# Modelling for decision making in water risk scenarios

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*All these achievements could not have been possible without all of the persons who walked with me for these three years. These persons are the ones who have been with me since I can remember and the ones I met and with whom I share different stages of my life, specially in these last three years. These persons have always contribute to carry on my work, my life and my personality, by means of building up entire parts of me or adding just a little something, giving me a hand, a world, a smile when they were needed or when they were not and by means of making all of that to be something special. Thank you.*

# Introduction

The Oxford Dictionary defines a model *"A simplified mathematical description of a system or process, used to assist calculations and predictions"*. Just from the mere definition, the importance of a model to manage and analyze a process is underlined. The scenario modelling has a vital importance in all of the branches of the decision analysis. In fact, the cognitive process that leads to reach a decision, that is the basis of the decision making, needs a deep analysis and knowledge of the "real world". This knowledge is achieved by means of studying the physics of the process and the empirical observations. For that, the decision makers needs to analyze different hypothesis and scenarios, that are not often available in the empirical observation. Furthermore to test and apply decision models, different scenario-developers are needed, to give an input for the model itself. For that, starting from the physical knowledge, the modelling discipline has been developed. When different scenarios are needed, the main aim of the modeller is to find a solution to represent the real world in a consistent way.The representation must also be a simple, non strongly data hungry and easily reproducible. In this thesis, different modelling techniques have been analyzed.

In the first part a weather model has been developed and applied, involving knowledge in statistics, probability theory, hydrology, and empirical observations. This part has been developed in order to give back a weather generator to test a rainfall-runoff model. Starting with the literature analysis, a new concept of weather generator has been developed, in order to combine the Markov Chain approach with the Circulation Patterns data.

The second part analyzes the development of an hydraulic flood spreading model to give back inundation scenarios for the risk analysis in one very "hydrologically" interesting area, the Thames estuary. This part analyzes the process to assess this kind of model, starting from the choice of the scenarios to be represented, the boundary conditions, the field work and the assessment of the model itself. Furthermore, and interesting historical analysis has been developed in order to reconstruct the 1953 flood scenario. In this part, the modelling technique has been explored and presented, and the main

original contribution concerns the application to an interesting pilot site for the present scenario and to an historical case study.
In the third part, has been analyzed a field that is not often developed from the modellers, that is, the flood evacuation modelling. The analysis of the problem from different point of views and the review of some of the existing models have been firstly developed. Furthermore, the testing and the application of a model in a deeply densely populated area has been performed. In this thesis, an important contribution in the testing and the updating of this model has been reached, while for the first time, an evacuation model has been performed in the London estuary pilot sites.
In the forth part, different decision techniques has been developed and tested to analyze the results of the modelling. This techniques are developed beneath the work of this thesis, and they are also tested thanks to the availability of the evacuation model dataset. Finally, a small evacuation model has been developed and applied to the case study, in order to show an alternative way to apply the optimization techniques for the evacuation problem.

# Part I

# Modelling for rain scenarios

# Introduction

This part has been developed in order to support a project concerning a rainfall-runoff model for the risk analysis. This model needs a scenario-developer that was able to give back the daily rain amount for different years and for different periods of the year. Furthermore, the interest in the application of the Circulation Pattern data in the daily micro-scale model has brought to an original development of a weather generator.In this part, different approaches to model the daily precipitation has been studied. In order to simulate the spell, that is the binary sequence of dry-wet days, the Markov analysis has been chosen. The aim of this study was to find a way to improve the way to calculate the conditional probabilities. For that, the needing was to add more information to the model. An interesting issue in the daily precipitation modeling is the link between the microscale precipitation data coming from the single station observation and the macroscale measured Circulation Pattern. After exploring three different approaches in the spell simulation, the precipitation depths have been modelled by means of choosing the best statistical distribution. Finally the three developed models have been tested and compared with the two classical first and second order approaches.

# Chapter 1

# Generating rain scenarios

The first issue in the modeling for weather risk scenarios, is concerning the reproduction of the precipitation behavior. The precipitation scenarios reconstruction is different from the study of the extreme events, that take in account the probability of some event form the risk point of view, considering the return time and often reproducing the storm development. On the contrary, this study is focused on reconstructing the day-by-day scenarios, in dry and wet condition, in order to give an output to test the rainfall-runoff models, that must be validated for every precipitation scenarios. This problem is interestingly faced with the class of models known as *Weather Generators*. The Weather Generators have been deeply studied in the past 30 years (cfr [34], [16], [46], [47], [19], [29], [27]). Therefore, an interesting issue in the daily precipitation modeling is to link the microscale precipitation data coming from the single station observation and the macroscale measured Circulation Pattern see 1.3. In this chapter, three new concepts to use only the Circulation Patterns, without needing a further Circulation Model, in order to add this information to Markov-based weather generators are presented. Firstly, the influence of the Circulation Patterns to the local conditional probabilities is investigated. Furthermore, the Circulation Pattern itself is clustered by means of the "Wetness Index" in "dry" and "rain" Circulation Patterns. Then, the three models, based on three different ideas of introducing the Circulation Patterns information in the Markov process are presented and tested. The testing methods are based on the investigation in finding the best response in conditioning the local conditional probabilities introducing the Circulation Pattern information, without using any external Circulation Model, that needs different atmospheric circulation input and the use of a whole external model. The models have been applied in the Weißer Elster basin, Saxony, Germany. The main reason for choosing this pilot site is related to the fact that this work has been developed on behalf of the Helmholtz-Zentrum für Umweltforschung UFZ in Leipzig, Saxony. The Weißer Elster basin is studied as a part of a rainfall-runoff modelling studies, and the present work is a part of this research project. The results show very good results for the model using Circulation Pattern macroscale information averaged with the basin conditional probabilities, by means of using this information to correct the local conditional probabilities. In the past, many approaches to the problem of simulating the daily precipitation time series have been developed, by means of using different techniques. Even if different approaches have been studied for the daily precipitation modeling, as stochastic-based multidimensional models [4], Neural Network-based models [8], Pattern Recognition methodology [23], one of the most consolidated methodology is the one involving the Markov chain process [34], [16], [46], [47], [19], [29], [27]. An interesting issue in the daily precipitation modeling is the link between the microscale precipitation data coming from the single station observation and the macroscale measured Circulation Pattern. This idea has been interestingly developed by means of correcting the Markov model response with the General Circulation Model outputs, which are daily precipitation time series [47], [44], [45]. This approach has the drawback of implying the developing of two different models, the Markov model that needs to estimate all of the conditional probabilities and the General Circulation Model, which needs different atmospheric circulation input and could be quite complicated. In this work a different methodology for using the Circulation Pattern (CP) data in the microscale daily precipitation modeling has been presented. The first idea in approaching the work is to study how the macroscale CP daily measurement are connected with the actual microscale station-level precipitation measurement, from the conditional probabilities point of view. In other words, how the Circulation Pattern influence the local conditional probabilities. Once this connection is established, we are able to add a conditioning in the Markov chain in order to take into account both the local conditioned probability and the macroscale information.

## 1.1 Micro - Meso - Macro spatial scales analysis

The problem of generating rain scenarios could be faced in different spatial scaling point of view. Usually the principal scale levels are: the single station level, in which the information is punctual and depend on the station measurement; the basin level, in which the low-scale properties are averaged and extrapolated for all the basin; the regional level, that is similar to the basin level but using a greater amount of stations. In this level, a bias analisyis is performed to take in account the fact that the stations does not belong to the same basin; the global/continental/subcontinental level, in which the climatic features are studied in a continental scale. This is possible taking in account the circulation characteristics in global, continental or subcontinental scales. The data used for the scenario generation depends on the chosen scale. At the station and basin level the precipitation measurements are used. At the regional level, the station measurements are complemented with regional features. At the global level, the circulation pattern data are generally mostly used.

## 1.2 The Weather Generators concepts

As remarked before, many approaches to the problem of simulating the daily precipitation time series have been developed, by means of using different techniques. In this study, an intense bibliographic review has been developed, in order to understand th techniques that have already been explored, choosing the one that seems more feasible to our case, and analyzing the methodology that could be applied to improve that. The most consolidated and used methodology is the one involving the Markov chain process [34], [16], [46], [47], [19], [29], [27]. Basically, in this technique, the Markov conditional probabilities are estimated by means of different methodology, in order to have the spell distribution (that is the binary string 0-1 that represents the wet-dry series). Then a statistic distribution is used to assign to each wet day a precipitation level. Starting from this approach, the aim of this work has been to improve this technique by means of adding the Circulation Pattern information. In fact, the concept of the weather generator model that is developed here, is based on the idea that the information of the station, basin and continental levels could be used together to create a precipitation model whose performance are better than using only one kind of information at time. Despite this concept has been already used in literature [4], an important improvement has been presented in this thesis. In fact in the usual approach, the CP are used passing through a model that takes in input the Circulation pattern and gives back the precipitation series. After this series have been obtained, another model is built to correct the basin-scale calculated precipitation series with those calculated with the CP model. The new improvement obtained in this work has been to avoid to build an extra model for translate the Circulation Pattern values in precipitation series. First of all, the use of Markov Model in reconstructing the spell series has been established, because of the proven strength of this methodology. Then, the way to add the different scale informations to the Markov process, without recurring to any extra model has been investigated. The main idea has been to study how the CP are related with the local (single station scale) conditional probabilities of rain. This relation has been investigated by using the cluster analysis and by means of the "'Wetness Index"' that is explained below. Then, a different way to use the CP information in the Markov process has been investigated. Once the spell sequence has been obtained, the Gamma distribution has been used to calculate the precipitation depths. This is the structure of the proposed models. These models have been then tested and compared with the classic first order and second order Markov based weather generators.

## 1.3 Adding information to the models: Circulation Patterns

The Grosswetterlagen (European atmospheric circulation patterns) system according to Hess and Brezowsky [14] is a well-known subjective classification system in synoptic climatology, which describes the circulation patterns over Europe and the eastern part of the North Atlantic Ocean. The classification system recognizes three groups of circulations divided into ten major types, 29 sub-types and one additional sub-type for the undetermined cases. The three circulation groups are defined as zonal, half-meridional (mixed) and meridional, respectively. A circulation pattern generally persists for several days while the entailed weather features remain constant. The zonal circulations, particularly the sub-type "West cyclonic" (Wz), are often associated with rain. The sub-types Southwest cyclonic (SWz) and Northwest cyclonic (NWz) within the half-meridional group refer to weather conditions similar to those associated with the sub-type Wz. Although additional information (500 hPa heights) was used in the classification since the late 1940s, no systematic homogeneity in the Grosswetterlagen records was found for the period 1930-1960, except that the major type SW showed a possible change point in the late 1940s [5]. The main hypothesis in this work is concerning the assumption that an empirical relationship can be established between the macroscale CP and the microscale precipitation. This relationship has been investigated and proven by different authors [32], [4]. Starting from this assumption, we focus on the study of this relationship regarding the examined basin. For that, the Circulation Pattern observation (that are qualitative information) has been analyzed with the pattern analysis point of view, trying to find the main feature that could give back a connection with the local precipitation phenomena. In this sense, two analyses have been developed. First of all, a cluster analysis has been performed in order to find if a "natural" clustering of the CP in the precipitation perspective exists. Two feature selection approaches have been used here. In the first case, the chosen feature has been the conjunct probability of having a given Circulation Pattern and a wet or dry day (that is translated classifying as wet the days in which the precipitation is greater than $0.125mm$):

$$P_j\{X_i = 0|CP_i = j\} \quad i = 1...n_{days} \tag{1.1}$$

$$j = 1...n_{cp} \tag{1.2}$$

Where $n_{days}$ is the number of days in the time series and $1...n_{cp}$ is the number of Circulation patterns. $X_i$ is the precipitation occurrence:

$$X_i = \begin{cases} 1 & \Rightarrow h_i \geq 0.125mm \\ 0 & otherwise \end{cases}$$

[34], [16],[46]. We refer as this clustering as "Probability Clustering". In the K-Means clustering clustering, the chosen features were the precipitation height and the precipitation occurrence. For both of the feature sets, the K-Means clustering algorithm has been chosen. As shown in the table 1.1 the results of the two clustering models are quite different, and the Probability Clustering has been considered more reliable because it takes in account the conjunct probability of rain/dry day under a given Circulation Pattern. Besides of that, we cannot consider really satisfactory both classifications because of the strong closeness of the cluster points in both of the feature spaces. This is the first interesting result in the analysis of the relation between the CP and the precipitation phenomenon: due to the macro-microscale gap of this measurements, the assumption of directly finding a relation between the two phenomena could be considered too strong. For that, the mesoscale (basin level) data level has to be taken into account to mediate the procedure. With this assumption, a further classification has been implemented, basing this clustering procedure to the Wetness index. The Wetness index formulation [36] is:

$$W_j = \frac{\frac{1}{P}\sum_{i \in n_{days}} p^i_{\Omega_j}}{\frac{1}{n_{days}}\sum_{i \in_{days}} \mu^i_j}$$

Where:

$$j = 1, ...n_{cp}$$

$$\mu^i_j = \begin{cases} 1 \Rightarrow CP(i) = j \\ 0 \Rightarrow otherwise \end{cases}$$

$$p^i_{\Omega_j} = \begin{cases} \overline{p}^d_{\Omega_j} \Rightarrow CP(i) = j \\ 0 \rightarrow otherwise \end{cases}$$

$$P = \sum_{d \in n_{days}} p^d_{\Omega}$$

Were $\Omega$ is the Circulation Pattern index, and $p^d_{\Omega_j}$ is the precipitation on of the $i_{th}$ day if in this day there is a Circulation Pattern $\Omega_j$.
The Wetness index has been calculated for all the 52 stations of the basin, for the period $1960-1980/1981-2000$. Then, the 50 quantile of the Wetness index has been taken into account in order to divide the Circulation Patterns in Rain Circulation Patterns and Dry Circulation Pattern. This classification has been used to link the Circulation Pattern and the local precipitation. The results of the three clustering methodology are shown in the table 1.1.

| Id | Description | Label | Kmeans Clustering | Probability Clustering | Wetness index Clustering |
|---|---|---|---|---|---|
| 1 | West, anticyclonic | Wa | Dry | Dry | Dry |
| 2 | West, cyclonic | Wz | Dry | Rain | Rain |
| 3 | Southern, West | WS | Dry | Dry | Rain |
| 4 | Angleformed West | WW | Dry | Dry | Rain |
| 5 | SW, anticyclonic | SWa | Dry | Dry | Dry |
| 6 | SW, cyclonic | SWz | Dry | Dry | Rain |
| 7 | NW, anticyclonic | NWa | Dry | Dry | Dry |
| 8 | NW, cyclonic | NWz | Dry | Rain | Rain |
| 9 | Centr European high | HM | Dry | Dry | Dry |
| 10 | Centr European ridge | BM | Dry | Dry | Dry |
| 11 | Central European low | TM | Dry | Rain | Rain |
| 12 | North, anticyclonic | Na | Dry | Rain | Rain |
| 13 | North, cyclonic | Nz | Rain | Rain | Rain |
| 14 | North, Iceland high, anticyclonic | HNa | Rain | Dry | Dry |
| 15 | North, Iceland high, cyclonic | HNz | Rain | Dry | Rain |
| 16 | British Isles high | HB | Rain | Dry | Dry |
| 17 | Centr European trough | TRM | Rain | Dry | Rain |
| 18 | NE, anticyclonic | NEa | Rain | Rain | Dry |
| 19 | NE, cyclonic | NEz | Rain | Rain | Rain |
| 20 | F high, anticyclonic | HFa | Rain | Dry | Dry |
| 21 | F high, cyclonic | HFz | Rain | Rain | Rain |
| 22 | Norwegian SF high, anticyclonic | HNFa | Rain | Dry | Dry |
| 23 | Norwegian SF high, cyclonic | HNFz | Rain | Rain | Rain |
| 24 | SE, anticyclonic | SEa | Rain | Dry | Dry |
| 25 | SE, cyclonic | SEz | Rain | Dry | Dry |
| 26 | South, anticyclonic | Sa | Rain | Dry | Dry |
| 27 | South, cyclonic | Sz | Rain | Dry | Rain |
| 28 | British Isles low | TB | Rain | Dry | Rain |
| 29 | West Europe trough | TRW | Dry | Dry | Rain |
| 30 | Classific not possible | U | Dry | Dry | Rain |

Figure 1.1: Circulation Patterns classification by Hess and Brezowsky [14] and the results of the three clustering methods developed in this thesis.

# Chapter 2

# Markov chain analysis

Once the link between the Circulation Pattern and the local precipitation has been established, the former step is to build an algorithm that put together the macroscale and the microscale information, using the Markov chain. From this point of view, the idea has been of conditioning the Markov process acting on the conditional probabilities, in order to take in account the extra information given back from the Circulation Pattern Measurements. From this point of view, some examples in literature are available, which involve in this sense the output of the General Circulation Models (GCM), that are specific models that take the CP as input and give back precipitation and temperature data. This approach implies the use of one of these Models, that are not really straightforward to implement and in some cases require a quite relevant amount of data. On the contrary, in this work, three original approaches that allows us to use directly the CP data within the Markov chain models are presented.

## 2.1 First model: Circulation Pattern conditioned 1st order Markov Model

The first method could be described as a second order Markov chain, with the second order term referred to a present status that is lead also by a different factor (actual Circulation Patten occurrence instead of just the rain-dry past occurrence). In other worlds, it could be also described as a first order chain conditioned with the actual Circulation Patten occurrence coupled with the rain occurrence probability. In this case, the transition probabilities are defined as:

$$\begin{aligned} p_{r01} &= P\{X_i = 0|X_{i-1} = 1, cp_i = r\} \\ p_{d01} &= P\{X_i = 0|X_{i-1} = 1, cp_i = d\} \\ p_{r11} &= P\{X_i = 1|X_{i-1} = 1, cp_i = r\} \\ p_{d11} &= P\{X_i = 1|X_{i-1} = 1, cp_i = d\} \end{aligned}$$

Where, for example, $p_{r01}$ is the probability of a dry day (0) at the day $i - th$ if it has been a rain day (1) at the day $i - 1$ and if there is a rain Circulation Pattern at the day $i - th$. It is interesting to observe how the fact of adding the Circulation Pattern in the Markov process acts on the Conditional probabilities. For example, regarding the conditional probability of having two consequent wet days and a rain circulation pattern, $p_{r11}$, it could be noticed that this probability follows the probability of having two wet days, $p_{11}$, but it is shifted (increased) with a $\Delta p$ of 0.015, as shown in figure 2.1. By studying these relations it is possible to understand which is the influence level of the CP regarding the local conditional probabilities, and that with this model this influence is too overestimated, excessively forcing the process.

