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Natural Hazards and Earth System Sciences
Discussions

Interactive comment on "Flood risk assessment: concepts, modelling, applications" *by* G. Tsakiris

Anonymous Referee #3

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CONTENT OF THE PAPER The paper consists of four basic parts:

a. In the first part, the fundamental terms "hazard", "risk" and "vulnerability" are analyzed. In concrete terms, the theoretical mathematical definition of the hazard and the risk is given. Additionally, a systemic paradigm for the assessment of flood hazard and flood risk in flood-prone areas is presented. In the framework of this paradigm, the computational steps for the estimation of flood hazard and flood risk are described.

b. In the second part, the differences between the engineering studies for flood-prone areas, in the past, and the new EU flood directive 2007/60 are given. Additionally, the differences between the EU directive implementation and the paradigm presented by the author in the first part are stressed.

c. In the third part, a computational flood model developed for urban areas with mild

terrain is shortly described. The model was applied to the estuary of Sperchios River (Greece) with very satisfactory results.

d. In the fourth part, two critical points in the flood directive implementation are shortly discussed.

GENERAL COMMENTS 1. The practical merit of the paper consists in the presentation and discussion of engineering aspects for the confrontation of flood problems. Both methodologies for the confrontation of flood problems presented in the paper, namely the paradigm of the author and the EU directive, constitute practical solutios, applicable to flood-prone areas.

2. The EU directive takes into account the most unfavourable case, that no protection measures were planned, and the losses/damages are converted into monetary units. According to the paradigm presented by the author, in a first step, the maximum water depths are theoretically estimated in the potentially inundated area, that is totally unprotected from floods. In a second step, the inundation depths are estimated for the same area, protected now by some natural and man-made measures and structures.

3. In my opinion, both methodologies could be applied to a flood case, and the hydraulic engineer should decide which is the optimal solution concerning the mitigation of the flood consequences, on the one hand and the expenses for the construction of protection measures, on the other hand.

4. I believe that the quality of the paper can be improved through the "public" discussion.

SPECIFIC COMMENTS - QUESTIONS 1. Equations (1) and (2): What is D? What is fD(x)? (See also annotated manuscript!)

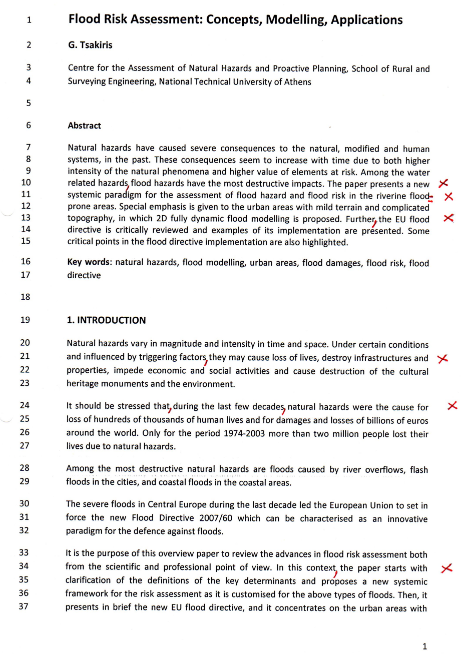
2. Page 9: Are water velocities illustrated in Figure 6? (See also annotated manuscript!)

3. Figures 3 and 4 need explanation in the text. (See also annotated manuscript!)

TECHNICAL CORRECTIONS 1. Figures 7 and 8: Variables should be written on the x-axis and y-axis. (See also annotated manuscript!)

2. See annotated manuscript!

Interactive comment on Nat. Hazards Earth Syst. Sci. Discuss., 2, 261, 2014.



Flood Risk Assessment: Concepts, Modelling, Applications

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Abstract

Natural hazards have caused severe consequences to the natural, modified and human systems, in the past. These consequences seem to increase with time due to both higher intensity of the natural phenomena and higher value of elements at risk. Among the water related hazards flood hazards have the most destructive impacts. The paper presents a new systemic paradigm for the assessment of flood hazard and flood risk in the riverine flood prone areas. Special emphasis is given to the urban areas with mild terrain and complicated topography, in which 2D fully dynamic flood modelling is proposed. Further the EU flood directive is critically reviewed and examples of its implementation are presented. Some critical points in the flood directive implementation are also highlighted.

