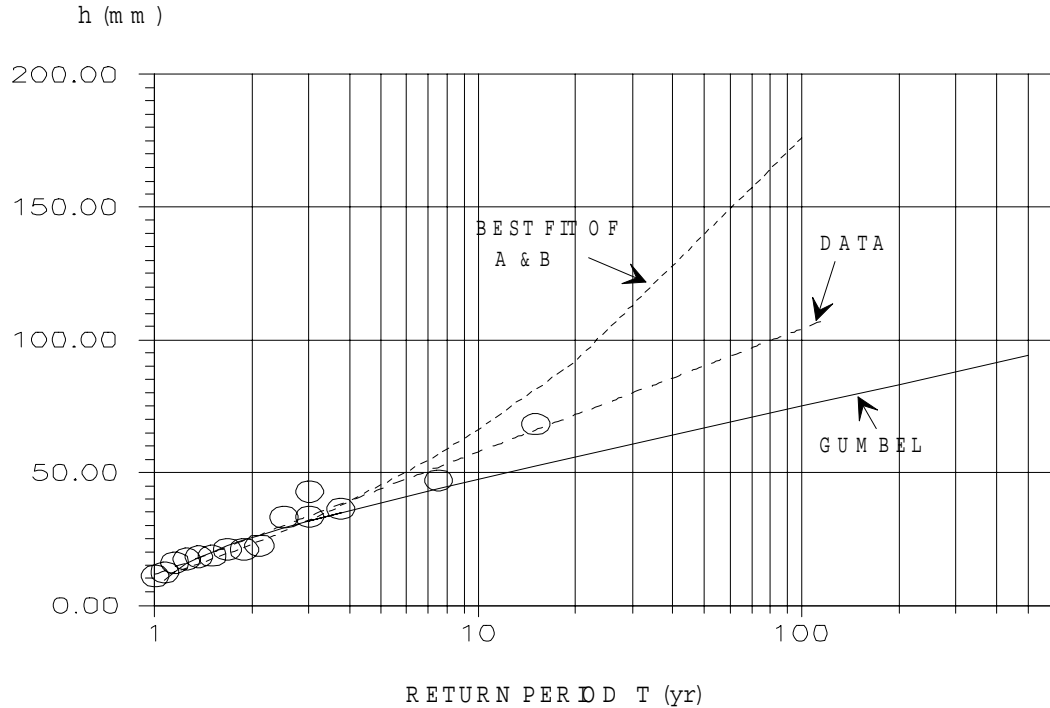


Figure 5. Maximum rainfall height (mm) versus the return period  $T$ (yr) for a 2-hour rainfall duration.

Alternative measures for floodplain protection are combinations of three different approaches:

- 1) Regulation of the downstream cross-section of the Giofyros Stream in order to increase the hydraulic capacity. Due to some hydraulic constraints (existing bridges) the maximum hydraulic capacity is about 300 m<sup>3</sup>/s, which corresponds to the 20-year flood. Environmentally sound regulation may preclude any concrete scaling and stream training, i.e. it should be based on the enlargement of the cross-section, use of natural materials for strengthening the bed and earthen flood levees, and it should be well-integrated into the landscape.
- 2) Design and construction of a multi-purpose reservoir to retain a substantial volume of the critical flood. Two reservoirs of different capacities have been proposed: (i) a  $28 \times 10^6$  m<sup>3</sup> reservoir dammed by an earthen structure approximately 70 m in height, and (ii) a smaller

reservoir with a total capacity of  $15 \times 10^6 \text{ m}^3$ . It should be noted that the net annual water balance for the catchment is estimated at  $20 \times 10^6 \text{ m}^3$ , although the maximum volume of a 50-year flood is about  $5 \times 10^6 \text{ m}^3$ .

- 3) Use of a stormwater detention basin network distributed over the catchment. The principal function of the system would be to reduce the peaks of the flood hydrographs. At the same time, important volumes of water may be retained locally, for agricultural purposes. Sizing and siting of the detention basin system may be designed in order to sustain the T=30-, 50-, or 100-year floods.

Combining the above three structural solutions, the following alternatives are currently under investigation:

1. Downstream regulation of the stream (R) and construction of a large capacity reservoir (LR)
2. (R) + Construction of a small capacity reservoir (SR)
3. (R) + Detention Basin Network of T=30-yr floods (DB30)
4. (R) + Detention Basin Network of T=50-yr floods (DB50)
5. (R) + Detention Basin Network of T=100-yr floods (DB100)

Main objectives for ranking the above 5 alternatives are (a) costs and benefits, (b) risk of failure, (c) environmental impact, and (d) social effects.