## 2.2 Second model: Circulation Pattern conditioned 2nd order Markov Model

The second model has been performed in order to increase the performance in the Rain Occurrence estimation by means of taking into account the Circulation Pattern of two days before the one to estimate. This model can be described as a second order Markov chain conditioned with the Circulation Pattern. The developed methodology, takes in account eight conditional probabilities:

$$\begin{aligned} p_{d001} &= P\{X_i = 0|X_{i-2} = 0, X_{i-1} = 1, cp_i = d\} \\ p_{r001} &= P\{X_i = 0|X_{i-2} = 0, X_{i-1} = 1, cp_i = r\} \\ p_{d011} &= P\{X_i = 0|X_{i-2} = 1, X_{i-1} = 1, cp_i = d\} \\ p_{r011} &= P\{X_i = 0|X_{i-2} = 1, X_{i-1} = 1, cp_i = r\} \end{aligned}$$

$$\begin{aligned} p_{d101} &= P\{X_i = 1|X_{i-2} = 0, X_{i-1} = 1, cp_i = d\} \\ p_{r101} &= P\{X_i = 1|X_{i-2} = 0, X_{i-1} = 1, cp_i = r\} \\ p_{d111} &= P\{X_i = 1|X_{i-2} = 1, X_{i-1} = 1, cp_i = d\} \\ p_{r111} &= P\{X_i = 1|X_{i-2} = 1, X_{i-1} = 1, cp_i = r\} \end{aligned}$$

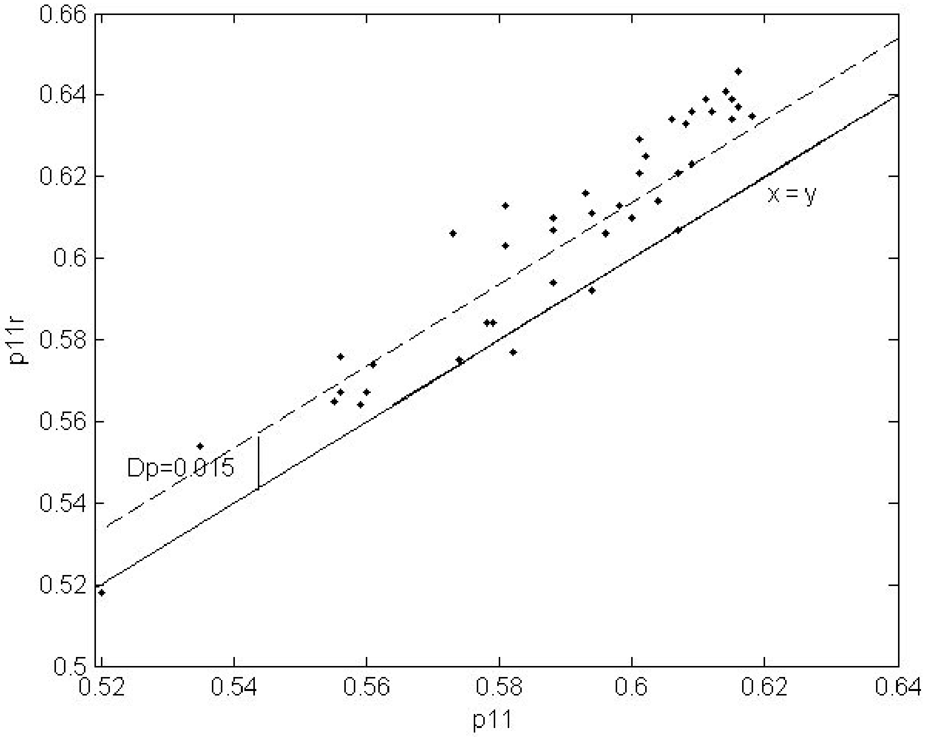



Figure 2.1: Horizontal shifting of the conditional probabilities p11r (probability of rain at the day $i$ if it has been rain at the day $i-1$ and the CP at the day $i$ is a rain CP) with respect to the p11 (probability of rain at the day $i$ if it has been rain at the day $i-1$) due to the conditioning with the rain circulation pattern. The two interpolation lines are shifted by a Dp of 0.015.

## 2.3 Third model: Circulation Pattern-Basin average conditioned 1st order Markov Model

The idea behind the third model is a direct consequence of the results of the first two models that will be shown below. In effect, conditioning the conditional probabilities with the Circulation Patterns led an over-forcing estimation on the conditional probabilities itself. This consequence is in perfect accordance with the result obtained for the cluster analysis, which concerns the non persistence of a direct correlation between the two phenomena, and that the actual relation between macro and microscale must be mediated taking in account the mesoscale of the problem. For that, a new developed methodology has been developed, aiming to correct the transition probabilities of the Markov model with both the basin-scale data and the Circulation Pattern data, as it will be shown in this section. Despite of the approach present in literature [47], in which the precipitation depth calculated by means of the General Circulation Model, a new methodology has been performed here, in order to avoid to implement a data-needing and time-consuming GCM to use it as input. This method takes into account the conditional probabilities in the station level, the one at the basin level, and computes a conditional probability based on the Rain-Dry circulation pattern. For that, the three sets of probabilities have been obtained. The first one is the set of the conditional probabilities for each single station, the second is the set of the conditional probabilities for the entire basin and the third is the set of the conditional probabilities referring to the Circulation Pattern occurrence:

$$
\begin{aligned}
p_{rr} &= P\{cp_i = r | cp_{i-1} = r\} \\
p_{dd} &= P\{cp_i = d | cp_{i-1} = d\} \\
p_{dr} &= P\{cp_i = d | cp_{i-1} = r\} \\
p_{rd} &= P\{cp_i = r | cp_{i-1} = d\}
\end{aligned}
$$

Once the probability sets have been calculated, it is possible to proceed in calculating the modified conditional probabilities. In this case, we found that the better results are obtained by simply calculating a first mean of the probability sets, using the unconditional probability of daily precipitation occurrence p and the lag-1 autocorrelation of the daily precipitation occurrence series r, calculated from each conditional probability set.

$$
\begin{aligned}
p_{k_{corr}} &= \frac{p_k + p_{basin} + p_{cp}}{3} \\
r_{k_{corr}} &= \frac{r_k + r_{basin} + r_{cp}}{3} \quad were \quad k = 1...n_{stations}
\end{aligned}
$$

Where the $p$s are the precipitation occurrences, corrected ($corr$), at station scale (simple), at basin scale ($basin$) and at CP scale ($cp$), and r are the lag-1 autocorrelation of the dayly precipitation occurrence series, that are related with the conditional probabilities with well known relations (see, for example, [34]).

# Chapter 3

# Precipitation depth: distributions analysis

In order to model the precipitation depth for the rainy days, the two parameters Gamma Distribution ([34], [46], [47]) has been used:

$$f(x) = \frac{(x/\beta)^{\alpha-1} exp(-x/\beta)}{\beta\Gamma(\alpha)} \quad (3.1)$$

This distribution has been chosen basing on the better results of Kolmogorov-Smirnov test performed between the measured data and the theoretical distributions. Four distributions have been tested: Gamma distribution, Mixed Exponential distribution, Exponential distribution and the Weibul distribution. The Gamma distribution is preferred for both the monthly data and the seasonal data, as it is shown in the table 3.1.

The parameters *alpha* and *beta* have been estimated using the Maximum Likelihood technique. Once obtained the distribution parameters, the precipitation depth is calculated following Richardson and Wright, 1984: three normally distributed random numbers $a_1$, $a_2$, $a_3$ are generated; then, the parameters $\tau_1$ and $\tau_2$ computed as:

$$\tau_1 = e^{-18.42\alpha}$$
$$\tau_2 = e^{-18.42(1-\alpha)}$$

and the two random-based parameters $s_1$, $s_2$:

$$s_1 = \begin{cases} 0 \rightarrow (a_1 - \tau_1) < 0 \\ a_1^{1/\alpha} \rightarrow otherwise \end{cases}$$

| | **chosen model** | | **chosen model** |
|---|---|---|---|
| **Winter** | Gamma | **January** | Gamma |
| | | **February** | Gamma |
| | | **March** | Gamma |
| **Spring** | Gamma | **April** | Gamma |
| | | **May** | Exponential |
| | | **June** | Gamma |
| **Summer** | Gamma | **July** | Mixed Exponential |
| | | **August** | Gamma |
| | | **September** | Exponential |
| **Autumn** | Gamma | **October** | Gamma |
| | | **November** | Mixed Exponential |
| | | **December** | Gamma |

Figure 3.1: Best distribution model chosen with Kolmogorov-Smirnov test for the measured time series.

$$s_2 = \begin{cases} 0 \rightarrow (a_2 - \tau_2) < 0 \\ a_2^{1/(1-\alpha)} \rightarrow otherwise \end{cases}$$

Then the parameter $s_{12} = s_1 + s_2$ is evaluated and if $s_{12} = 0$, the random variables $a_1$ and $a_2$ are generated. Finally, the precipitation depth is calculated as:

$h_i = -z \lg(a_3)\beta$ where $z = \frac{s_1}{s_{12}}$

# Chapter 4

# Choosing the best model: testing criteria

In order to evaluate the three developed models, three decision criteria have been adopted, to take in account the different aspects of the precipitation time series. In this analysis, the most significant features that have been considered to evaluate the accuracy of the obtained distributions are: the spell length distribution, where the "spell" is the continuous sequence of wet/dry days, that is important because it is really peculiar in the analyzed area. This feature is also really relevant in the soil/culture characterization, because different spell lengths with the same total mount of precipitation lead different soil moisturizing. Another feature considered in the distribution goodness evaluation is the precipitation depth density distribution that is the distribution obtained by means of the Gamma distribution, describing the probability density function of the precipitation amount. The last criteria adopted in evaluating the model output is the accuracy in the reconstruction of the extreme events, that is one of the most critical issue in the most of the weather generators. The first two features are evaluated by means of the reconstruction of the density function of the calculated data, and the testing of this distribution is performed by means of the Kolmogorov-Smirnov test for two distributions, the measured and the calculated one. The third feature is evaluated by means of comparing the higher value of the calculated precipitation depth time series with the one of the observed time series. In the model, also the "classic" first order and second order Markov models have been implemented, to compare the performances of the classical approaches with the new ones. These three criteria gave back a "score" for each of the five implemented models (see below) and the chosen model is the one having the better voting value, for each criterion.

# Chapter 5

# Applications

The weather generators have been applied and tested in the Weisser Elster Basin, Saxony, Germany, starting from the data of 53 rain stations in the basin itself. The Weisse Elster river basin (figure 5.1) covers an area of about $5300 km^2$. The basin shares parts of the Elstergebirge mountains (Southern Vogtland, 724 m a.s.l.), the Saxonian Mountains, the Saxonian-Thuringian hills as well as the Leipzig lowlands when reaching its outlet. The river flows into the Saale river near the City of Halle. The Weisse Elster basin is dominated by arable land use (60%) followed by densely populated settlement and traffic areas around Leipzig and Halle (16%).

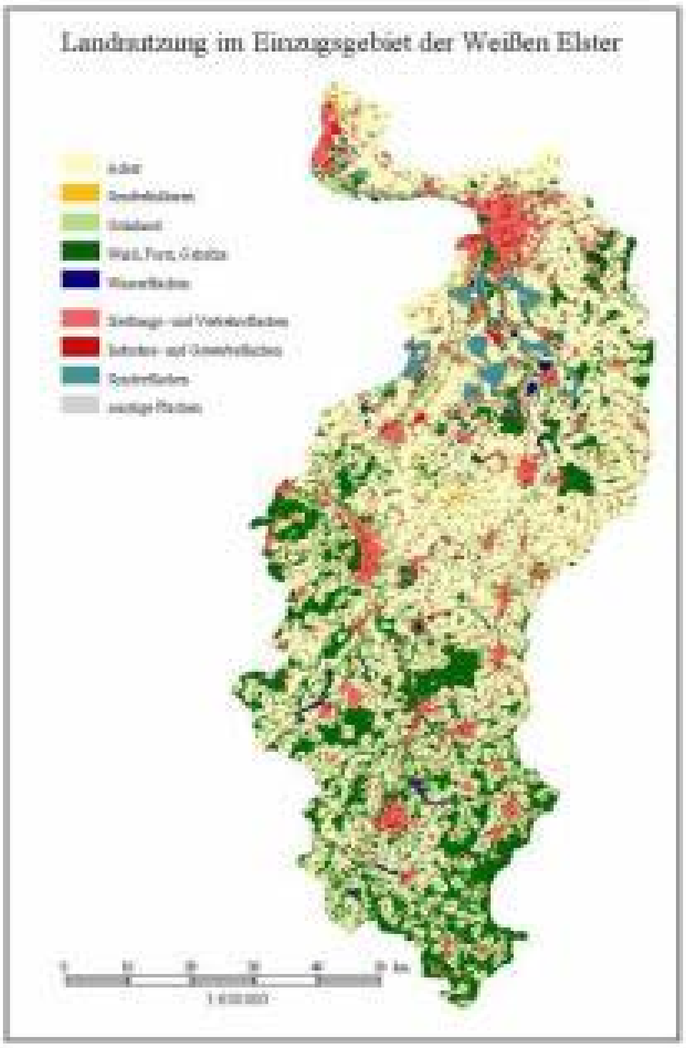



Figure 5.1: Weisser Elster river basin

The soil characteristics vary from Czernosems in the North to Luvisols and luvic Cambisols in the South. Of special interest for the retention potential in the catchment are the restoration areas of the former open cast lignite mines near Leipzig. The long-term mean annual precipitation varies from 832 mm in Bad Elster, 676 mm in Plauen and 621 mm in Leipzig whereas the mean temperature reaches 8.9 to 6.3 °C (Schmidt 1953).

Over the length of 257 km, some major tributaries contribute to the river course of the Weisse Elster. The basin is characterized by low precipitation depth level and short wet spells. Furthermore, in the past 33 years, the basin has shown an high variability in the monthly means precipitation, with an average of the oscillations in the monthly means of 3.2 mm.

The 33 years time series have been used to test the three weather generators here studied. Furthermore, the simple first order and second order Markov models have been implemented too, in order to compare the new concept Markov-based weather generator with the most classical ones. The tests have been carried on using the seasonal data.

## 5.1 First model: Circulation Pattern conditioned 1st order Markov Model

The first model could be defined as a second order Markov chain, with the second order term referred to a present status that is lead also by a different factor (actual Circulation Patten occurrence instead of just the rain-dry past occurrence). This model has shown a good answer in the Markov chain application. In effect, the model's answer in the spell length distribution is significant, just presenting an over estimation of the density of the shorter spells, that not exceed the 3.5% (figure 5.2).

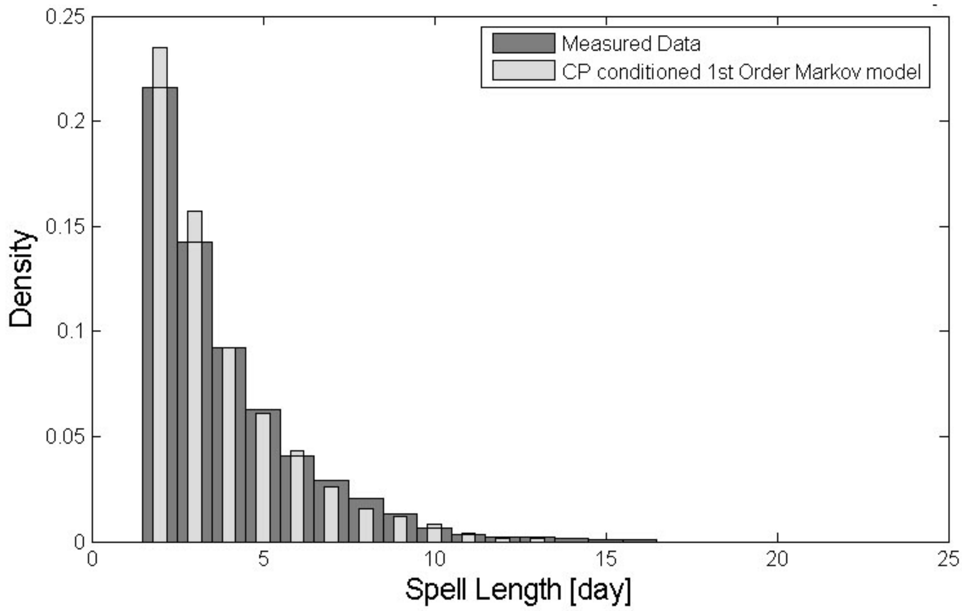



Figure 5.2: Comparison between the measured Spell Length density (dark gray) and the one modelled with the Circulation Pattern conditioned 1st order Markov Model (First model - light gray)

Regarding the precipitation depth density, the first model has not shown an extremely good fitting in the distribution itself, but it is the more accurate on in estimating the maxima (figure 5.3).

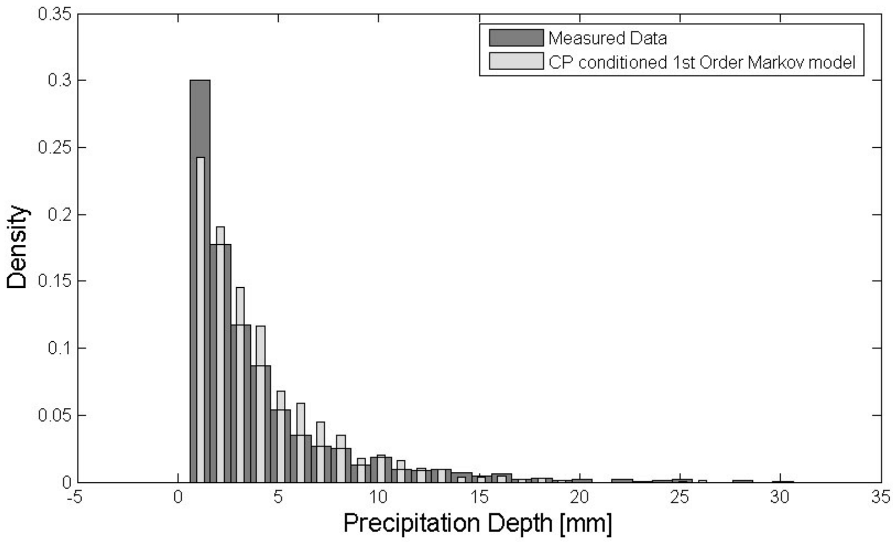



Figure 5.3: Comparison between the measured Precipitation Depth density (dark gray) and the one modelled with the Circulation Pattern conditioned 1st order Markov Model (First model - light gray)

## 5.2 Second model: Circulation Pattern conditioned 2nd order Markov Model

As described before, this model could be described as a second order Markov chain conditioned with the Circulation Pattern, divided in Rain Circulation Pattern and Dry Circulation Pattern by means of the Wetness index clustering. This model does not give back a really satisfactory answer concerning the spell length density and the precipitation density. In the first case, it gives back a slightly high underestimation in the density of the shortest spells (figure 5.4).

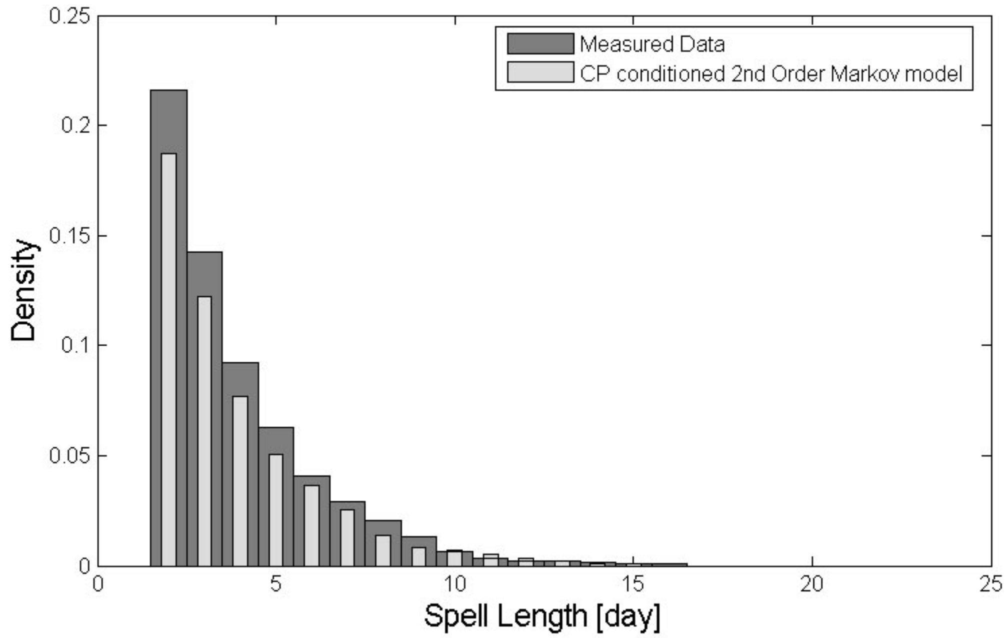



Figure 5.4: Comparison between the measured Spell Length density (dark gray) and the one modelled with the Circulation Pattern conditioned 2nd order Markov Model (Second model - light gray)

Whereas, in the second case, it overestimates the densities of the lower precipitation depths and not properly fit the whole distribution (figure 5.3).