Key words: natural hazards, flood modelling, urban areas, flood damages, flood risk, flood directive

1. INTRODUCTION

Natural hazards vary in magnitude and intensity in time and space. Under certain conditions and influenced by triggering factors they may cause loss of lives, destroy infrastructures and properties, impede economic and social activities and cause destruction of the cultural heritage monuments and the environment.

It should be stressed that during the last few decades natural hazards were the cause for loss of hundreds of thousands of human lives and for damages and losses of billions of euros around the world. Only for the period 1974-2003 more than two million people lost their lives due to natural hazards.

Among the most destructive natural hazards are floods caused by river overflows, flash floods in the cities, and coastal floods in the coastal areas.

The severe floods in Central Europe during the last decade led the European Union to set in force the new Flood Directive 2007/60 which can be characterised as an innovative paradigm for the defence against floods.

It is the purpose of this overview paper to review the advances in flood risk assessment both from the scientific and professional point of view. In this context the paper starts with clarification of the definitions of the key determinants and proposes a new systemic framework for the risk assessment as it is customised for the above types of floods. Then, it presents in brief the new EU flood directive, and it concentrates on the urban areas with

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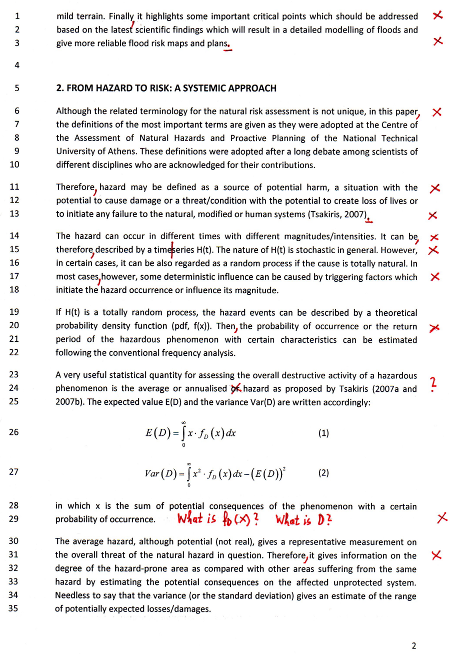
Fig. 1.



mild terrain. Finally it highlights some important critical points which should be addressed based on the latest scientific findings which will result in a detailed modelling of floods and give more reliable flood risk maps and plans.

2. FROM HAZARD TO RISK: A SYSTEMIC APPROACH

Although the related terminology for the natural risk assessment is not unique, in this paper the definitions of the most important terms are given as they were adopted at the Centre of the Assessment of Natural Hazards and Proactive Planning of the National Technical University of Athens. These definitions were adopted after a long debate among scientists of different disciplines who are acknowledged for their contributions.

Therefore hazard may be defined as a source of potential harm, a situation with the potential to cause damage or a threat/condition with the potential to create loss of lives or to initiate any failure to the natural, modified or human systems (Tsakiris, 2007)

The hazard can occur in different times with different magnitudes/intensities. It can be therefore described by a timeseries H(t). The nature of H(t) is stochastic in general. However, in certain cases, it can be also regarded as a random process if the cause is totally natural. In most cases however, some deterministic influence can be caused by triggering factors which initiate the hazard occurrence or influence its magnitude.

If H(t) is a totally random process, the hazard events can be described by a theoretical probability density function (pdf, f(x)). Then the probability of occurrence or the return period of the hazardous phenomenon with certain characteristics can be estimated following the conventional frequency analysis.

A very useful statistical quantity for assessing the overall destructive activity of a hazardous phenomenon is the average or annualised of hazard as proposed by Tsakiris (2007a and 2007b). The expected value E(D) and the variance Var(D) are written accordingly:

$$E(D) = \int_0^\infty x \cdot f_D(x)\,dx \quad (1)$$

$$Var(D) = \int_0^\infty x^2 \cdot f_D(x)\,dx - (E(D))^2 \quad (2)$$

in which x is the sum of potential consequences of the phenomenon with a certain probability of occurrence. What is $f_D(x)$? What is D?