#### 4.2 LOCAL SCALE FLOOD PROTECTION

Local authorities have expressed their desire for an urgent undertaking of the necessary flood protection measures for the city's Wastewater Treatment Plant. The issue was to determine the size of the flood levees around the sewage treatment facility required to save important civil and mechanical equipment from future extreme floods. Emphasis was placed on safety rather than cost, due to the importance of the plant and the relatively small volume of the levees.

For the design of the flood levees on the local scale, a two-dimensional mathematical model was used to propagate the flood hydrograph. Different hydrographs representing the historical flood (13 January 1994) and the T = 30-, 50-, 100-year return periods were simulated. The mathematical model consists of the following Saint-Venant and mass continuity equations :

$$\frac{\partial h}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = 0 \quad (5)$$

$$\frac{\partial q_x}{\partial t} + \frac{\partial}{\partial x} \left( \frac{q_x^2}{h} \right) + \frac{\partial}{\partial y} \left( \frac{q_x q_y}{h} \right) = -gh \left\{ \frac{\partial h}{\partial x} - (I_{fx} - I_{0x}) \right\} \quad (6)$$

$$\frac{\partial q_y}{\partial t} + \frac{\partial}{\partial x} \left( \frac{q_x q_y}{h} \right) + \frac{\partial}{\partial y} \left( \frac{q_y^2}{h} \right) = -gh \left\{ \frac{\partial h}{\partial y} - (I_{fy} - I_{0y}) \right\} \quad (7)$$

where  $h$  = the flood stage in m;  $q_x, q_y$  = the flowrates per unit width in  $m^3/s/m$ ;  $I_{0x}, I_{0y}$  = the bed slopes; and  $I_{fx}, I_{fy}$  = the friction slopes.

Manning's formula has been used to compute  $I_{fx}$  and  $I_{fy}$  as functions of  $q_x, q_y$  and  $h$ . Numerical integration of the above equations has been performed over a two-dimensional grid using finite differences. A 100 m grid size was selected. The model was validated by comparing the numerical results with data available from the historical flood of the 13th of January 1994. On that day, the maximum water levels at different locations inside the wastewater treatment plant were recorded.

Results of the numerical simulation indicating the contour lines of the water stage during the 1994 flood are shown in Fig.6. For the same flood, water stage hydrographs computed at characteristic locations surrounding the water treatment plant are shown in Fig.7. After defining the size of the flood levees around the wastewater plant, results of the simulation of the  $T = 100$ -year flood are shown in Fig. 8. We may observe that the space where the wastewater treatment plant is located is well protected from this extreme flood. Further protection of the local area will be provided after implementation of the flood detention basin network in the upstream catchment area as described in Section 4.1.

## 5. SUGGESTED AREAS FOR RESEARCH

- Develop risk-based multi-objective planning criteria for floodplain management.
- Flash floods in semi-arid regions : analysis, simulation, and control.
- Rainfall runoff relations and flood propagation in karstic areas.
- Efficiency of environmentally sound, small size structures distributed over the catchment area versus traditional hydraulic works to protect from floods.
- Role of soil erosion, solid transport, and sedimentation in the design and operation of flood protection structures.

## 6. CONCLUSIONS

Special attention should be paid to floodplain management measures in areas with semi-arid climates. In these areas, flash floods in ephemeral streams are violent and unpredictable. Risk-based design methodologies for protective measures may result in trade-offs between risk, costs, and environmental and social impacts. Distinction is made between catchment scale planning and local scale protection from floods. In the former scale, a multi-criteria optimization approach under risk may help in selecting between different alternatives. In areas without too many constraints (high population, intensive agriculture), a stormwater detention basin system distributed over the entire catchment area seems to be the most appropriate alternative. On a local scale, reliability of the protective measures may be based on more traditional techniques

involving hydrologic and hydraulic modeling of two-dimensional steady flows. The above methodology has been applied to the Giofyros Basin, Crete Island, Greece.