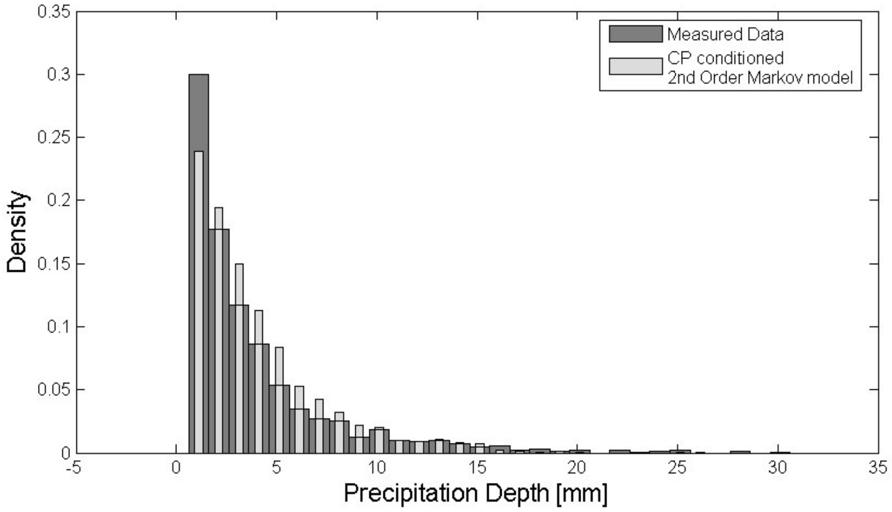



Figure 5.5: Comparison between the measured Precipitation Depth density (dark gray) and the one modelled with the Circulation Pattern conditioned 2nd order Markov Model (Second model - light gray)

On the other hand, this model has revealed to be the better one in reconstructing the extreme events, giving back a good estimation of the peak depth levels, as it will be shown in the section 5.4

## 5.3 Third model: Circulation Pattern-Basin average conditioned 1st order Markov Model

The third model is the one in which the conditional probabilities are corrected by means of the Circulation Pattern dry/rain conditional probabilities and the basin averaged data. This model has shown a good modeling of the spell length density (figure 5.6).

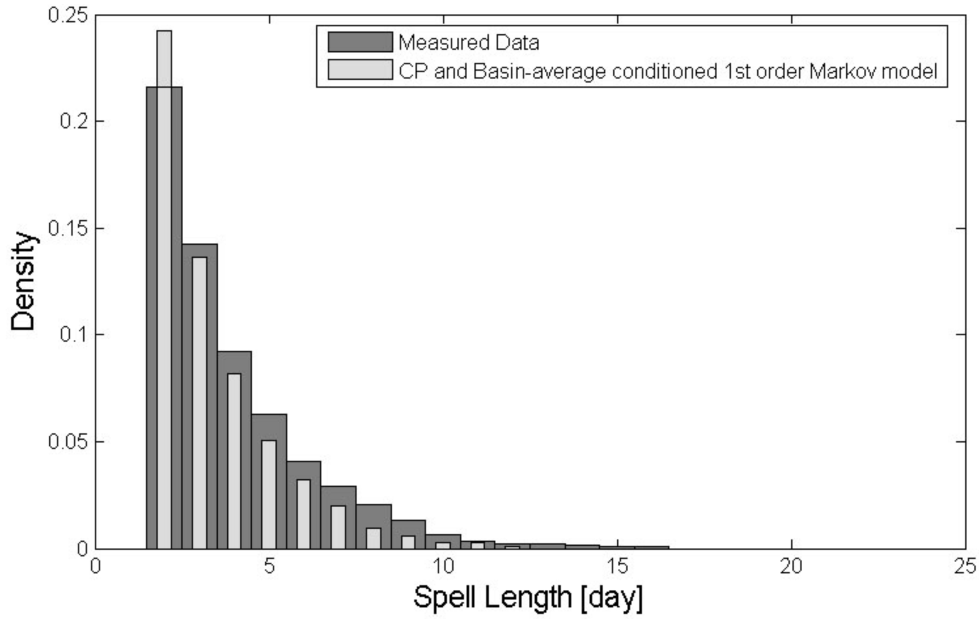



Figure 5.6: Comparison between the measured Spell Length density (dark gray) and the one modelled with the Circulation Pattern-Basin average conditioned 1st order Markov Model (Third model - light gray)

Furthermore, the modelled data have shown very good results in the Precipitation Depth density reconstruction, while this model tends to underestimate the extreme events values (5.7).

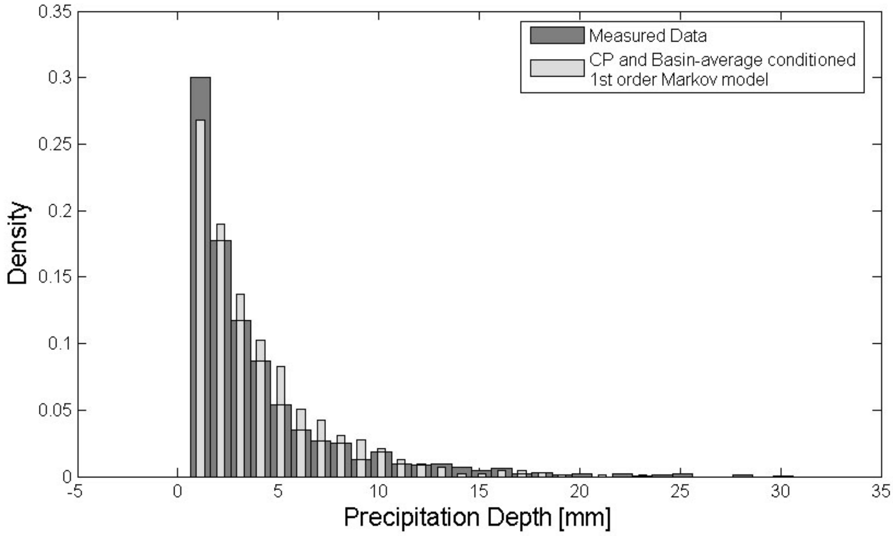



Figure 5.7: Comparison between the measured Precipitation Depth density (dark gray) and the one modelled with the Circulation Pattern-Basin average conditioned 1st order Markov Model (Third model - light gray)

## 5.4 Model comparison

The results of the comparison by means of the decision criteria described in the previous sections are here presented. The tests have been carried on in 100 runs for all the 53 stations, with a total of 5300 generated time series for each model. As mentioned before, regarding the Precipitation densities, the model that gives back the better results is the third model, as shown in 5.8.

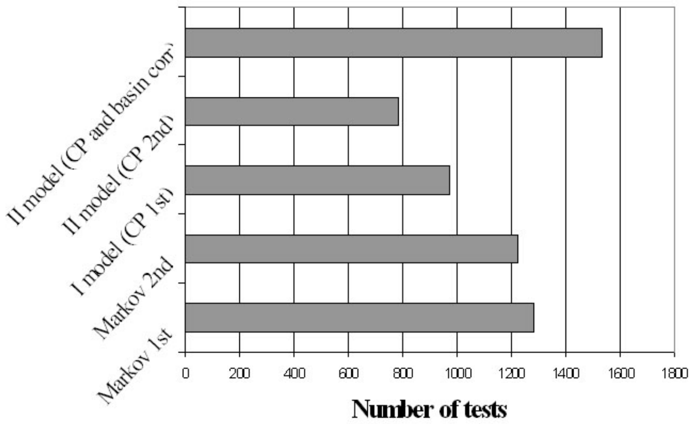



Figure 5.8: Kolmogorov-Smirnov test on the Precipitation Depth density for the three proposed models and for the classic 1st order Markov chain model and 2nd order Markov chain model

The Kolmogorov-Smirnov test performed for the Spell length densities has given back a substantial accordance of the third model and the first-order Markov model that has been chosen approximately in the same number of simulations (figure 5.9).

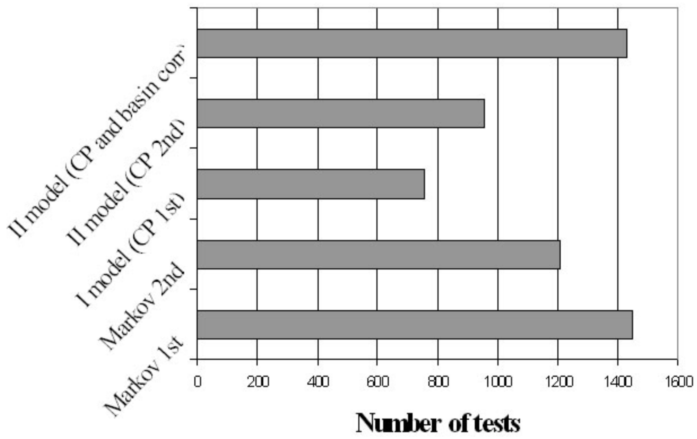



Figure 5.9: Kolmogorov-Smirnov test on the Spell Length density for the three proposed models and for the classic 1st order Markov chain model and 2nd order Markov chain model

Finally, the test performed by means of analyzing the minimum differences between the higher precipitation values of the modelled data and the measured ones, has shown that the better performances are given back from the second model, that is as the second order Markov chain conditioned with the Circulation Pattern (figure 5.10).

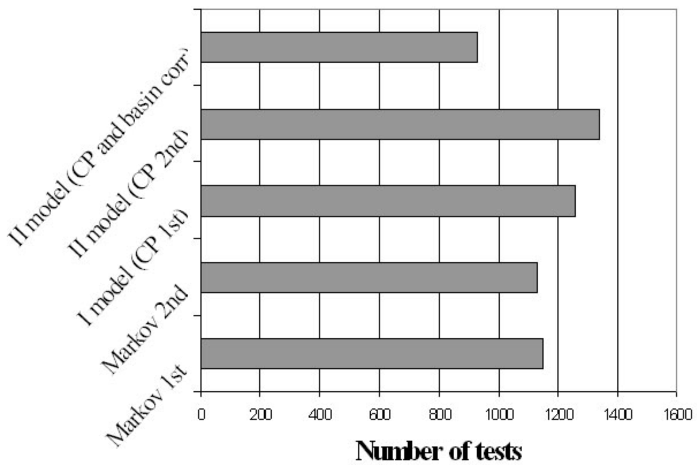



Figure 5.10: Kolmogorov-Smirnov test on the Spell Length density for the three proposed models and for the classic 1st order Markov chain model and 2nd order Markov chain model

As results of the test, the third model has been considered the best one, due to the strong preference in the Precipitation density test and to the good behaviour in the Spell Length test. The model does not give back a good answer in the Maximum Values test. This behaviour could be the consequence of some extreme values. For that, the general model response in terms of monthly means has been investigated. As it has been shown in figure 5.11, the monthly means calculated for the models that are been performed as test-case, are nearly below the 10% of error in the measured data, with the natural oscillation in the trend-changing months (April and September), but with a good response in the extreme events months (June, July and August). This fact means that the model gives back a global good answer in the months that present the critical extreme values.

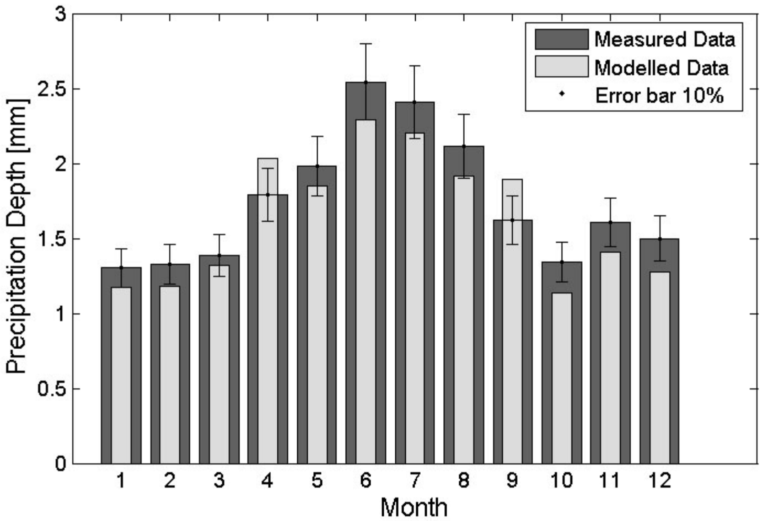



Figure 5.11: Comparison between the measured monthly means (dark gray) and the ones modelled with the third model (light gray), with the error bar of 10% of the measured data

Furthermore, assuming the Median of the Measured data as confidence value, the modelled data means are all below the confidence, showing a global good model response (figure 5.12).

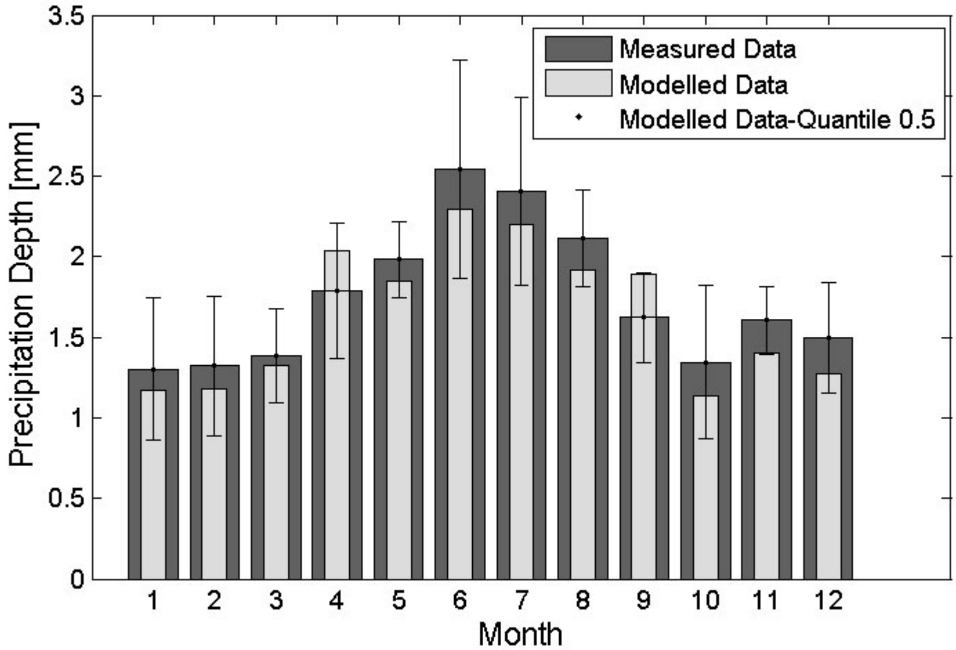



Figure 5.12: Monthly means comparison using the 0.5 Quantile as confidence interval in order to evaluate the model response

The results for each test in figure 5.13 show a variability in the monthly values, that is a good evidence of the generalization capability of the model. In fact, the basin shows a strong monthly means variation, that is on the average 3.2$mm$ for the measured data, while is 2.8$mm$ for the modelled data.

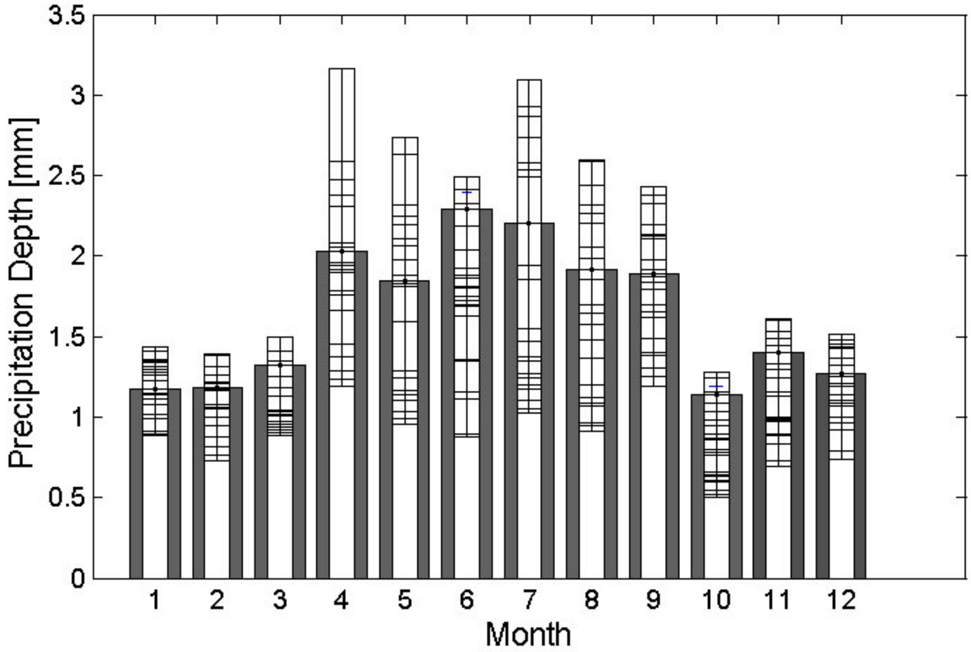



Figure 5.13: Monthly means variability for the modelled scenarios

The 0.95 Quantile and the 0.05 Quantile are then considered in order to give another measure of the confidence. This method shows a good response that is coherent with the natural response of the measured data, as is presented in figure 5.14.

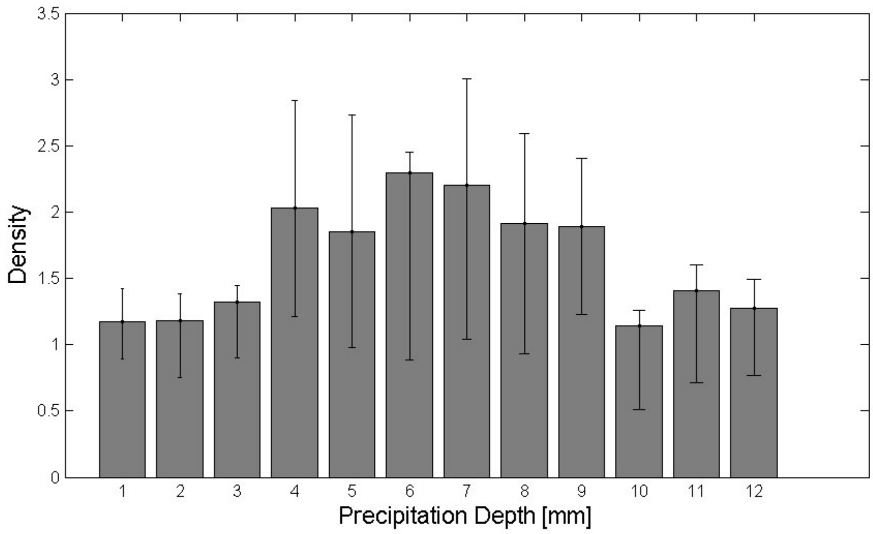



Figure 5.14: absolute means of the model with the 0.95 and the 0.05 Quantiles error bar

# Conclusions

In this part, three new concepts to use the pure Circulation Patterns, without needing a further Circulation Model, in order to add this information to Markov-based weather generators have been presented. In order to construct the models, first of all the influence of the Circulation Patterns to the local conditional probabilities has been investigated. The results show that the relationship between the CP macroscale and the single station microscale is not as strong as having a direct influence the local conditional probabilities that are overestimated in this case. Therefore, averaging the Circulation Patterns influence with the basin conditional probabilities, it is possible to reasonably downscale the CP information in order to condition the local conditional probabilities. This has been made using directly the Circulation Patterns, without resorting to any Circulation Model, thanks to the use of the "Wetness Index" that allowed to cluster the CP pattern in "dry" and "rain". These three models have shown that the third model gives back the better results from the Precipitation depth reconstruction, and shows good results also in the Spell length modeling. Therefore, the second model has shown a good response regarding the reconstruction of the extreme events.