The average hazard, although potential (not real), gives a representative measurement on the overall threat of the natural hazard in question. Therefore it gives information on the degree of the hazard-prone area as compared with other areas suffering from the same hazard by estimating the potential consequences on the affected unprotected system. Needless to say that the variance (or the standard deviation) gives an estimate of the range of potentially expected losses/damages.

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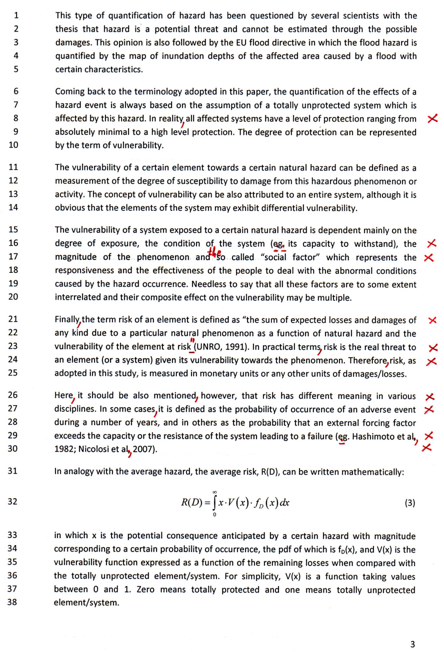
Fig. 2.



This type of quantification of hazard has been questioned by several scientists with the thesis that hazard is a potential threat and cannot be estimated through the possible damages. This opinion is also followed by the EU flood directive in which the flood hazard is quantified by the map of inundation depths of the affected area caused by a flood with certain characteristics.

Coming back to the terminology adopted in this paper, the quantification of the effects of a hazard event is always based on the assumption of a totally unprotected system which is affected by this hazard. In reality all affected systems have a level of protection ranging from absolutely minimal to a high level protection. The degree of protection can be represented by the term of vulnerability.

The vulnerability of a certain element towards a certain natural hazard can be defined as a measurement of the degree of susceptibility to damage from this hazardous phenomenon or activity. The concept of vulnerability can be also attributed to an entire system, although it is obvious that the elements of the system may exhibit differential vulnerability.

The vulnerability of a system exposed to a certain natural hazard is dependent mainly on the degree of exposure, the condition of the system (eg. its capacity to withstand), the magnitude of the phenomenon and the so called "social factor" which represents the responsiveness and the effectiveness of the people to deal with the abnormal conditions caused by the hazard occurrence. Needless to say that all these factors are to some extent interrelated and their composite effect on the vulnerability may be multiple.

Finally the term risk of an element is defined as "the sum of expected losses and damages of any kind due to a particular natural phenomenon as a function of natural hazard and the vulnerability of the element at risk" (UNRO, 1991). In practical terms risk is the real threat to an element (or a system) given its vulnerability towards the phenomenon. Therefore risk, as adopted in this study, is measured in monetary units or any other units of damages/losses.

Here it should be also mentioned however, that risk has different meaning in various disciplines. In some cases it is defined as the probability of occurrence of an adverse event during a number of years, and in others as the probability that an external forcing factor exceeds the capacity or the resistance of the system leading to a failure (eg. Hashimoto et al, 1982; Nicolosi et al, 2007).

In analogy with the average hazard, the average risk, R(D), can be written mathematically:

$$R(D) = \int_0^\infty x \cdot V(x) \cdot f_D(x)\,dx \quad (3)$$

in which x is the potential consequence anticipated by a certain hazard with magnitude corresponding to a certain probability of occurrence, the pdf of which is $f_D(x)$, and V(x) is the vulnerability function expressed as a function of the remaining losses when compared with the totally unprotected element/system. For simplicity, V(x) is a function taking values between 0 and 1. Zero means totally protected and one means totally unprotected element/system.