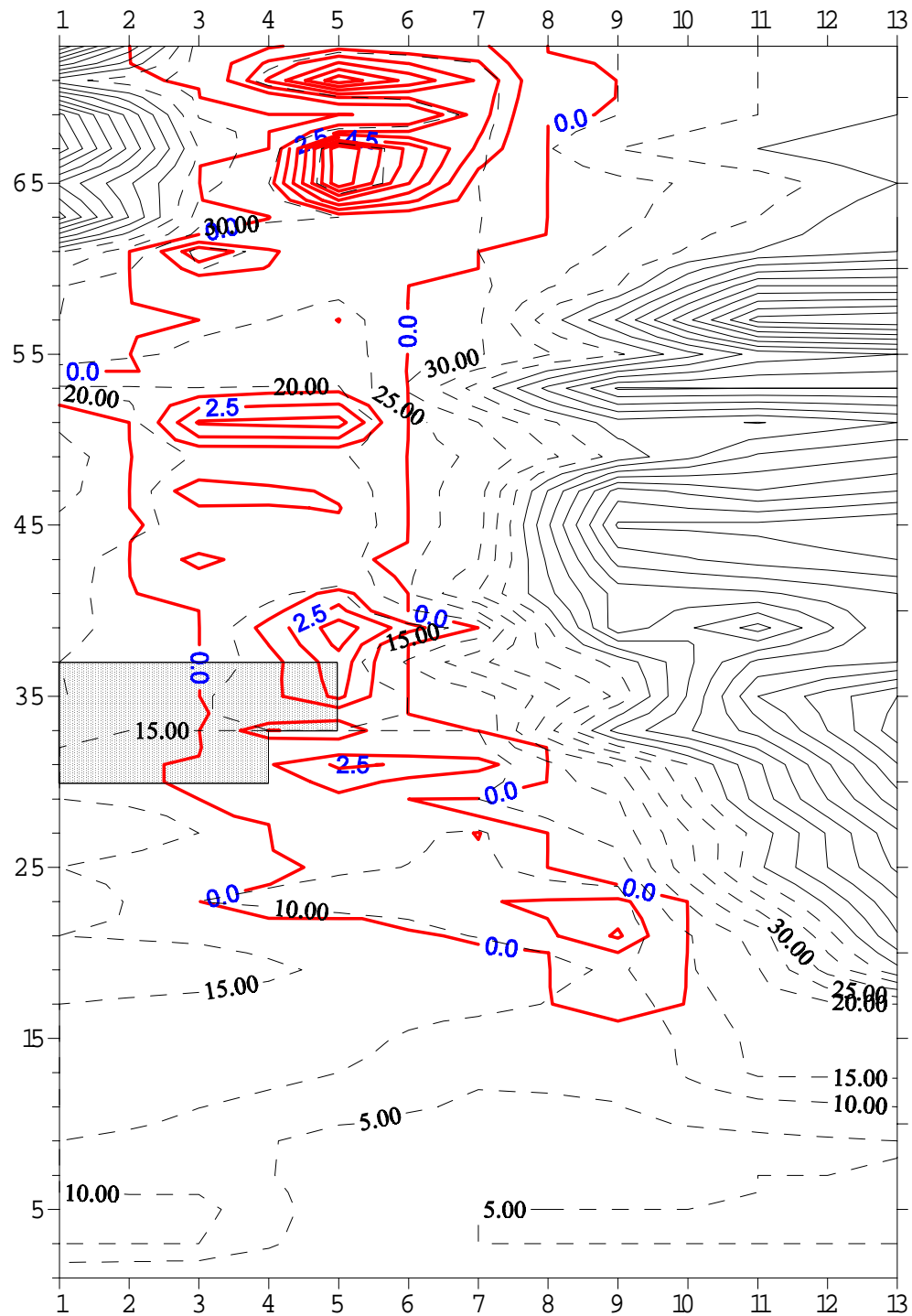


Figure 6. Contour lines of water stage for the 1994 flood (no flood levees around the wastewater treatment plant).