# Part II

# Hydrodynamic modelling

# Introduction

The Hydrodynamic modelling is a branch of the Computational Fluid dynamics that has been developed during the last century. This thesis does not aim to bring any innovation in terms of hydrodynamical modelling theory. in fact, the main original contribution of this part is concerning the study carried on in one of the interesting (hydrologically speaking) area, the Thames estuary, in order to build meaningful scenario models to analyze the consequence of a defence failure. This study has been here presented going through all the different phase that are needed to build a meaningful model, analyzing all the way through building a model in this area, from choosing the most meaningful scenario, to the collection of the boundary condition, the field work, the model building and the analysis of the consequence.

# Chapter 6

# Modelling Breach scenarios, the statistics of the failure

## 6.1 Introduction

The first step in performing a hydrodynamic model is obviously the choice of the scenario to be model. While the area involved is strictly connected with the one chosen for the evacuation modelling area, the inundation scenarios need to be assessed taking in account different characteristics. First of all, being the chosen area protected by tidal defences, the natural choice is to simulate a breach failure scenario. In order to locate the failure, different criteria are here considered:

- The upper bound of the annual probability of failure
- The lower bound of the annual probability of failure
- The breach corresponding to a particular low ground area.

In the following sections, a brief description of the selected area and its defences are presented, with the relative breach analysis.

## 6.2 Thames estuary

The Thames estuary (figure 6.1) is the area chosen as pilot of this study. In fact, the Thames estuary is particularly vulnerable to flooding for a number of reasons. The South-eastern area of the British Isles area slowly decreasing in the ground level and sea levels are rising. As a result, the high tide in central London is rising at a possible rate of 75cm per century. Furthermore, when an area of low pressure, that could be hundred of miles apart, moves trough east across the Atlantic toward the British Isles, it raises the level of seawater beneath it by up to a third of a meter. This increasing in the sea water level can cause very high surge tides in the Thames Estuary, that could be raise of up to 4 meters in the proximity of London. When a surge tide also coincides with a spring tide flooding would be a serious possibility (font Environmental Agency).Tide levels are steadily increasing due to a combination of factors. These factors include higher mean sea levels, greater storms, increasing tide amplitude, the tilting of the British Isles and the settlement of London on its bed of clay. this factors have as direct consequence a rising in the Thames Estuary by about 60cm per century, respect to the ground level.

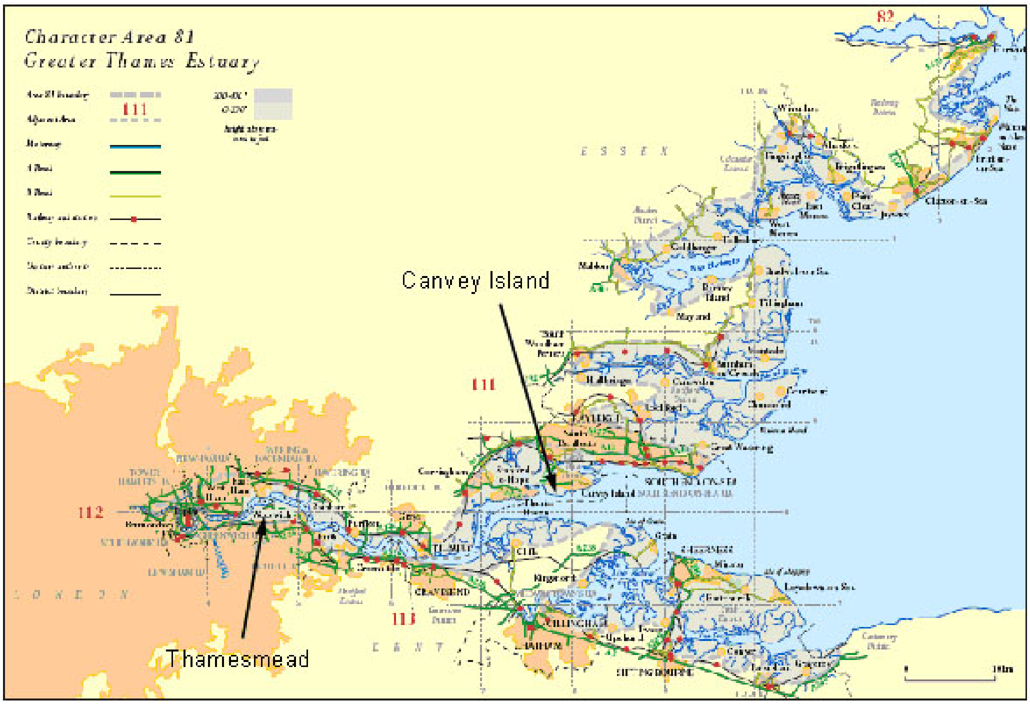



Figure 6.1: Locations of Thamesmead and Canvey Island (the pilot site) within the Thames Estuary

In order to protect the central London, a massive system of barriers has been build in late 1974. The "Thames barriers" became operational in October 1982, and it was first used in February 1983, while the official opening was performed by Her Majesty the Queen on 8 May 1984. Basically the barrier is a series of ten separate movable gates positioned end-to-end across the river. Each gate is pivoted and supported between concrete piers that house the operating equipment. Closing the barrier seals off part of the upper Thames from the sea. When not in use, the six rising gates rest out of sight in curved recessed concrete cills in the riverbed, allowing free passage of river traffic though the openings between the piers. During the development of the present thesis, a interesting site visit to the barrier has been performed thanks to the Environmental Agency and HR Wallingford Ltd.

Figure 6.2: The Thames barrier

The area interested in this study is located downstream the barrier, and does not take advantage of the protection of the barrier itself. Therefore, the Thames estuary area is protected downstream by a system of defences that are constituted by $Km$ of flood defence, built in 1971. These defences where provided to bank levels 2m higher than had previously existed and included the 60m high Barking Barrier.

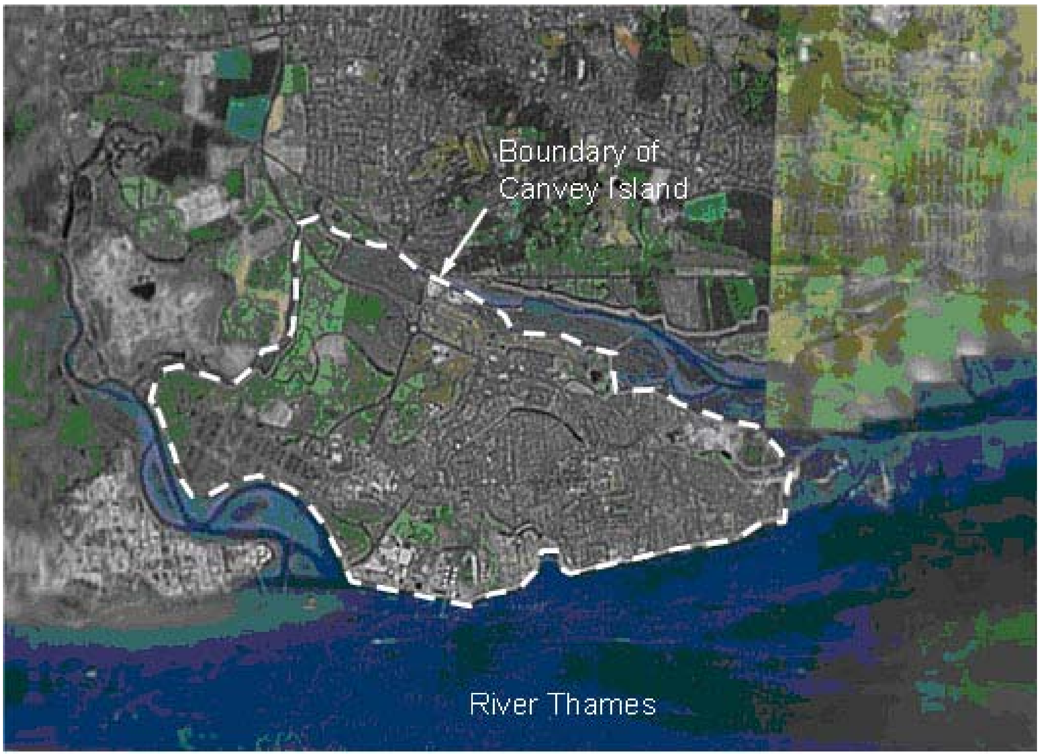



Figure 6.3: Satellyte photography of Canvey Island

The selected site for the hydrodynamic study is the site of Canvey Island. The Island is and island having an area $18.45km^2$ off the coast of Essex, England, created by the currents of the Thames estuary. Canvey Island was originally part of the mainland, then the coastline broke up into smaller pieces, and the modern island is made up of five of those pieces (see figure 6.3). The morphology of the island is really interesting from the hydrodynamic point of view: while the Island is now protected by the downstream tidal barriers, the subsidence has generated wide areas characterized by low grounds, that would allow the water spreading in the interior of the island (figure 6.4).

Figure 6.4: The downstream tidal defences in Canvey Island

## 6.3 Breach failure scenario

The probability of failure of embankments is complex and dependent of several parameters (including geotechnics, structural integrity, loading condition, etc.) and research is still being undertaken to better understand the relationships between these parameters. In order to decide which breach failure scenario would have been more likely or interesting to model, the probability of failure calculated beneath the RASP model development in HR Wallingford Ltd [37] has been analyzed. The data used in the present study has been calculated starting from the concept of Defence Fragility curve. A defence fragility curve provides a consistent methodology to characterise defence performance as a plot of the conditional probabilities of failure of a defence over a range of loading. This curves depend on the characteristic of the defence and on the feasibility of the defence to be exposed to a certain type of load. Starting from this results, three breaches has been chosen:

- The defence having the peak value of the upper bound of the Annual Probability of Failure (see figure 6.5)
- The defence having the second peak value of the upper bound of the Annual Probability of Failure (see figure 6.6)
- The defence having the peak value of the lower bound of the Annual Probability of Failure (see figure 6.7)

Due to the particular morphology of the island, a fourth scenario has been selected:

- The defence closest to the lower ground area (see figure 6.8)

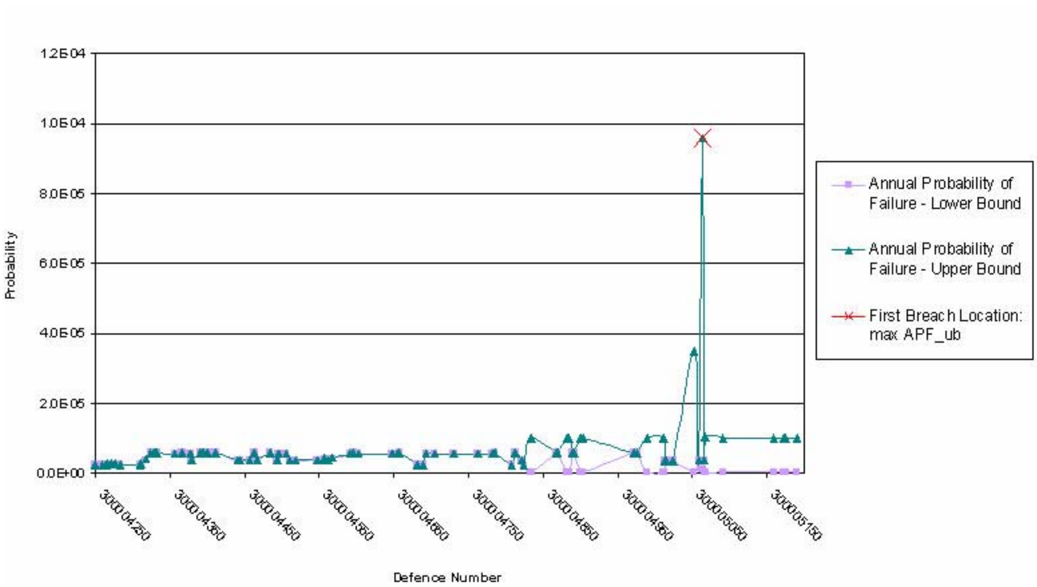
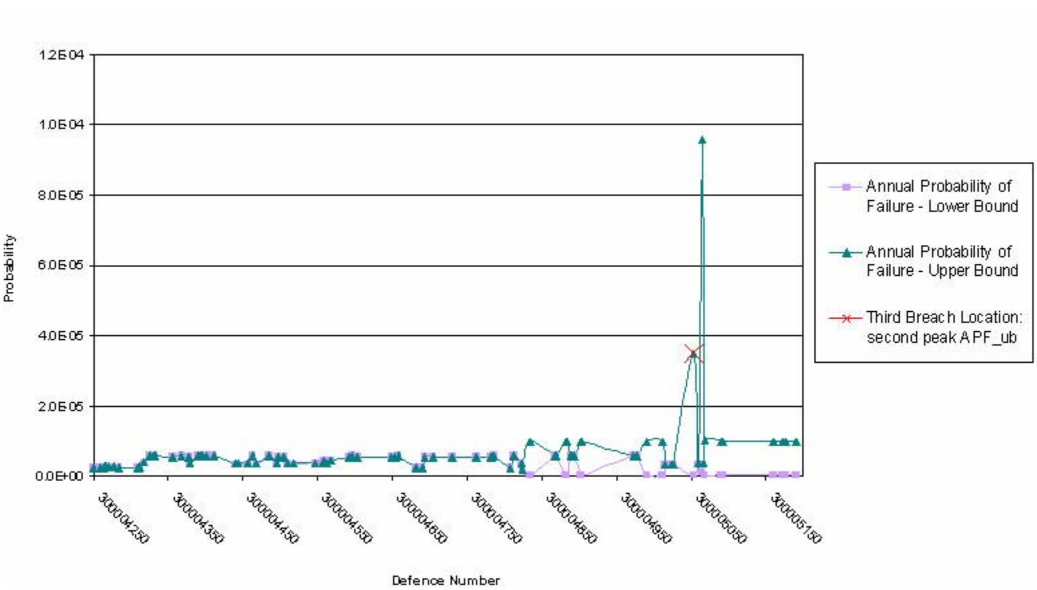



Figure 6.5:

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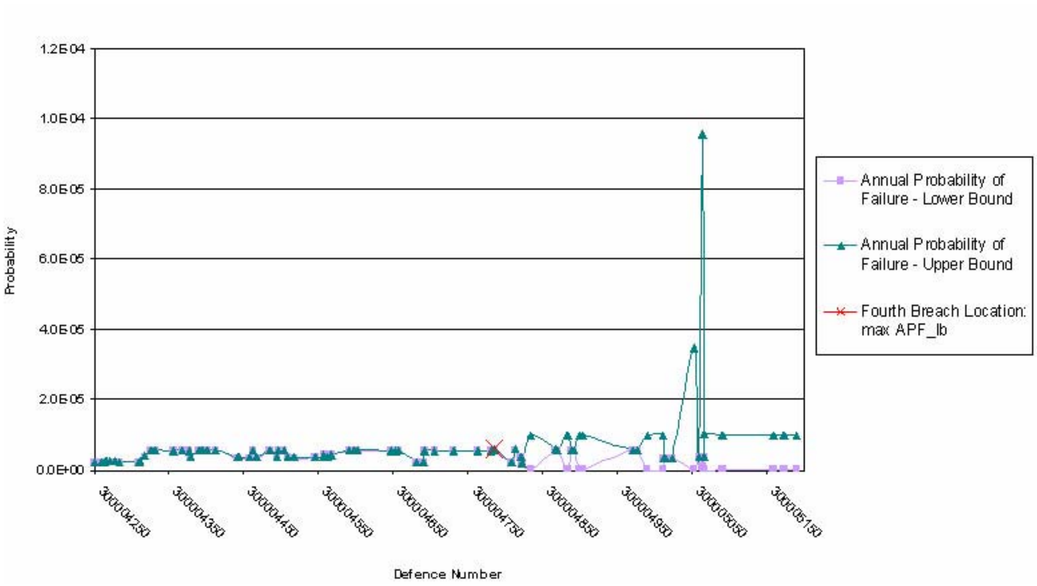


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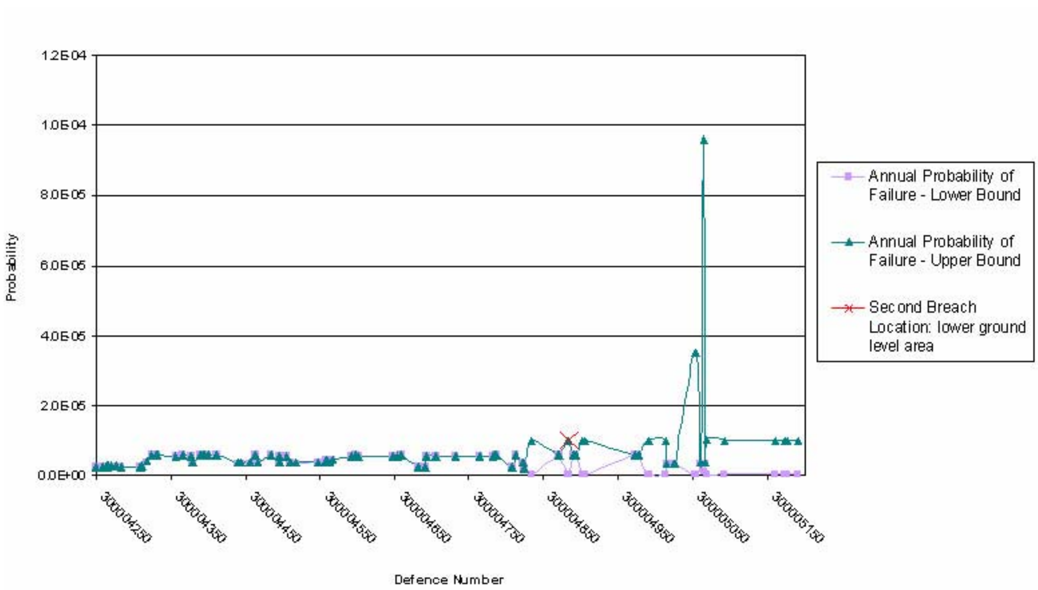


Figure 6.8:

# Chapter 7

# Modelling Tidal scenarios

## 7.1 Introduction

The hydrodynamic analysis in the United Kingdom needs to take into account the tidal phenomena, that are the most impactant phenomena regarding the floods. Tides are the alternating rise and fall of sea level with respect to land, as influenced by the gravitational attraction of the moon and sun. Other factors influence tides; coastline configuration, local water depth, seafloor topography, winds, and weather alter the arrival times of tides, their range, and the interval between high and low water. Sir William Thomson (Lord Kelvin), [39] devised the method of reduction of tides by harmonic analysis about the year 1867. The principle upon which the system is based, which is that any periodic motion or oscillation can always be resolved into the sum of a series of simple harmonic motions, is said to has been discovered by Eudoxas as early as 356 B.C., when he explained the apparently irregular motions of the planets by combinations of uniform circular motions. In the early part of the nineteenth century Laplace recognized the existence of partial tides that might be expressed by the cosine of an angle increasing uniformly with the time, and also applied the essential principles of the harmonic analysis to the reduction of high and low waters. Dr. Thomas Young [40] suggested the importance of observing and analyzing the entire tidal curve rather than the high and low waters only. Sir George B. Airy [2] also had an important part in laying the foundation for the harmonic analysis of the tides. To Sir William Thomson, however, we may give the credit for having placed the analysis on a practical basis. The methods for the prediction of the tides may be classified as harmonic and nonharmonic. By the harmonic method the elementary constituent tides, represented by harmonic constants, are combined in to a composite tide. By the nonharmonic method the predictions are made by applying to the times of the moon's transits and to the mean height of the tide systems of differences to take into account the average conditions and various inequalities due to changes in the phase of the moon and in the declination and parallax of the moon and sun. Up to and including the year 1884, all tide predictions for the tide tables were computed by means of auxiliary tables and curves constructed from the results of tide observations at the different ports. From 1885 to 1911, inclusively, the predictions were generally made by means of the Ferrel Tide-Predicting machine [11]. From 1912 to 1965, inclusively, they were made by means of the Coast and Geodetic Survey Tide-Predicting Machine No. 2 [12]. Without the use of a tide-predicting machine the harmonic method would involve too much labor to be of practical service, but with such a machine the harmonic method has many advantages over the nonharmonic systems. Predicting machines were superseded in 1966 by the advent of digital electronic computers. Initially these computers were of the large main-frame type. In the late 1980s main-frames were replaced by the growing sophistication of desktop computers. These are now used exclusively by the National Ocean Service in making predictions for the standard ports of this country and at other locations, where sufficient observational data exists.