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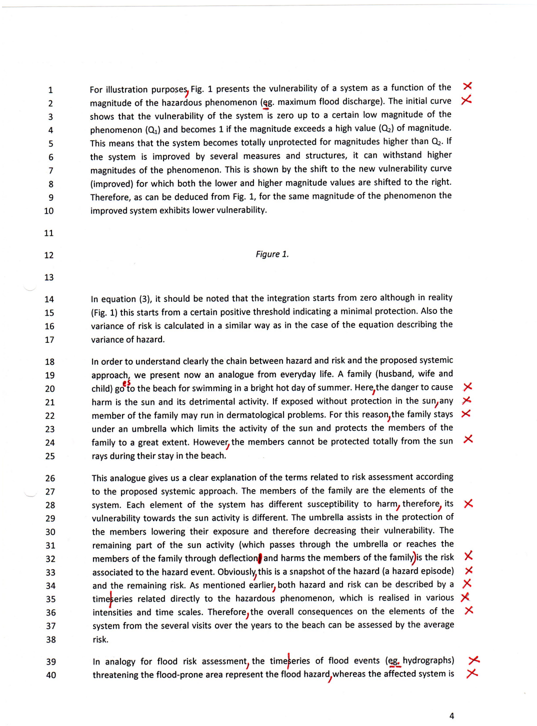
Fig. 3.



For illustration purposes Fig. 1 presents the vulnerability of a system as a function of the magnitude of the hazardous phenomenon (eg. maximum flood discharge). The initial curve shows that the vulnerability of the system is zero up to a certain low magnitude of the phenomenon (Q_1) and becomes 1 if the magnitude exceeds a high value (Q_2) of magnitude. This means that the system becomes totally unprotected for magnitudes higher than Q_2. If the system is improved by several measures and structures, it can withstand higher magnitudes of the phenomenon. This is shown by the shift to the new vulnerability curve (improved) for which both the lower and higher magnitude values are shifted to the right. Therefore, as can be deduced from Fig. 1, for the same magnitude of the phenomenon the improved system exhibits lower vulnerability.

Figure 1.

In equation (3), it should be noted that the integration starts from zero although in reality (Fig. 1) this starts from a certain positive threshold indicating a minimal protection. Also the variance of risk is calculated in a similar way as in the case of the equation describing the variance of hazard.

In order to understand clearly the chain between hazard and risk and the proposed systemic approach, we present now an analogue from everyday life. A family (husband, wife and child) go to the beach for swimming in a bright hot day of summer. Here the danger to cause harm is the sun and its detrimental activity. If exposed without protection in the sun any member of the family may run in dermatological problems. For this reason the family stays under an umbrella which limits the activity of the sun and protects the members of the family to a great extent. However the members cannot be protected totally from the sun rays during their stay in the beach.

This analogue gives us a clear explanation of the terms related to risk assessment according to the proposed systemic approach. The members of the family are the elements of the system. Each element of the system has different susceptibility to harm therefore its vulnerability towards the sun activity is different. The umbrella assists in the protection of the members lowering their exposure and therefore decreasing their vulnerability. The remaining part of the sun activity (which passes through the umbrella or reaches the members of the family through deflection and harms the members of the family is the risk associated to the hazard event. Obviously this is a snapshot of the hazard (a hazard episode) and the remaining risk. As mentioned earlier both hazard and risk can be described by a timeseries related directly to the hazardous phenomenon, which is realised in various intensities and time scales. Therefore the overall consequences on the elements of the system from the several visits over the years to the beach can be assessed by the average risk.

In analogy for flood risk assessment the timeseries of flood events (eg. hydrographs) threatening the flood-prone area represent the flood hazard whereas the affected system is

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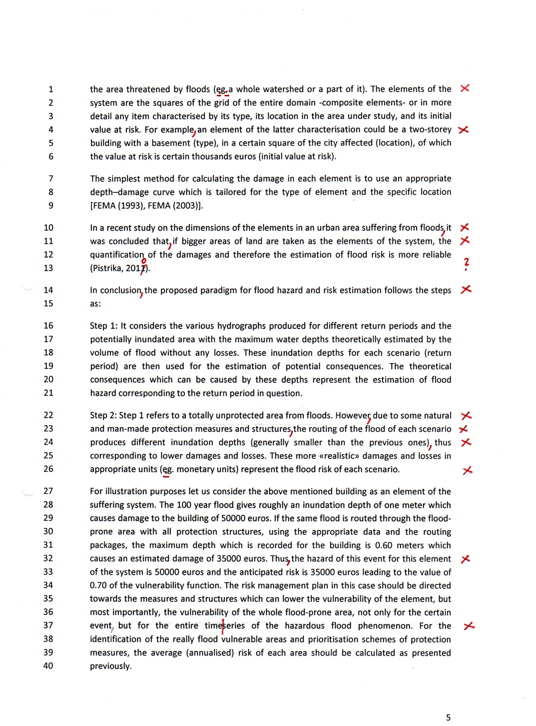
Fig. 4.