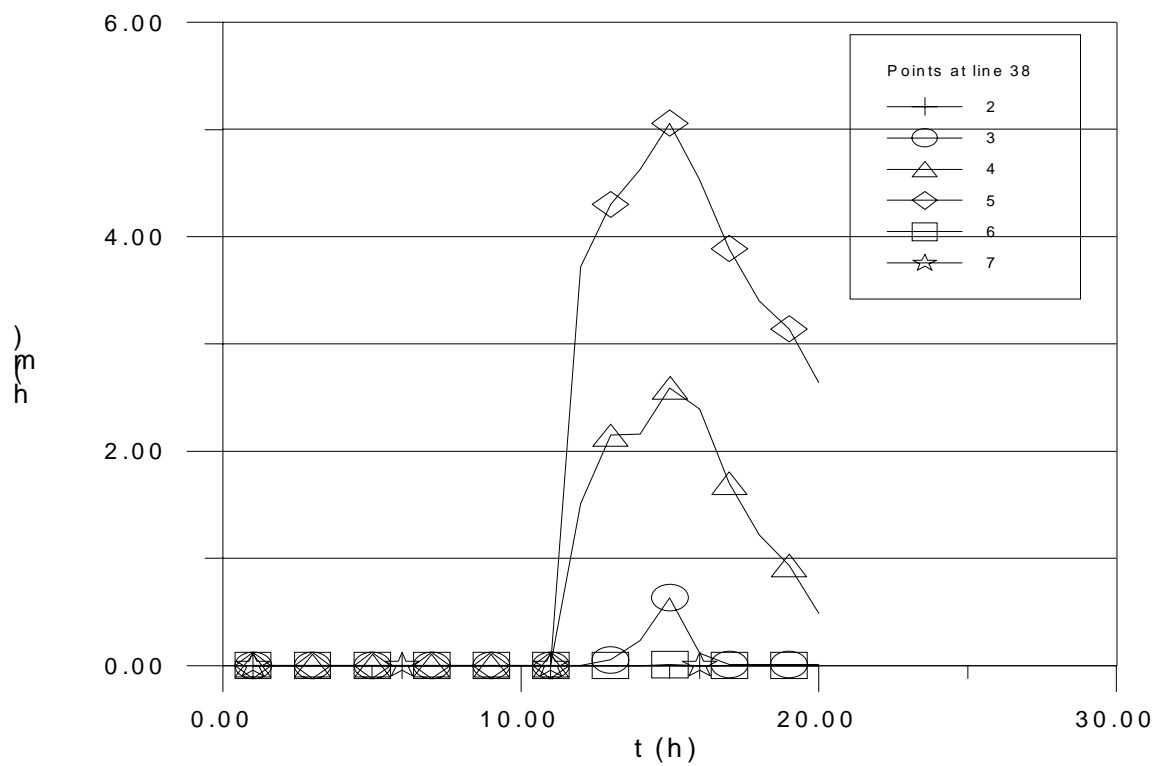
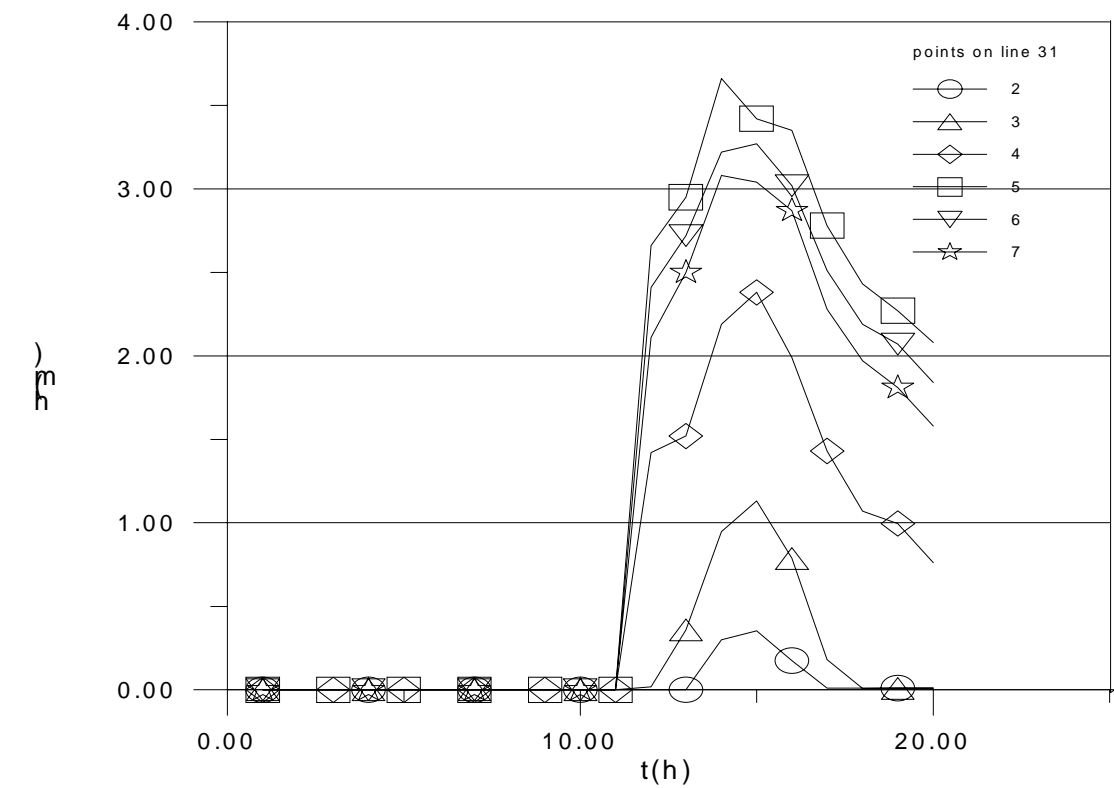


Figure 7. Water stage hydrographs  $h(t)$  at characteristic locations.