## 7.2 Tide series

The maximum tide level for the areas involved in the study has been calculated in corespondance to the chosen defences by means of the ISIS 1D model developed by Wallingford softwares, using historical data for the River Thames for a 100 years return time. The obtained levels are shown in the figure 7.1.

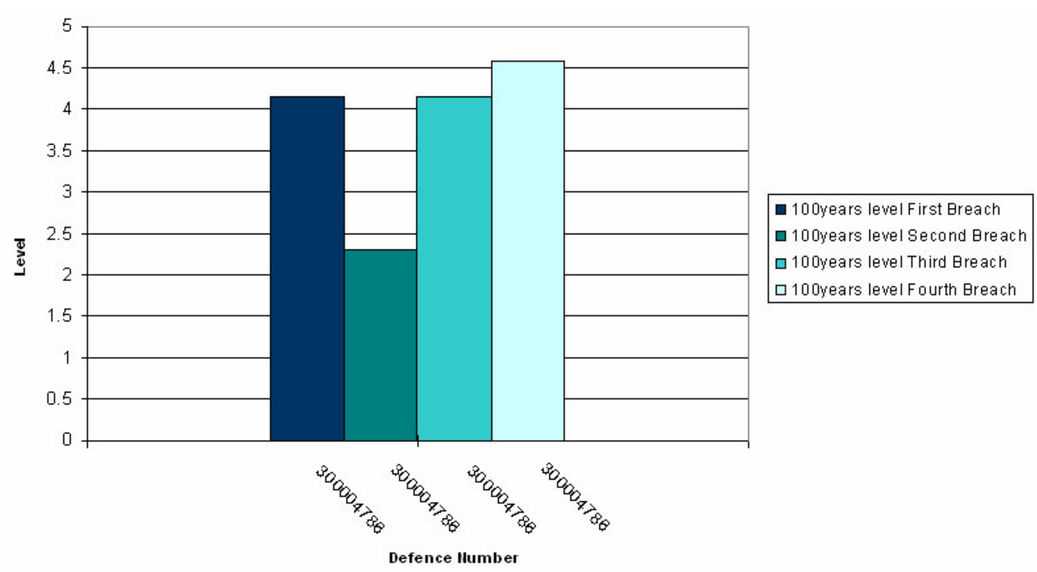


Figure 7.1: Tide maximum levels calculated for the selected defences for a return period of 100 years

## 7.3 Tide reconstruction

After estimating the maximum tide levels for a return time of 100 years, the shape of the considered tide must be obtained. The harmonic curves corresponding to the location of the selected defences were not available in this study, whereas the tidal shapes of different locations, calculated by means of the data coming form four different measurement floats close to the island, where available. Starting from this curves, and known the peak level, the four tidal events to be used as boundary condition for the model have been reconstructed, as it is shown in figure 7.2

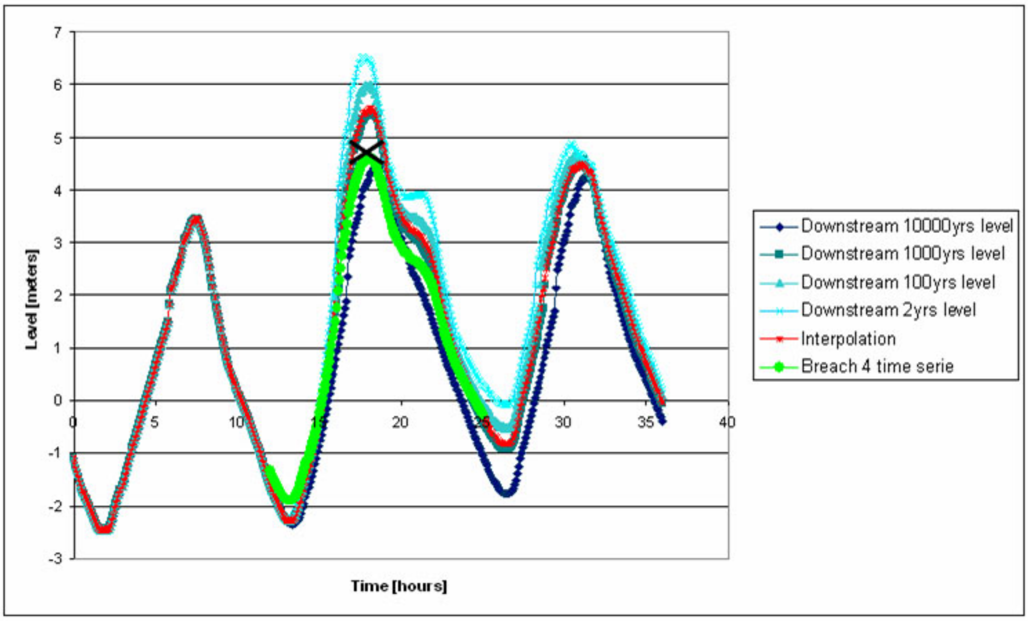


Figure 7.2: Reconstruction of the tide for one of the four breach locations

# Chapter 8

# Modelling Inundation scenarios

## 8.1 Finite Difference modelling

The Hydrodynamic modelling is a branch of the Computational Fluid dynamics. Computational Fluid Dynamics (CFD) can be described as the use of computers to produce information about the ways in which fluids flow in given situations [38]. The theory underneath the fluid motions has been developed during the centuries, with the branch of the science called Fluid Mechanics, which study goes back at least to the days of ancient Greece, when Archimedes made a beginning on fluid statics, and which development has been carried on in parallel with the human history, just mentioning Bernoulli's principle (1738) [17] and Navier-Stokes equation (1822) [33]. However, fluid mechanics, especially fluid dynamics, is an active field of research with many unsolved or partly solved problems. In fact, fluid mechanics can be mathematically complex. Sometimes it can best be solved by numerical methods, typically using computers. For that, the modern discipline of Computational Fluid Dynamics (CFD), has been developed to follow this approach to solving fluid mechanics problems. The fundamental basis of any CFD problem are the Navier-Stokes equations, which define any single-phase fluid flow. The most fundamental consideration in CFD is how one treats a continuous fluid in a discretized fashion on a computer. One method is to discretize the spatial domain into small cells to form a volume mesh or grid, and then apply a suitable algorithm to solve the equations of motion (Euler equations for inviscid, and Navier-Stokes equations for viscous flow). In this thesis, the discretization method adopted for the used model is the Finite difference method. This method has historical importance and is simple to program. It is currently only used in few specialized codes. Modern finite difference codes make use of an embedded boundary for handling complex geometries making these codes highly efficient and accurate. Other ways to handle geometries are using overlapping-grids, where the solution is interpolated across each grid. In this work, the 2D Finite Difference Model TUFlow has been used. TUFLOW's 2D solution is based on the Stelling finite difference, alternating direction implicit (ADI) scheme that solves the full 2D free surface shallow water flow equations. The scheme has been improved in the latter TUFlow package to handle upstream controlled flow regimes (eg. supercritical and weir flow), bridge decks, box culverts, robust wetting and drying, and other features. [54]

## 8.2 Geographical data validation and convergence analysis

Once defined the scenarios to be modelled and the boundary conditions to apply, the geometry of the model needs to be defined. In this case, the base of the terrain elevation model has been provided by the lidar maps of the area. The use of this maps is conditioned to a field analysis, in order to give back all of the adjustment that could be needed in order to reproduce the present morphology of the area. In fact, it is necessary to take into account the most recent modification in the infrastructures, in the defences and the possible obstacles to the flow path that are not reproduced or filtered in the lidar. The site visit of the area has not shown great differences in the morphology. The site visits have shown the presence of two pumping stations, that have been chosen not to be reproduced in this case. The defences and the breaches have been added in the model as additional layers. The model has been tested using a grid of 50 meters to test the convergence of the model itself. The only problem that has been encountered has regarded some "holes" in the lidar in which the "non data" value of -9999 has not been filled with the quotation of the grid. For these areas, manual corrections has been provided.

## 8.3 Depth-velocities results analysis

Both the overtopping and the presence of buildings have not been considered in this model due to the lack of data. The first factor is a negative factor in terms of severity of the flood, while the second one is a positive contribution. For that, lack of the two factors could be roughly considered as balancing in terms of the results of the model. Furthermore, the present study aims to show the procedure, the methodology the usefulness of the developed models and does not want to be a technical study to be applied for the area, that should be done with the same procedure but with a better data availability. The results of the hydrodynamic analysis has been analyzed by means of the depth velocities maps, gave back from the model. The results has shown that the case of the first breach is probably the more problematic because it is characterized by a great area that is involved in the flood (see figure 8.1). This result is also due to the fact that this model and the third one are the ones with the highest tidal levels.

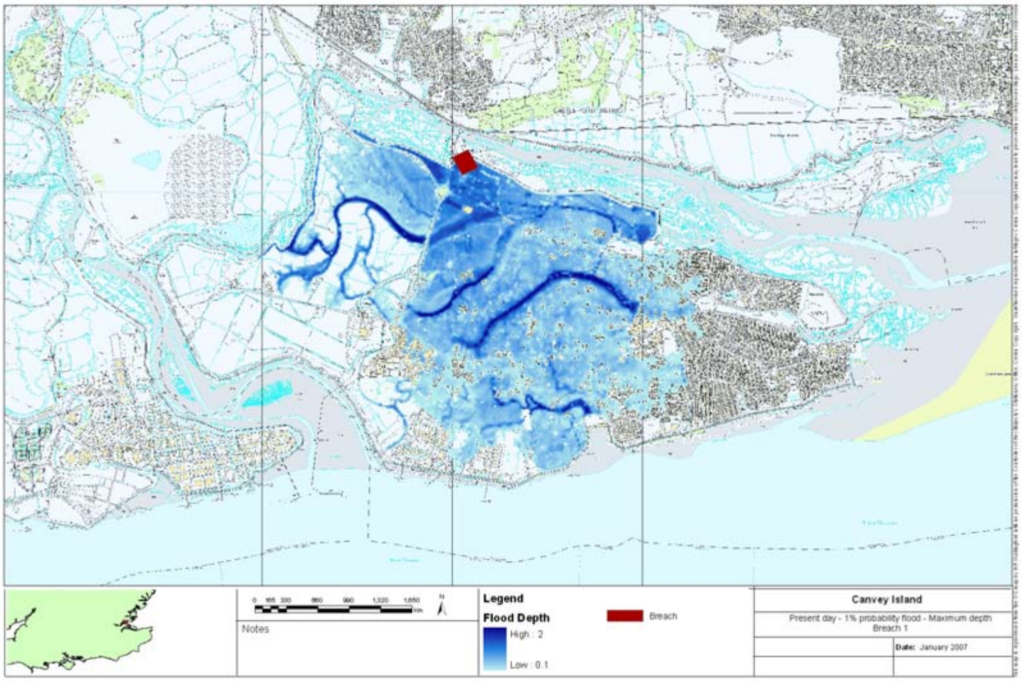


Figure 8.1: First breach model, maximum depth

Furthermore, the velocities that results in this model (see figure 8.2), even if are not really high in the whole area, assume a highest value in the area close to the breach, that it is also characterized by having a consistent urban development in the surrounded area.

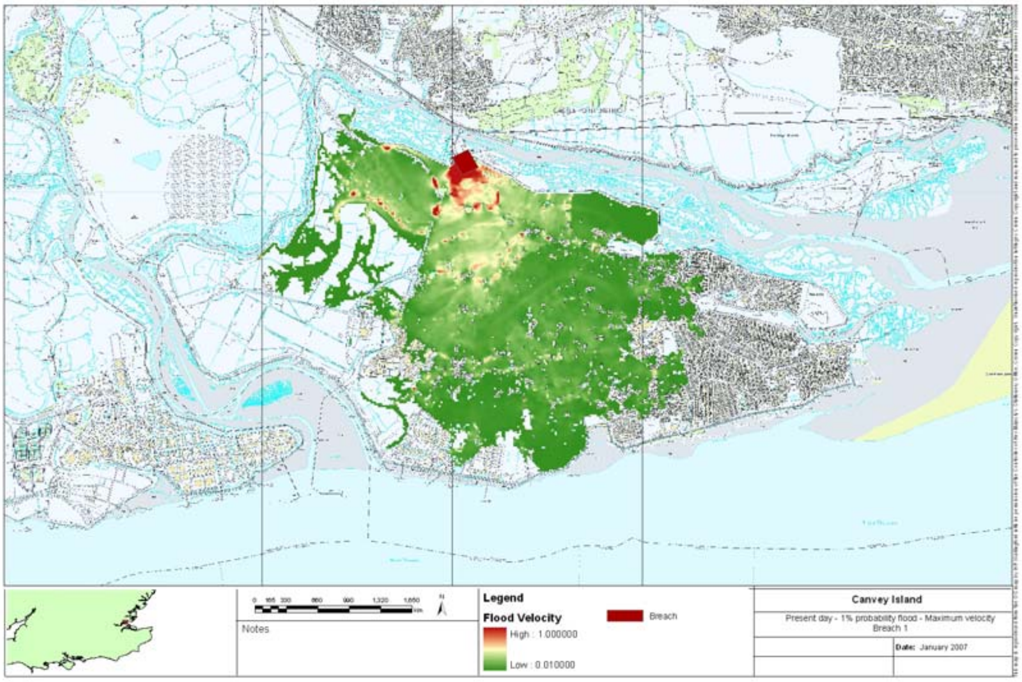


Figure 8.2: First breach model, maximum velocity

The second breach model has been developed because the area downstream the breach is a low ground area, and the incoming volumes could have been spread with high velocity. Therefore, this area is characterized by a low level of tide, and the flood scenario it seems not to be really extreme (figure 8.3), also because it is characterized by low velocities (figure 8.4).

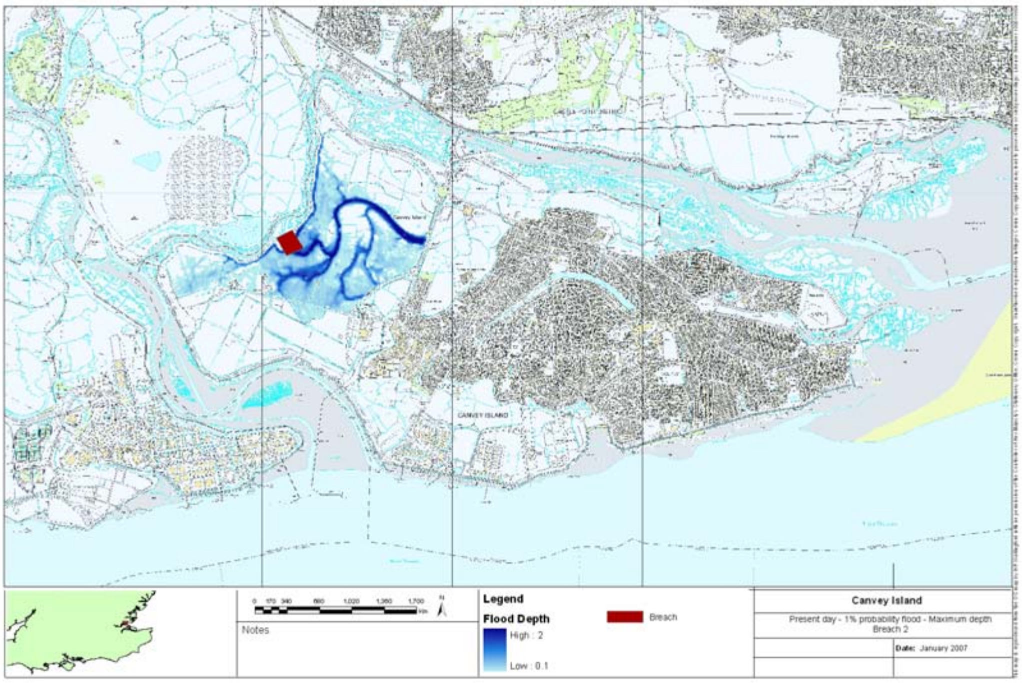


Figure 8.3: Second breach model, maximum depth

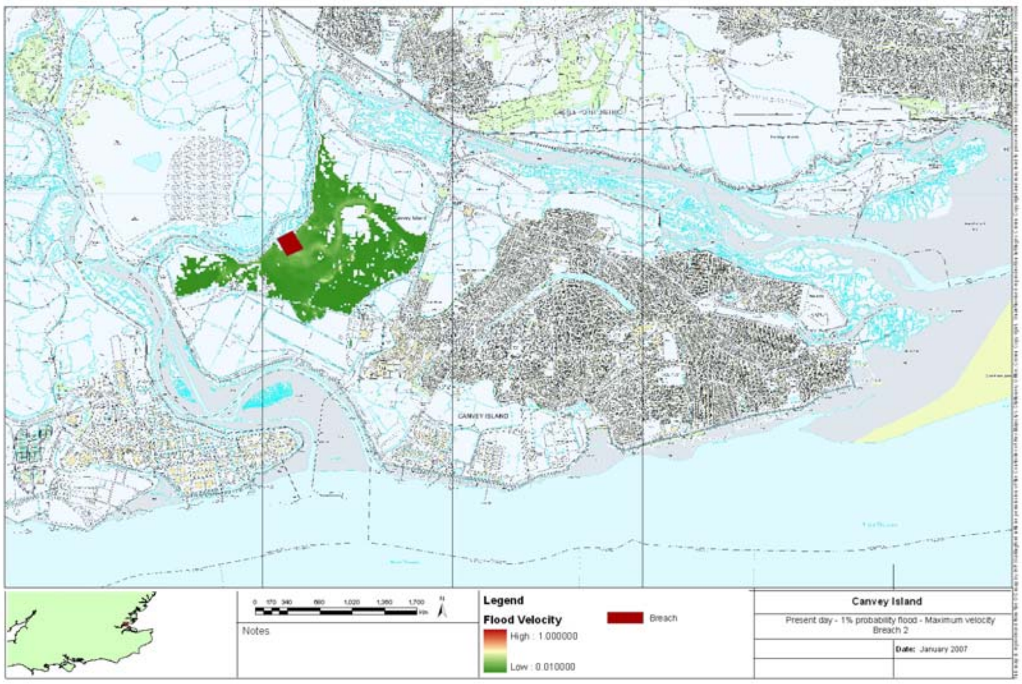


Figure 8.4: Second breach model, maximum velocity

The third model is really similar to the first, except for a lower water spreading (see figure8.5), probably due to the fact that the breach position forces the water flow to pass through the road that causes a sort of barrier to the flow path and slowing down it (see figure 8.6).