the area threatened by floods (eg.a whole watershed or a part of it). The elements of the system are the squares of the grid of the entire domain -composite elements- or in more detail any item characterised by its type, its location in the area under study, and its initial value at risk. For example an element of the latter characterisation could be a two-storey building with a basement (type), in a certain square of the city affected (location), of which the value at risk is certain thousands euros (initial value at risk).

The simplest method for calculating the damage in each element is to use an appropriate depth–damage curve which is tailored for the type of element and the specific location [FEMA (1993), FEMA (2003)].

In a recent study on the dimensions of the elements in an urban area suffering from floods it was concluded that if bigger areas of land are taken as the elements of the system, the quantification of the damages and therefore the estimation of flood risk is more reliable (Pistrika, 2011).

In conclusion the proposed paradigm for flood hazard and risk estimation follows the steps as:

Step 1: It considers the various hydrographs produced for different return periods and the potentially inundated area with the maximum water depths theoretically estimated by the volume of flood without any losses. These inundation depths for each scenario (return period) are then used for the estimation of potential consequences. The theoretical consequences which can be caused by these depths represent the estimation of flood hazard corresponding to the return period in question.

Step 2: Step 1 refers to a totally unprotected area from floods. However due to some natural and man-made protection measures and structures the routing of the flood of each scenario produces different inundation depths (generally smaller than the previous ones) thus corresponding to lower damages and losses. These more «realistic» damages and losses in appropriate units (eg. monetary units) represent the flood risk of each scenario.

For illustration purposes let us consider the above mentioned building as an element of the suffering system. The 100 year flood gives roughly an inundation depth of one meter which causes damage to the building of 50000 euros. If the same flood is routed through the flood-prone area with all protection structures, using the appropriate data and the routing packages, the maximum depth which is recorded for the building is 0.60 meters which causes an estimated damage of 35000 euros. Thus the hazard of this event for this element of the system is 50000 euros and the anticipated risk is 35000 euros leading to the value of 0.70 of the vulnerability function. The risk management plan in this case should be directed towards the measures and structures which can lower the vulnerability of the element, but most importantly, the vulnerability of the whole flood-prone area, not only for the certain event but for the entire timeseries of the hazardous flood phenomenon. For the identification of the really flood vulnerable areas and prioritisation schemes of protection measures, the average (annualised) risk of each area should be calculated as presented previously.

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Fig. 5.

The above simplistic examples demonstrate the proposed new paradigm for analysing floods as natural hazards, assess flood risk in the flood-prone areas and formulate plans for lowering their vulnerability. However the implementation of this paradigm faces some severe difficulties. One of them is how we can, even roughly, estimate the damages and losses without taking into account any natural or man-made existing protection. The answer to this is that the hazard damages can be roughly estimated since they do not play any important role in the final risk assessment. Even for the comparison of different flood-prone areas and prioritisation of areas for action against floods, the average risk is the key determinant and can be assessed independently.

Another important drawback of the method (and any method based on loss/damage estimation), is the estimation of loss of lives associated with the phenomenon and its transformation to units compatible to the losses and damages. This is still an open issue with not definite answer yet although it has been addressed from various angles (Pistrika, 2010).

3. THE EU FLOOD DIRECTIVE

In the past engineering studies conducted for the flood-prone areas and based on a certain probability scenario, reclamation measures and protection structures were usually proposed as the engineering view of protection. The aim was always to protect the flood-prone area from flooding provided that future floods would not exceed the probability level of design flood protection structures.