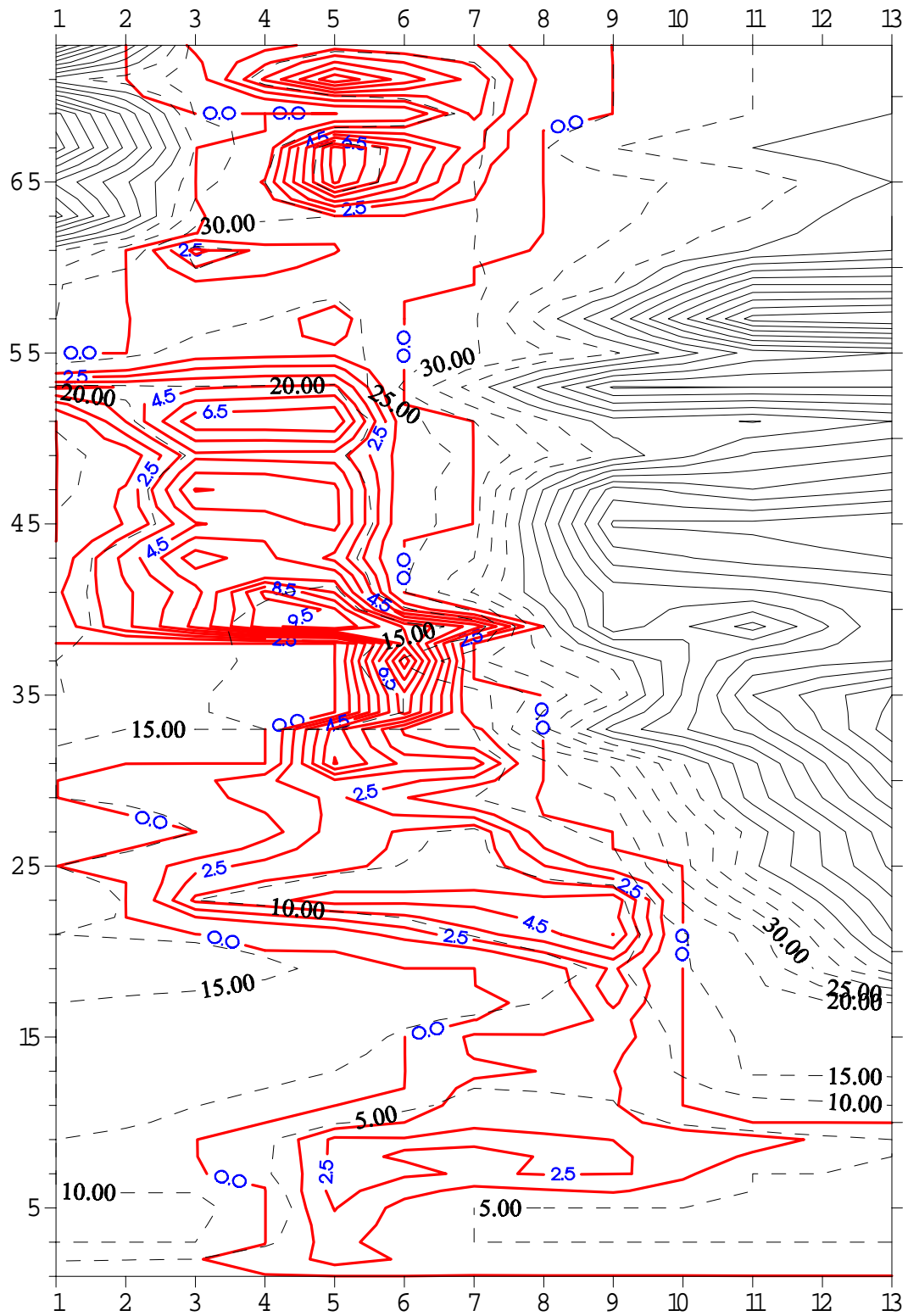


Figure 8. Contour lines of water stage for the T=100yr flood, after construction of the flood levees around the wastewater treatment plant.

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