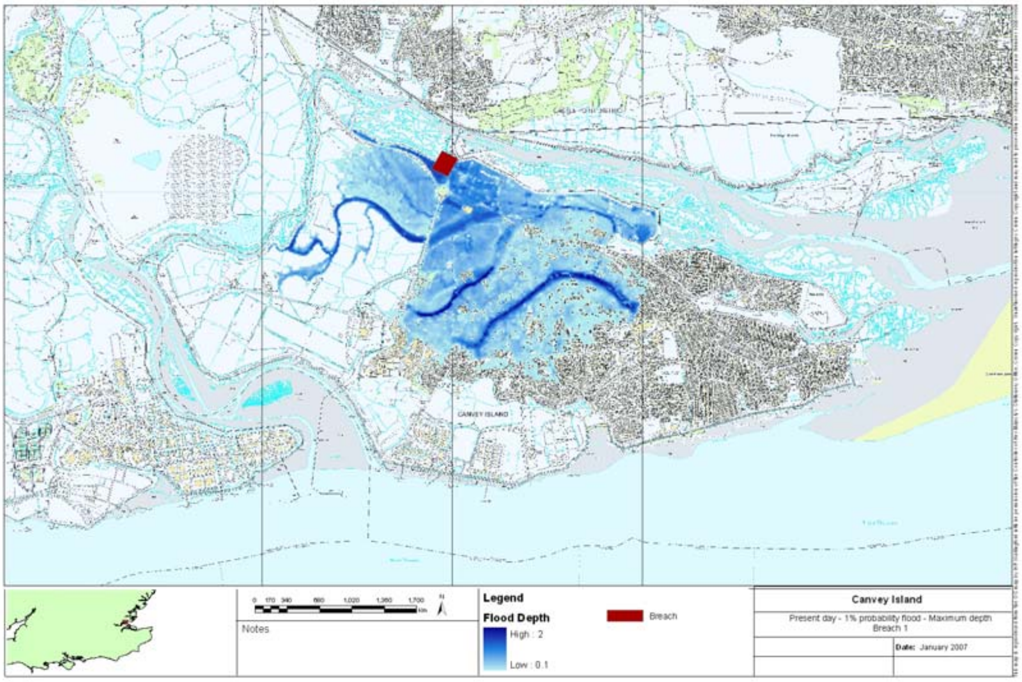


Figure 8.5: Third breach model, maximum depth

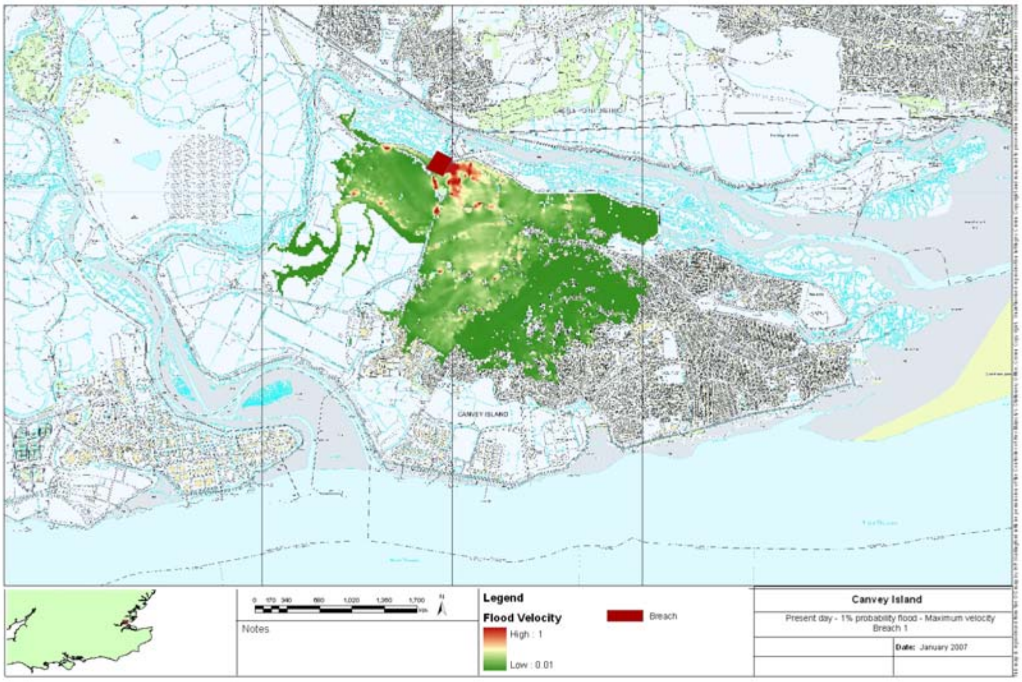


Figure 8.6: Third breach model, maximum velocity

The fourth breach scenario is considered really important, due to the high population density close to the breach position. In the model results, in fact it could be noticed that the flood spreading involves entirely the urban area downstream the breach (figure 8.7), and that is also characterized from high velocity (see figure 8.8). Furthermore, the inner flood go channelling in the existing small river, and make it floods, involving also the surrounding area.

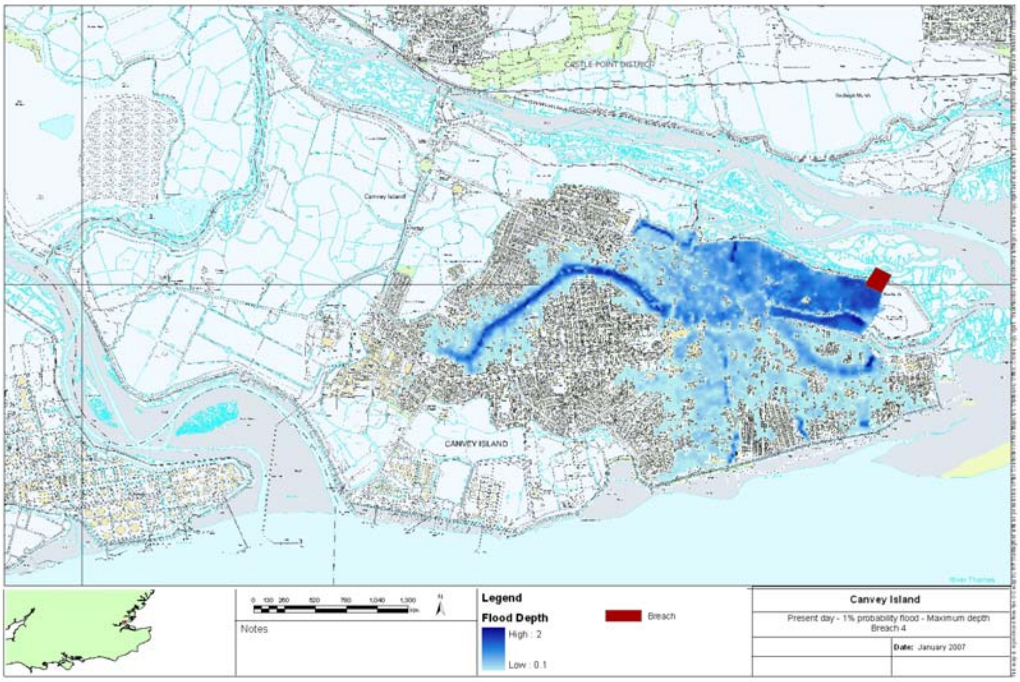


Figure 8.7: Fourth breach model, maximum depth

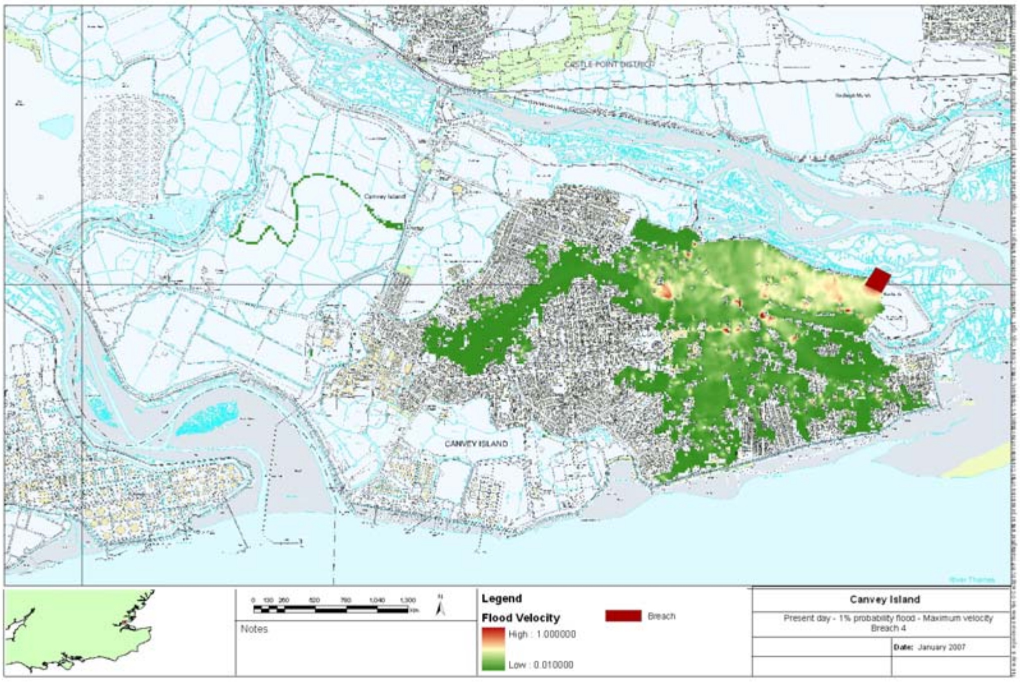


Figure 8.8: Fourth breach model, maximum velocity

# Chapter 9

# Historical analysis, modeling the past

## 9.1 Introduction

The River Thames tidal defences have provided protection against the increasing threat of tidal flooding from the North Sea for more than 2000 years. In the past, the Thames estuary has been interested in different floods that had caused injuries of hundreds of people. One of the worst flood that has interested the area in the last two centuries has been the 1953 flood. This disastrous flooding on the east coast and the Thames Estuary caused a toll of over 300 lives. If this flood had reached central London's highly populated low-lying areas, the result could have been horrifying beyond measure. This event has been therefore the catalyst for the construction of the current system of River Thames tidal defences, which includes the Thames Barrier, and has provided one of the best standards of flood defence in the UK for over 20 years. Just before this flooding, the previous one was in 1928 and interested the central London, where 14 people drowned. The consequences of the 193 floods has been deeply visible and taken into account to build the new system of defences, that has been set up in the '70s. For that, a physical model was build in these years, to study the breach mechanism and the flood spreading. Since then, no records of further modelling of this disastrous flood for Canvey Island has been found. For that, in this thesis a study has been developed to set up a model of this flood. This model could be a good case study for further risk-damage analysis, as the interesting one developed by I. Kelman [24]. In this thesis it has been used in order to validate the evacuation model (see the part III). Furthermore, the study has been a very interesting case study, from both the hydraulic and the social aspects. In fact, it happens very often that who study flood risk has never actually faced any real case of floods. Studying the documentation, both the technical and the non-technical ones, allows to have a picture of all of the aspects of a flood catastrophe, and it allows to experience what are the floods mechanism, the impact on the society, the authority reactions, the immediate interventions and which aspect to take into consideration for the future mitigation.

## 9.2 Collecting the historical data

### 9.2.1 Maps in the Oxford Bodleian Library

The undertaken work regarding the 1953 floods in Canvey Island has involved different fonts. The study has been developed in HR Wallingford Ltd, Oxfordshire. Due to the study location, one of the first font that has been taken in account has been the Bodleian Library in Oxford. The Library is the main research library of the University of Oxford, that has been founded in the VII century and has been developed continuously during the years. The Library contains one copy of each book printed in england since the 1610. The research in the library mainly involved the Map Room session in the Department of Special Collections and Western Manuscripts. In fact, thanks to this session, the maps of Canvey Island of 1939, 1961 and 1975 has been studied. This step of the analysis has been deeply important in order to build the digital model of the Island of 1953. In fact, starting from the modern Lidar available, the Island urban morphology history has been studied and updated, to bring the Digital Terrain Model back to the 1950. In this phase of the research, the main work has consisted in examine all the maps and tracks all of the changes that has been occurred between the 1953 and now. This job as been done manually and then the highlighted modification has been transferred in the digital map.

### 9.2.2 Newspaper collection

The newspaper collection has been definitely the most interesting and significant archive to be investigated. In fact, in order to find useful data that could help in reconstructing the event, the local newspaper articles have been examinated. That has allowed to find some useful information (mainly regarding the flood path and pictures) but the study of the population and the public force reaction on the tragedy has been really important. The Canvey Island population in 1953 was a low-middle class population, and the Island was characterized by a good sense of community. The most interesting aspect has been to collect the newspaper's pictures that help to have an idea of what a flood catastrophe means, specially when it happens in the middle of the nights and to a practically unaware population. Another interesting aspect that has been discovered, is that the Canvey Island event has been characterized by a great effort of the public force. While the firemen rang the alarm bell at 1a.m. (nearly half an hour before the first breach happened), both them and the local police started a door-by-door advising of the population, collected the ones left in the house and disseminated the warning. After the tragedy, then, the rescue operation continued for days by boats or by tracks. A deep look in the human aspect of the tragedy is a good point of view for the modeller, to take in account the main aspect of the events, that often look merely distant when one is used to look at that just through a model.

### 9.2.3 Television archives

The Essex Life in Archive Film ([51]) has been a very interesting font of data in the historical collection. Essex Life in Archive Film is a video streaming resource for the East of England using archive film from the East Anglian Film Archive and new video material produced by Essex schools. In this archive it is possible to find a movie of the immediate "day after" of the Canvey Island flood. The movie was recorded by Richard Pike of Southend, a keen film maker, that went out the next morning at daylight and filmed around Canvey Island. In the movie, people were still being searched for, and transport was taking survivors out of the Island. Apart from the interesting visual experience of the flood, the video gave an important trace to localize more precisely one of the main breach and its extension. In fact, the other reference found about the position ([3]) has been quite approximative, while the video clearly shown the breach picture that is easily localizable during a site visit.

### 9.2.4 Site visit and books

The site visits have been really interesting in order to both check the state of the actual defence, to reconstruct which were the preexistent defences (they are visible in some parts) and to have an idea of the type of the area that could have been in the past. From this point of view, a visit to the Canvey Island press office has been really interesting, because it has allowed to find two books that contain a lot of historical pictures and informations [6], [7]. For example, it had been possible to have the final confirmation that the small damn in the has been built in 1939, while in the 1939's map the dike is not already there. This fact had caused some doubts concerning the presence of the dike in the 1953, doubt that had been definitely clarified with the picture and the information in the book.

### 9.2.5 Metereological data and literature [3].

The tidal shape has been collected thanks to the Meteorological data archive in HR Wallingford Ltd. The peak of the 1953 flood has been found in literature, but the information of the agreeing newspaper and police report of that night has been decisive to set the final level and to positioning the peak in the time scale. In fact, both fonts agree that the peak level was reached at about 1.30 a.m. and was 4.6 meters. The main literature reference for this work has been certainly the paper in [3]. In fact, besides the digital data, this paper contains the observed information related to the incoming volume in the area of Canvey Island. This volume has been observed to be of $9510 acre/feet$. This data has been really useful to validate the data of the model.

## 9.3 Results

Some corrections have been made in the DTM starting from the historical data. This correction involves the defences and the road close to the roundabout, that it was not built in the 1953. Also here, both the overtopping and the presence of buildings have not been considered in this model due to the lack of data. The first factor is a negative factor in terms of severity of the flood, while the second one is a positive contribution. For that, lack of the two factors could be roughly considered as balancing in terms of the results of the model. Furthermore, in the case of the 1953 scenario, the literature reports that the total volume of overtopping in all of the Thames estuary had not reached the 25% of the total volume, and in the Canvey island the police reports state that the breach occurred when the tide was about half an hour to the maximum level. Then, the two breaches have been allocated in the most feasible positions, taking in account the collected data. The results shown a great flood spreading that involves almost all the surface of the island (figure 9.1). From the first analysis of the flooding map, the results seems partially overestimated, in therms of flood extension. In fact, in terms of depth, the results seem to be in accordance with the fonts. The flood spreading does reach a depth of three-four meters in the point closest to the breach, but the mean depth is about 0.8 and 1 meters. This is quite according the fonts and the pictures.

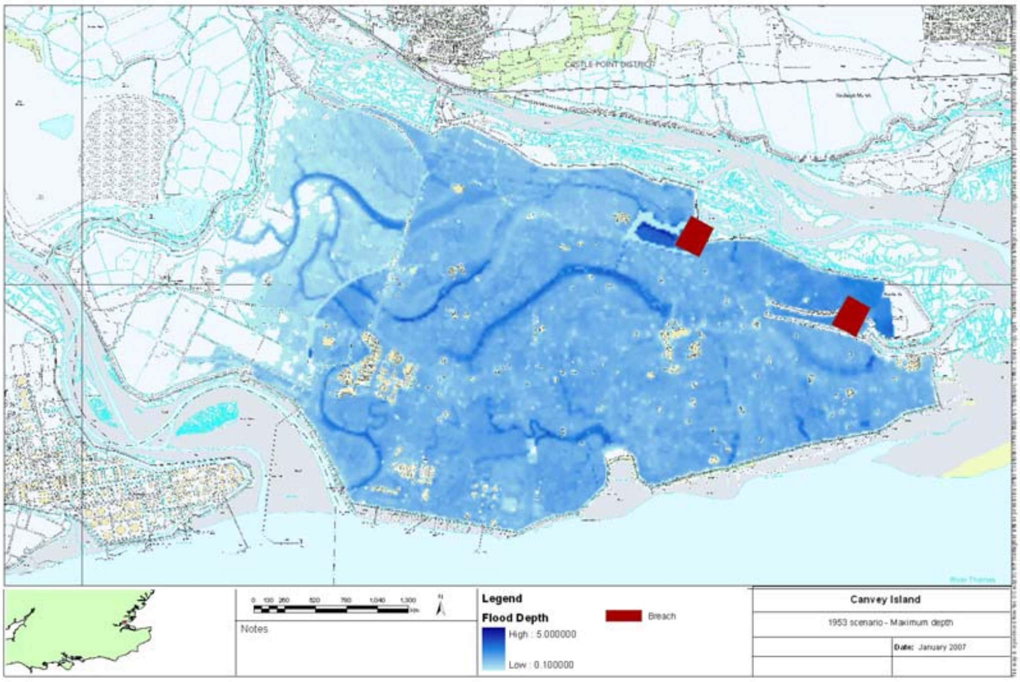


Figure 9.1: Canvey Island 1953 breach model, maximum depth

In terms of volume, the model slightly overestimate the inner volume, that is about $11200 acre/feet$, against the $9510 acre/feet$ in the observed data. The fact that the depth seems to be in concordance with the observation and the volume is overestimated could means that the velocity of the flood entrance could be properly estimated, and that means that the width of the breaches could be appropriate. The overestimation of the volume could be due to an imprecise tide shape reconstruction, that could have been characterized by a narrower peak than the one used here. Starting from this results, it could be possible to adjust the model's parameter to better fit the model with the observed data, and to have a clear picture of the development of the flood. An interesting information could be regarding the exact location of the destroyed buildings, information not available here. In fact this model reconstruct the velocity fields. Stating from that, it would be possible to have given an interesting benchmark for the vulnerability of the houses.