With the new EU flood directive 2007/60 (EC, 2007) there is a paradigm shift in the studies of floods. The studies are oriented towards the rationalisation of the procedure, flood risk mitigation measures. According to this innovative paradigm flood scenarios are formulated corresponding to high, medium and low probability and the associated risk (in term of losses/damages expressed in monetary units) is evaluated. Further improvements are proposed if the anticipated losses/damages cost is higher than the proposed protection measures. That is to say that from "structural defence" based on a certain probability of exceedence we move to balance risk and measures. As a statesman mentioned the new directive can be summarised by the slogan "we have to live with floods".

The new directive implementation is based on three consecutive steps: the preliminary delineation of flood-prone areas, the flood hazard maps, and the flood risk map resulting for each probability scenario. The flood hazard map shows the highest inundation water depths in the entire domain whereas the flood risk map shows the damages/losses at each cell of the computational field in monetary units. From the above two maps several improvement measures can be evaluated based on a clearly rational approach.

It should be stressed at this point that although the EU directive resembles to the paradigm presented in the previous paragraphs, there are two major differences between the two procedures: (a) The flood hazard in the EU directive is not evaluated as the damage/losses level of the totally unprotected system as it is the case for the proposed paradigm of this paper, but as the set of the highest inundation depths which can be recorded in all cells of

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Fig. 6.

the flood-prone area for the examined scenario. (b) The EU directive proposes only three levels for probability scenarios which should be tested. Therefore information is derived only on the three proposed probability scenarios. On the contrary the paradigm proposed in this paper is based on the calculation of average risk for which at least 5-6 probability levels/return periods scenarios should be tested (eg. Return periods 10, 25, 50, 100, 500, 1000 years). This is because the level of damages/losses should be described covering the whole range of magnitudes of the phenomenon.

From the first glance the implementation of the Flood Directive looks rather simple. However in reality it is a very difficult to apply mainly due to the large bulk of data required. Detailed topographic data, assets data, economic activities data, and many others should be available on GIS layers in order to be used both for the hazard and risk maps. The critical point is that in most of the cases reliable and complete data are very seldom available and their collection is not always an easy task. Furthermore this type of data is often of dynamic nature influenced by a number of factors. Therefore they are not totally reliable for supporting decisions on measures against floods since they are not stationary.

Another critical point is how we transform the hazard map to the risk map. The only practical way so far is through the depth-damage curves. That is the damage is expressed as a 1-1 function of inundation depth. However this type of curves should be derived specifically for the location in which they will be applied. They include a high possibility of error which somehow should be accounted for (Pistrika and Tsakiris, 2007).

Also damages /losses cannot be uniquely related to the highest simulated inundation depth at each cell from a certain flood episode. The damages/losses can be influenced by other hydraulic parameters such as water velocity for instance. Damages/losses can be direct or indirect, simultaneous or delayed, tangible or intangible. Therefore the type of approach based on the estimation of damages/losses as a unique function of the highest depth of water recorded in each cell is very simplistic and may result in misleading conclusions.

Apart from the above the decision for implementation the flood directive by the member states is useful and it will gradually assist in proposing rational systems for the protection of the flood-prone areas (early warning, non-structural measures, structural measures).

Following are proposals for the improvement of modelling of floods particularly in mild and urban terrains. In these areas the risk is generally higher and therefore these areas deserve more detailed and careful analysis.

As an example for the implementation of the Flood Directive the case of Rapentoza watershed above the Marathon gulf in Attica, Greece is presented. The watershed has an area of 35 km^2 and on the main stream a flood defence dam is built to protect from frequent floods, the mild terrain downstream valley, which is a densely populated area with intense agricultural activities and a big number of glasshouses. In this area there are also important monuments of cultural heritage which are also in danger.

In the Figs 2, 3 and 4, the land use map of the flood–prone area, the flood hazard map for the scenario of 100 years return period, and the flood risk map for the same scenario are

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Fig. 7.

presented, respectively. This application was made in the framework of the DISMA Project (Tsakiris et al, 2007). The tasks related to the production of flood hazard and risk maps are concisely presented in the flowchart of fig.5. As can be seen the flowchart comprises three sections of calculations, one referring to geo-information, the second to the formulation of scenarios and the hydrologic and hydraulic computations, and the third to the demographic data, the economic activities and information on the important environmental sites and cultural heritage monuments. To some extent the flowchart is self explanatory. However details of the application can be found in the final report of the DISMA project (Tsakiris et al, 2007).

Figure 2.

Figure 3.

Figure 4.

Figure 5.

4. FLOOD MODELLING IN URBAN AREAS WITH MILD TERRAIN

For the implementation of the EU directive on floods (2007/60) various scenarios should be formulated based on the corresponding return periods (eg. 10,100 and 1000 years). Each scenario results in a design hydrograph which is then routed through the hydrographic system of the area of interest. The inundated area is delineated and a timeseries of the most important determinants (eg. water depth, velocity, etc) of this unstready phenomenon are recorded in the total number of cells of the physical domain.

For the most accurate modelling of each flood scenario the most powerful tools should be used. Normally 1-D modelling is practiced in order to reach practical results with low computational cost. However in areas with mild terrain, this, rather simplified approach, can produce misleading results. Furthermore additional complications are inserted into the modelling process if there are obstacles in the computational field (e.g. buildings, bridges etc). Therefore in the areas of the mild terrain and particularly in the built-up areas a more comprehensive modelling approach should be adopted (eg. 2D and possibly 3D models)(Abderrezzak et al, 2008; Mignot et al, 2006; Ravagnani et al, 2009; Testa et al, 2007).

Fig. 8.

Several packages are already available for the 2D flood modelling. The most popular of them are MIKE 21, CCHE2D, TELEMAC-2D, ISIS-2d, SOBEK, TUFLOW, RiverFLO-2D, and Infoworks-2D.

It is interesting to note that the 3D models are still very expensive to run and the additional information they offer is not of great importance for the calculation of the impacts (Tsakiris and Bellos, 2013).

Therefore it seems that the 2D models are sufficient for this type of modelling. However it should be stressed that the modelling should be based on the fully dynamic approach and not on simplifications which are attractive but not appropriate. For instance kinematic wave models can perform satisfactorily in steep areas but fail to work accurately in mild terrains.

One of the most comprehensive models recently constructed at the Centre for the Assessment of Natural Hazards and Proactive Planning of the National Technical University of Athens is the FlOW-R2D. Details of the model can be found in other publications (Tsakiris and Bellos, 2013). Here only a brief description follows:

The model is based on the two-dimensional Shallow Water Equations (2D-SWE) with discretization based on the two-step McCormack numerical scheme (McCormack, 1969). As known the McCormack scheme is explicit and therefore stable under the Courant-Friedricks-Lewy condition (Szymkiewicz, 2010; Benedini and Tsakiris, 2013). The simulation of moving boundaries between wet and dry bed is achieved through a threshold of water depth which distinguishes wet and dry cells. Further the model has shock capturing capabilities and therefore can describe discontinuities of the flow such as hydraulic jumps. Finally, a diffusion factor is incorporated in the model to diffuse oscillations which may be encountered during the numerical simulation. Quite recently, the model incorporated facilities to account for the buildings or other structures by using the reflection boundary method proposed (Bellos and Tsakiris, 2013).

After extensive testing the model was applied to real world applications with very satisfactory results. Figure 6 shows the results of the model application in the estuary of Sperchios river in Greece. Both the maps of water depth and water velocities are presented in Fig. 6. In other applications of the model the representation of the built-up areas was given the first priority. Figures 7 and 8 show the inundation maps resulted from the routing of a hydrograph through an urban area with buildings in aligned arrangement (Bellos and Tsakiris, 2013).

Figure 6.

Figure 7.

Figure 8.

Fig. 9.

5. CRITICAL POINTS IN THE FLOOD DIRECTIVE IMPLEMENTATION

Several critical technical points in the implementation of the flood directive mainly towards the data requirements have been highlighted in a paper by Tsakiris et al (2009).

From the points raised in the above paper, among others, the bi variate flood scenario should be reminded. As known the key flood scenario variables are the flow and the volume. Therefore by considering only the flow characteristics in the uni variate analysis we neglect the volume which may be the critical determinant for causing flood (Tsakiris and Spiliotis, 2013).

In the present paper two additional concerns are pin pointed although they are based on theoretical grounds and cannot be easily addressed through the implementation of the flood directive in practice. These two points are the "nonstationarity in flood engineering design" and the "decision on plans under uncertainty". Both topics are vast and cannot be comprehensively presented in this paper. However some fundamental discussion on these subjects is provided below. For a more thorough analysis of these subjects the reader should consult specialised books (eg. AghaKouchak et al 2013).