# Conclusions

The results of the hydrodynamic model are very important for a decision maker because it gives back different information in order to asses the scenario evaluation and the future actions. First of all, the flood maps clearly shown the areas that are more likely affected by the flood. Each inundation map, then, is related to a particular probability of the failure and a particular probability of the tidal level (0.01 in this case, 1:100 years). This add an interesting factor to the analyzed map, that is the probability of the occurrence of the scenario. If we analyze the map from the risk point of view, first of all we can observe where the flood is directed and the probability of the given event. Knowing that, it is possible to have an evaluation of the risk. In fact, the location of the flood and the velocity maps give back a picture of the receptors of the flood, that are the element a risk. Knowing the characteristics of the elements, that could be, for example, the age distribution of the population or the structural features of the building, the vulnerability of the area could be calculated. Starting from that, the picture of the risk of the area related to the specified scenario is completed. The analysis of the 1953 flood is a really interesting real-case analysis, first of all because it allows to see the evolution of a flood before and after the event, by means of the historical analysis, and it is a great exercise for a modeller, because it allows to face the reality of the scenario that have been always experienced only through the model itself. Furthermore, analyzing the development of the flood from a hydraulic point of view, it is possible to link the consequences to the effective flood spread. Besides, knowing the floods observations, it is possible to calibrate the model and take the better expedient to better reconstruct the scenarios in future models.

# Part III

# Modelling Evacuation scenarios

# Introduction

Evacuation is a response to the immediate or forecast threat of flooding that is expected to pose a risk to life, health or well-being. It involves people moving from their houses or places of business to 'safe' locations, out of the flood risk area where they are able to shelter until it is possible and appropriate for them to return. In this part, the study finalized to the analysis, the set up and the application of an evacuation model are presented. The background analysis, the normative picture and the literature models are presented, while for the chosen model, the data requirement, the model set up and the results of the pilot application itself are analyzed, in order to give a full picture of this strongly complicated issue for a modeler and a decision maker.

# Chapter 10

# Analysis of the evacuation actions

## Introduction

Evacuation is a process by which people are moved from a place where there is immediate or anticipated danger to a place of safety, offered temporary welfare facilities and enabled to return to their normal activities, or to make suitable alternative arrangements, when the threat to their safety has gone. The emergency services and other public service organizations have key roles to play in ensuring that an evacuation is effective, safe, and comfortable for the people involved, and that they are given appropriate support to cope with any short-term or long-term impacts which may arise (font Global Energy Network Institute (GENI) [53]).

Table 10.1 describes the variables that may impact evacuation planning:

| Variable | Impact on Evacuation Process & Methods |
|---|---|
| Size | • An evacuation can involve anything from one person up to hundreds, and in extreme cases, thousands.<br>• The level and type of response will vary according to the number of people and size of area evacuated. |
| Location | • In urban areas, the density of occupation will mean that evacuation of a given area is likely to involve many more people than an equivalent rural area.<br>• Urban areas are also likely to suffer from increased congestion and traffic management planning will be a greater concern.<br>• Some areas may have good, safe access routes that are not at risk of flooding, whilst others may quickly become cut off, requiring evacuation by air rather than road. |
| Property type | • Evacuation can be required of any type of property that is at risk of flooding, including commercial and industrial premises, entertainment venues, parks and open spaces and domestic property.<br>• Evacuation planning tends to concentrate on domestic properties, but emergency and other services, plus commercial premises occupiers, owners of public spaces and event organisers all require appropriate flood event evacuation plans. |
| Timescale | • Evacuations can be required on a variety of timescales:<br>• Immediate evacuation in response to an imminent or existing threat of flooding. This tends to occur on flash flood catchments and little or no preplanning is possible. Evacuation certainty is, however, high.<br>• Evacuation required shortly – probably within hours - either in response to an imminent threat of flooding or as a precaution against escalation of the current flood risk. This may occur for rapid response catchments where lead times are short. Some basic planning is possible, e.g. obtaining transport and arranging for Rest Centres to be opened. Evacuation certainty is high.<br>• Evacuation is required but not for several days. Detailed planning is possible, however the certainty that evacuation will definitely be required is lower. In such situations, some people may start to self-evacuate. There is unlikely to be pre-planning for providing services to self-evacuees, but rapid consideration would have to be given as to whether the situation warranted a full, planned evacuation. |
| Duration | • Evacuations can last for several hours or several days, depending on the catchment type.<br>• For flash flood and rapid response catchments, the immediate risk of flooding may pass quickly, but buildings and the infrastructure of an area may be so damaged that evacuees are unable to return until initial clearing-up and repair (or possibly re-build either on the original site or elsewhere) has taken place.<br>• For slow response catchments (such as the River Thames), high flood levels may last for many days, or even weeks. This situation will cause significant deterioration in the fabric of properties and they may become uninhabitable. |

Figure 10.1: Impacts of the different environmental factors on Evacuation Process and Methods

## Structure of an evacuation response

In considering the relationship between a flood event and an associated evacuation, three observations can be made:

- The evacuation is not a stand-alone incident. The nature and effects of the flood will define the parameters of the evacuation;
- The evacuation is not just a sub-set of the response to the flood. Most of the evacuation activities will proceed independently of the direct response to managing the flood risk;
- The evacuation is not a single, unified activity. It is made up of many individual activities and groups of activities, undertaken by a wide range of organizations.

The following 10.2 sets out a model for the structure of an evacuation. This represents the main division of functions and key relationships, however within each functional group there may be further breakdowns possible, with each sub-unit also requiring specific management and co-ordination requirements.

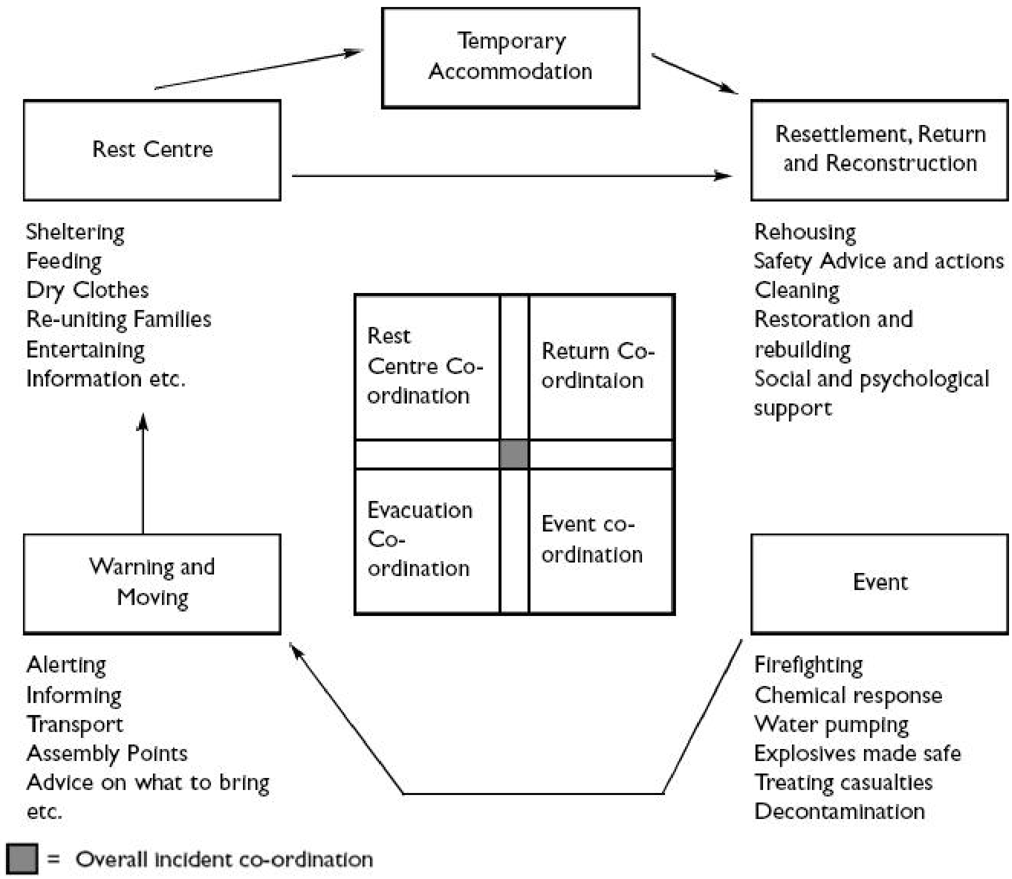


Figure 10.2: Structure of an evacuation

An evacuation situation divides into four functional areas:

1. The event
2. Warning and moving
3. Rest centers.
4. Resettlement, return and reconstruction.

**The event** The objective of the core response to the flood event would be to bring the emergency situation to a safe conclusion as quickly as possible. If responders consider that evacuation is necessary, their primary concern would be that people are moved from the danger zone. However, the flood event does define the parameters of the evacuation - what the limits of the danger zone are, who should be evacuated, for how long, and what problems are likely to be encountered by people returning after the evacuation.

**Warning and moving** The process of moving people out of a dangerous, or potentially dangerous, area to a place of safety is a complex and difficult one. It involves warning and informing people, identifying safe areas and providing some help for people to reach the safe areas. Often all this must be done at very short notice and in adverse conditions.

**Rest centers** Rest Centers provide short-term shelter and other facilities for those evacuated. In them, evacuees would have access to appropriate physical necessities and welfare facilities and receive information on what was happening in the evacuation zone.

**Resettlement, return and reconstruction** Evacuation may include those whose homes are potentially at risk rather than under imminent or existing threat. Such properties may never become flooded and as a result, many people may be able to return within hours. However, in some situations the evacuation may last overnight or for a few days, in which case it would be helpful to find evacuees more comfortable temporary accommodation than the Rest Center. For some people, the evacuation may be long-term or even permanent. This may be because the physical damage is too great to be repaired, because the fabric of the property requires significant rehabilitation, or because they are unwilling to live with an ongoing risk.

Where a flood event has caused damage or loss of life, an area may need to be made safe before people return. On their return, evacuees may need to clean and repair their properties. Essential services such as electricity may be disrupted. The evacuation and the flood event which caused it may have increased stress levels in the community, resulting in health and social problems.

## The event

Evacuations should not be undertaken lightly, as they are difficult to organise and carry through effectively. Organisations responding to an event should consider whether the considerable material and social costs of evacuation are justified by the level of risk.

Evacuation can result in considerable stress to evacuees, loss of business, disruption to personal and work routines and a risk of accidents occurring during the process. These factors should be taken into account in deciding whether and when to evacuate.

In some situations, it may be advised that only a certain part of the population should be evacuated. For example, a fit person in a two-storey property may be able to sit out a short-term flood, while the young and old, and occupiers of single-story properties, would be recommended to evacuate for their own comfort and safety.

Factors which will influence the decision on whether or not to evacuate include:

1. Whether buildings would provide protection for the period the hazard is expected to last

2. Whether the evacuation can be carried out without exposing people to more danger than if they had stayed indoors

   The risk has to be assessed of the event reaching a critical stage, or escalating, while people are in the open and most exposed to danger. Evacuation can itself be a hazardous process. With many people moving at once, there is a danger of crushing or traffic accidents . The old, the young and the infirm may be adversely affected by having to move.

3. Whether the evacuation can be carried out without exposing responding staff to an unacceptable degree of danger

   Each organisation has a statutory responsibility for the health and safety of its staff. This requires them to assess the risks faced by their staff and to take all possible steps to mitigate them. This may involve ensuring that staff are provided with appropriate protective clothing or deciding that an area poses too great a threat to allow staff to enter.

4. Whether a situation currently not requiring evacuation has potential to reach a point where evacuation would be necessary

   Foresight permits forward planning, and thus facilitates an effective and safe evacuation. A precautionary evacuation may be considered desirable in order to protect people from escalation of the incident.

5. If precautionary evacuation is considered, whether the economic and social cost is justified by circumstances

   Evacuation disrupts people's lives, shuts down businesses and interrupts the delivery of essential services. Moving and accommodating the evacuees is expensive, often to the detriment of budgets for everyday services. If time is available to plan an evacuation, opportunities for minimising the costs should be explored. For example, where the date of the evacuation can be set, a weekend is likely to cause less disruption to business and working lives, but more to personal and family lives.

## Warning and moving

Once a decision has been taken that evacuation is necessary, consideration has to be given as to how it will be accomplished. Issues to be addressed include:

- When, where and how to evacuate;
- How the instruction to evacuate can be communicated effectively within the time-frame available. What instructions need to be given in order for people to respond effectively;
- How people will be enabled to carry out the instruction to evacuate, especially those without their own transport or those with restricted mobility;
- What special arrangements need to be made for the welfare of evacuees, particularly those with special needs, and of staff in responding organisations;

- What arrangements, if any, could be made to record who has evacuated, where they have gone to and how they can be contacted during the evacuation.

## Deciding how to evacuate

Once a decision has been taken to evacuate, further decisions will have to be taken as to how the process will be carried out. This decisions concern the activities to put decisions into effect that would be:

- Identify the exact geographical area to be evacuated, estimate the population size and composition in the area, and/or identify buildings such as hospitals and schools likely be occupied by people with particular needs;
- Alert people to the need to evacuate, being specific about the streets or areas to be involved. Postcodes can be useful as a means of identifying an area with accuracy;
- Inform people of when and how they should evacuate and what personal arrangements they need to make, such as bringing medicines with them and what to do with pets / livestock;
- Inform people of any Assembly Points or Rest Centers which have been established. If more than one Rest Center has been established, people should be told a specific Center to attend (egg on a geographical basis) to ensure that roughly equal numbers arrive at each;
- Ensure that as far as possible in the time available, these messages can be received and understood by people with special communication needs;
- Arrange the provision of transport, if required, especially for those with mobility difficulties;
- Where appropriate, provide evacuation staff to the area to help people, answer queries, give directions, keep traffic moving, and as far as possible ensure that the whole area has been evacuated.

Clearly, the organisation taking the lead in managing the movement of people is unlikely to have all the resources necessary to carry out all these activities, and will need input from a range of organisations. In those situations where people self-evacuate without being advised to do so, the decision would have to be taken as to whether they were justified in doing so and whether the flood event merits a formal evacuation. Since it takes a very strong sense of danger to persuade people to leave their homes, businesses or entertainment, it is unlikely that most self-evacuees could be persuaded to return in the short term, even if an objective risk assessment indicated that evacuation was unnecessary. Arrangements should therefore be made to provide for their immediate needs.

## When and were to move

The decision on when and where to evacuate will largely depend on the nature of the flood event. Wherever possible, the aim should be to evacuate before the hazard becomes critical, so that evacuees and staff of responding organisations are not put at risk. However, this strategy carries with it the risk that the evacuation will prove to have been unnecessary. The organisation making the decision to evacuate should weigh up the respective costs of evacuating or waiting to see how the situation develops. However, the costs, and legal implications of failure to take an opportunity for safe evacuation should not be under-estimated.

Where people should be evacuated from and to will be determined by the likely spread of the flood. In order to avoid having to expand the evacuation zone and possibly having to re-evacuate some people, allowance should be made for the event to escalate. In particular, Assembly Points and Rest Centers should be chosen to be accessible from the evacuated area, but not likely to be overtaken by an escalating event.

## Lesson learnt

The management of natural risks is a public task for which governments at all levels hold a certain amount of responsibility. The management of risk involves a wide range of actions and activities that fall within one of the following four activities:

- Prevention;
- Preparation;
- Response;
- Recovery.

Evacuation management is an activity that forms part of the response to a flood emergency. As such it is one of the many options decision makers have available for dealing with floods. Other possible options could be the construction of structural measures such as emergency barriers or flood storage areas and non-structural measures such as the implementation of flood forecasting schemes. Figure 10.3 shows how emergency management fits into the disaster cycle.

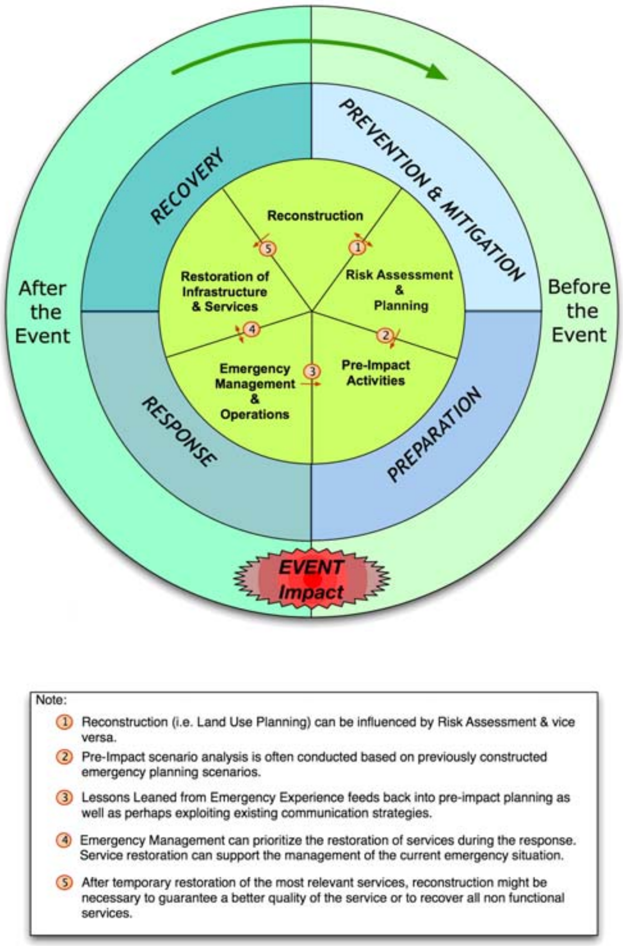


Figure 10.3: The disaster cycle

The response of authorities toward emergencies is often cyclical. This means that this year's disasters are next year's preparation. Organizations like governments and civil protection authorities expand their experience and knowledge about their activities each time a disaster occurs. In this way the organizations learn from previous experiences in disasters and strive toward improving their knowledge and skills in order to be better prepared for the next disaster. It is therefore important that the documentation of these lesson learnt plays a large role in defining user requirements. For that, in the evacuation management, is really important to follow the procedure identified in the years. Analyzing the literature, it could be possible summarize these policies in eight main stages that can be identified in evacuation planning. These stages are detailed below.