For practical reasons we adopt the following definition of "wide-sense stationarity". This type of stationarity is satisfied when neither the mean nor the autocorrelation change with time. Therefore there is no interest on trends, seasonalities or cycles. For the engineering design if stationarity is satisfied, the return period for hydrological determinants is calculated.

Obviously detecting and attributing trends in hydrological data is a complicated process and often it is misled by the intrinsic climatic variability. There are several scientific methods to analyse nonstationarity such as the testing for break points, spectral analysis, wavelet analysis, trend detection, estimation of time varying parameters etc. However in most of the cases reliable data of long timeseries are not available and therefore nonstationarity analysis may produce ambiguous results.

What remains from this very concise synopsis of the problem of nonstationarity is that in Flood Risk Management Plans, man-induced and climatic changes should be carefully studied, adequately understood and considered in a broad sense.

Directly related to the problem of nonstationarity (due to man-induced and climatic changes) is the problem of uncertainty which is embedded in all data and decisions concerning flood risk management. Methods for incorporating uncertainty into the decisions are many. Here an attempt is made to present some of the most popular options to incorporate the uncertainty into the design of structural and nonstructural measures for flood defence.

These methods are epigrammatically presented as follows:

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Fig. 10.

- sensitivity analysis
  To evaluate the sensitivity of existing or planned infrastructure to expected variability. This can be phrased as «what level of change can happen to have a significant effect».
- adaptive approach
  To design with certain flexibility so that upgrades can be realised in the future.
- scenario approach
  To run precalibrated models with projected future conditions (which for the climate change can be produced by downscaling of bias-corrected GCMs).
- spatial gradient
  That is to simulate the future conditions in an area which may resemble to present conditions of other areas.
- revision of IDF curves
  To revise the Intensity-Duration-Frequency curves of an area based on the analysis of long reliable timeseries of rainfall data.
- empirical approaches
  To design with higher return periods from those adopted so far, based on empirical observations.

6. CONCLUDING REMARKS

In this overview paper a new paradigm for the defence against floods, formulated on the basis of flood risk management, is presented. The new paradigm is based on the systemic approach and the rational sequence «hazard-vulnerability-risk». Selection and prioritisation of reclamation measures are based on the average (annualised) flood risk which is calculated from a wide range of flood probability scenarios.

Further, the new European flood directive was presented in brief and it was concluded that in general it is in line with the proposed paradigm. However in the flood directive the reclamation measures are selected based on a limited range of flood probability scenarios. Sample applications of the directive were presented for illustration purposes. Also some critical points of its implementation were highlighted.

Emphasis was given to urban flood modelling and in particular to flood modelling in the flood-prone built-up areas with mild terrain. Two-dimensional fully dynamic models were proposed for the realistic simulation of flood evolvement in these areas.

Finally the nonstationarity of flood events and the uncertainty of calculation of flood damages/losses were also discussed.

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Fig. 11.

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Fig. 12.

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Fig. 13.

Figure captions

Figure 1. The vulnerability of a system (initial and improved) as a function of the magnitude of the phenomenon.

Figure 2. The land use map of Rapentoza watershed.

Figure 3. The flood hazard map of Rapentoza watershed for the scenario of T=100 years.

Figure 4. The food risk map for the Rapentoza watershed for the scenario T=100 years.

Figure 5. The flowchart of the procedure followed for the derivation of flood hazard and flood risk maps.

Figure 6. A snapshot from the application of FLOW-R2D in the estuary of Sperchios river. r ✕

Figure 7. A snapshot of the distribution of inundation depths in an experiment with aligned buildings as produced by FLOW-RD2.

Figure 8. A snapshot of the distribution of velocities in an experiment with aligned buildings as produced by FLOW-RD2.

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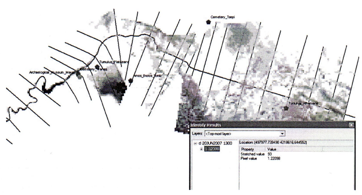
Fig. 14.

Figure 3



The figure needs explanation!

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Fig. 15.