1. Organizing the planning
   Before the actual start of the planning takes place it is important to recognize who should be involved in the planning process.

   Research has demonstrated a huge added value of involving appropriate stakeholders since they bring with them an amount of experience and knowledge that might be useful for planning an organization.

2. Designing the plan
   In this stage the actual emergency plan is designed. The previous stage should have provided a clear idea of the responsibilities of different actors in the process.

3. Pre-flood preparedness
   This will determine the level of flood awareness and is likely to influence whether people receive official (or unofficial) warnings and how they act on them. People who have had previous experience of flooding may extend or reduce the time between warning and evacuation, depending on the level of the previous flood and their understanding of the warning codes.

4. Flood emergency stage
   In this stage, some subprocedure could be identified:

   **a** Recognition of critical situation
   The physical parameters of the flood define the emergency, and the official recognition of an emergency defines the response. The depth of water and velocity of the flow are just two of the factors upon which a decision about the seriousness of a flood and evacuation may be made, whether by an official or by the individual householder.

**b** Assessment of evacuation options

Given a certain flood forecast and the estimation of the likely flood extent the availability of the various escape routes can be assessed. On this basis an assessment of evacuation options will be carried out. The results of this assessment form the basis for the decision to evacuate and for any of the actions to be taken in the rest of the process.

**c** Decision to act upon critical situation

The development of the source of risk (e.g., floodwater depths and velocities) needs to be monitored. After recognizing a critical situation and its potential development over time, the decision is taken to evacuate.

5. Evacuation (leaving home)
   Whether or not people evacuate in a structured manner (i.e., on recommended routes, using recommended transport modes, to recommended shelter zone) will depend on whether an official evacuation recommendation is given, and how much guidance is provided to assist evacuees in their decision-making.

6. Emergency shelter
   The official response at the scene will direct those affected toward the official rest centers or reception centers that have been set up by teams coordinating response. Clearly this necessitates good liaison and communication between all those involved, but in particular between the official responders and those coordinating that response across different local authority departments. For some, emergency response terminates when householders reach the rest center, whereas for many the disaster may only just have become apparent at this stage. Communication and coordination between those involved in the response and the public is paramount at the rest center.

# Chapter 11

# Studying the local policies: normative for the evacuation in the UK

## 11.1 Legislative background

This section covers the legislative background that is relevant to flood event management in the UK. In this work, the United Kingdom has been taken as site in which to plot the study, due to the fact that this research itself has been developed in collaboration of HR Wallingford Ltd, Oxfordshire, United Kingdom, beneath the FLOODsite project [52]. The main piece of legislation is the Civil Contingencies Act. This legislation and accompanying non-statutory measures give us a single framework for civil protection in the UK. This objective of the Civil Contingencies Act is to improve the UK's ability to deal with the consequences of major disruptive incidents by improving the planning process at a local level, building better contacts between agencies and improving the link between local areas and central government.

### 11.1.1 Civil Contingencies Act (CCA)

The Civil Contingencies Act (CCA) and accompanying non-legislative measures and Regulations deliver a single integrated framework for civil protection. The Act applies to the whole of the UK, including devolved administrations. "Emergency" is defined under the Act as "an event or situation which threatens serious damage to human welfare in a place in the UK, the environment of a place in the UK, or war or terrorism which threatens serious damage to the security of the UK." Part 1 of the Act establishes a new statutory framework for civil protection at the local level. Part 2 repeals existing emergency powers legislation and allows the development of special temporary legislation aimed at providing the powers required to deal with a serious emergency. The Act provides a basic framework defining what tasks should be performed during an emergency, and how co-operation should be conducted. Working to a common framework, local responders are required to make their own decisions in the light of local circumstances and priorities about what planning arrangements are appropriate in their area. The CCA recommends an Integrated Emergency Management (IEM) procedure that comprises six related activities:

- Anticipation;
- Assessment;
- Prevention;
- Preparation;
- Response;
- Recovery.

Responders are categorised into two categories. Category 1 (core) responders are those organisations at the core of emergency response:

- Emergency Services (police, fire, ambulance, maritime and coastguard agency);
- Local authorities (all principal, port health authorities);
- Health bodies;
- Government agencies (Environment Agency, Scottish Environment Protection Agency (SEPA)).

Category 1 responders are subject to the full set of civil protection duties, as follows:

1. Risk assessment;
2. Business continuity management (BCM);
3. Emergency planning;

4. Maintaining public awareness and arrangements to warn, inform and advise the public.
   A fifth duty applies to local authorities alone:

5. Provision of advice and assistance to the commercial sector and voluntary organisations.

Category 2 responders are "co-operating" bodies who, while less likely to be involved in the heart of planning work, will be heavily involved in incidents that affect their sector. They include:

- Utilities (electricity, gas, water, sewerage, telephone);
- Transport (rail, underground, airport, harbour, highways);
- Strategic health authorities;
- Government agencies (e.g. Health and Safety Executive).

Two duties that are prescribed for all responders include:

1. Co-operation;
2. Information sharing.

Part 2 of the Act was brought into force on 10 December 2004. The bulk of the duties in Part 1 of the Act will came into force on 14 November 2005, with the duty on local authorities to give business continuity advice coming into force on 15 May 2006.

**Risk Assessment** Risk assessment is the first step in the emergency planning and business continuity processes. It ensures that Category 1 responders make plans that are sound and proportionate to risks. The Act places a duty on all Category 1 responders to carry out risk assessment. Multi-agency co-operation in maintaining a community risk register is also a statutory duty.

**Business Continuity Management** The Act requires Category 1 responders to maintain plans to ensure that they can continue to exercise their functions in the event of an emergency so far as is reasonably practicable. The duty relates to all functions, not just their emergency response functions. The plans must be risk-based and generic and/or specific, as appropriate. There must be a clear procedure for invoking the Business Continuity Management (BCM) plan, which should be based on the Business Continuity Institute's five stage cycle:

1. Understanding the business;
2. BCM strategies available;
3. Developing the response;
4. Establishing the continuity culture;
5. Exercising and plan maintenance.

**Emergency planning** The Act requires Category 1 responders to maintain plans for preventing emergencies, reducing, controlling or mitigating the effects of emergencies, and taking other action in the event of emergencies. The Regulations require plans to contain a procedure for determining whether an emergency has occurred; provision for training key staff; and provision for exercising the plan to ensure it is effective, procedures to ensure the plan is reviewed periodically. Plans may be generic and/or specific, and can be multi-agency. Category 2 responders should also be involved in the process.

**Communicating with the public** The Act includes public awareness and warning, and informing as two distinct legal duties for Category 1 responders. Arrangements must have regard to emergency planning arrangements, and be risk-based. They are required to maintain arrangements to warn the public if an emergency is likely to occur or has occurred. In addition, they must have arrangements to provide information and advice to the public if an emergency is likely to occur or has occurred. The Act does not place a duty on Category 1 responders to warn, only to maintain arrangements to warn. To avoid duplication, the Regulations require Category 1 responders to co-operate for the purpose of identifying which organisation will take lead responsibility for maintaining arrangements to warn in regard to the particular emergency.

The lead responder for warning, informing and advising the public must:

- Be able to contact other Category 1 responders whose functions are exercisable in relation to that emergency;
- Inform those Category 1 responders of the actions it is taking;
- Be able to collaborate with those Category 1 responders in warning, informing and advising the public.

**Advice and assistance to business and voluntary organisations** The Act requires local authorities to provide advice and assistance to those undertaking commercial activities and to voluntary organisations in relation to business continuity management in the event of emergencies.

**Co-operation** Local co-operation.
Category 1 and 2 responders are obliged to co-operate with other each other and other organisations engaged in response in the same local resilience area. The principal mechanism for multi-agency co-operation between Category 1 responders is the Local Resilience Forum (LRF). Each Local Resilience Forum (with the exception of London) is based on a police area. This is not a statutory body, but it is a statutory process. Its overall purpose is to ensure that there is an appropriate level of preparedness to enable an effective multi-agency response to emergencies which may have a significant impact on the local communities. The Local Resilience Forum is required to meet at least once every six months. The LRF process should deliver:

- The compilation of agreed risk profiles for the area, through a Community Risk Register;
- A systematic, planned and co-ordinated approach to encourage Category 1 responders, according to their functions, to address all aspects of policy in relation to:
  - risk;
  - planning for emergencies;
  - planning for business continuity management;
  - publishing information about risk assessments and plans;
  - arrangements to warn and inform the public; and
  - other aspects of the civil protection duty, including the promotion of business continuity management by local authorities; and
  - Support for the preparation by all or some of its members of multi-agency plans and other documents, including protocols and agreements and the co-ordination of multi-agency exercises and other training events.

Regional Working.
Cooperation at regional level involves the representation of Category 1 and 2 responders and central government bodies working together to address larger-scale civil protection issues. The Regional Resilience Forum is the main forum

for multi-agency cooperation. Each region must produce a generic emergency response plan with the following objectives:

- Improving co-ordination across the region and between regions (mapping of resilience, gap identification, multi-agency preparedness facilitation);
- Improving co-ordination between the center and the region (facilitating information transfer on threat assessment and risk management, capability planning, best practice);
- Improving co-ordination between the region and the local response capability (facilitating information transfer, as above);
- Supporting planning for a response capability (e.g. personnel, equipment etc).

**Information Sharing** The process of information sharing is crucial to all civil protection work including sound risk assessment, business continuity management, emergency planning. It allows responders to make the correct judgments, right decisions about how to plan and what to plan for.

# Chapter 12

# Evacuation modelling

## 12.1 Introduction

The modelling of the evacuation process generated by an approaching flood is important for those responsible for the efficient and safe movement of people during evacuation. It can identify bottlenecks in the system before they are experienced in an evacuation, it can be used to determine the impact of road closures due to flooding, the impact of phased evacuation on traffic loading, and many other possible consequences of an evacuation event. Being able to model alternative evacuation scenarios can lead to the establishment of appropriate evacuation policies, strategies, and contingency plans and can help facilitate communication and information transfer.

Preparation for emergency action must be taken before the crisis. Some of the reasons for early preparation are that the conditions within a disaster-affected region tend to be chaotic. Communication is difficult and command structures can break down because of logistical or communications failure. Human behaviour during the emergency is hard to control and predict. There is an obvious need for improving (a) our understanding of the social side of emergency management processes; (b) our understanding of human behaviour during the emergency; (c) the communication between the population affected by the disaster and emergency management authorities; and (d) preparedness through simulation, or investigation of "what-if " scenarios.

## 12.2 A review of the existing model in literature

### 12.2.1 Comparison of Alternative Trip Generation Models for Hurricane Evacuation. Wilmot, C and Mei, B; Natural Hazards Review, ASCE, November 2004 [48].

Estimation of evacuation demand is the first step in the modelling of the evacuation process and yet it is the part of the evacuation modelling process that has received the least attention in the past. Existing evacuation models are typically computerized software packages in which the major emphasis is on traffic assignment. In most of these evacuation models, traffic assignment is conducted using simulation. A recent addition to the evacuation modelling packages is the Oak Ridge Evacuation Modelling System which can be used to model evacuation from a variety of disasters. Input to the model is time-dependent travel demand with or without specification of the destination of the demand. When origin-destination information is not provided, the model uses a combined distribution-assignment procedure to distribute traffic to destinations. Macro-simulation, based on the TRAF family of models, developed over several years for the Federal Highway Administration to ultimately produce CORFLO, was adapted for use in this model to simulate travel on the network. The model estimates link flows, speed, and percent evacuated at each time period as well as the total evacuation time. However, time-dependent travel demand must be provided as input. A model package that does estimate evacuation demand, although it does not estimate it by time period, is the evacuation traffic information system (ETIS). The review of the results regarding the accuracy of the model has suggested that logistic regression and artificial neural network models estimate evacuation demand more accurately than conventional participation rate models.

### 12.2.2 Computer-based model for flood evacuation emergency planning, Slobodan, P, Simonovic, Ahmad, S. Natural Hazards, 2005 [41].

The model presented in the paper presents a computer-based model that simulates the evacuation process (movement of people from the region under the threat to safety) during flood emergency including the mental decision process that leads toward evacuation decisions at a family level. The dynamic interactions among model components are captured using a feedback based modelling approach called system dynamics. The main purpose of the model is to allow for the different policy options available to flood emergency managers to be evaluated before the emergency situation occurs. In this study the different policy choices related to the evacuation warning dissemination in particular are investigated using the model. Data collected after the flood of 1997 in the Red River Basin are used to demonstrate the utility of the model. The human decision making process for evacuation, in response to disaster warning, is divided into four psychological phases (a) concern; (b) danger recognition; (c) acceptance and (d) evacuation decision. This model takes in account mainly the psychological aspect of the evacuation.

### 12.2.3 Micro Model Simulation Tools for Performance-based design of a flood risk management system, Hori, T and Shiba M. Journal of Natural Disaster Science [21].

The model developed in the paper here cited include two simulation models of people's reactions to flood disasters. One is a micro simulation model of flood evacuation, the other an object-oriented simulation model of communication processes during a flood hazard. The micro simulation model of flood evacuation is based on parameterization of people's attitudes toward flood risks and the recognition of danger during flooding. The relationships among information issued, changing conditions during flooding, and people's actions are expressed by fuzzy inference rules. The parameterization and fuzzy rule expressions of these mental factors enable simulation of those cases in which people follow or neglect the information provided by authorities. This model focus on the behavioural aspects, relating them to the floods characteristics.

## 12.3 The model in use: British Columbia Life Safety Model [22]

### 12.3.1 Model description

Operators of dams or other major flow control structures need to assess the risk that these systems can pose to downstream communities, particularly from a major breach failure, although this can apply to any high flow event. Traditional simplistic and empirical methods that have been used to determine loss of life from such catastrophes have tended to over-predict the fatalities. It was considered that the variability and site-specific nature of each flood event was not well represented in these simple techniques, and that a "phenomenological" approach should be developed, that better simulates the physical interactions of people, vehicles and buildings in a major flood event. Although the Life Safety Model (LSM) requires a significant amount of input of time and resources to set up the model for any flood catchment, it does provide a far more transparent and defensible set of predictions, which incorporate a wider range of variables influencing loss of life than traditional "black box" approaches.

For a given population at risk, LSM:

- Estimates the potential loss of life due to an extreme flood event;
- Produces a spectrum of virtual representations of how a flood emergency could evolve;
- Support emergency analysis activities which aim to support the development of mitigation strategies that could reduce the potential loss of life.

### 12.3.2 Overview of the LSM system

Figure 12.1 shows the main conceptual components of the LSM. As it will be explaned in chapter 13, the model reproduces the "real world" dividing it in "objects", that are the People At Risk Units (PARU), the People At Risk Group (PARG), the Vehicles and the Buildings. All of the object could be affected by the flood. (see figure 12.2

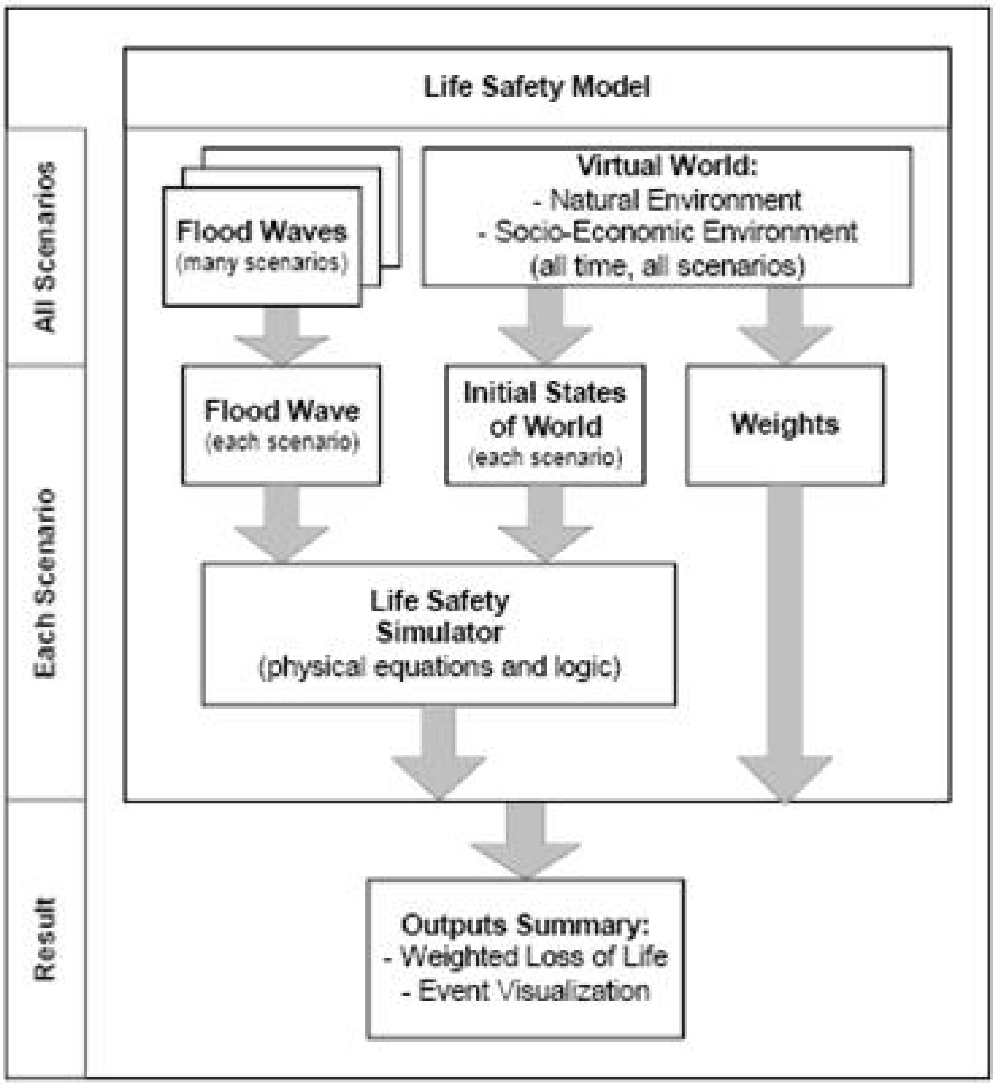


Figure 12.1: British Columbia Life Safety Model: the conceptual scheme

Each object can have a set of properties that describes its normal location/condition during a week, such as travel times, school/work hours, and weekend activities. Other time-varying properties would include the ability of the object to withstand the effect of the flood wave, and how it would react to the approaching wave, with and without a formal evacuation warning. The Simulator uses a generalised event logic to determine the location of each object, whether it is aware of the flood wave, whether it is trying to find a safe haven, what happens if it encounters the flood (as dictated by the Object Damage and Loss Function - ODLF), and whether the object survives or not. The ODLF specifies the ability of an object to resist the impact from the flood wave, in terms of depth and velocity, and how these can change during an event. So there can be instantaneous loss when an individual encounters fast-flowing water, or a group who have sought safety in a building can suffer cumulative loss if they are exposed to the flood water for a significant time (as a result of hunger or cold).


Figure 12.2: Schematization of the objects included in the model: People At Risk (PARU), the People At Risk Group (PARG), the Vehicles and the Buildings

The Life Safety Modelling system provides the computation of evacuation scenarios due to an extreme flooding event, such as a dam breach. It is composed by three tools: LSME, LSM2D and Read Kenue tools:

- The LSME (Life Safety Model Environment) tool attend to data files arrangement for each user defined time periods and provides the computation of weighted loss of life (LOL).

- The LSM2D (Life Safety Model 2D) tool is properly the modelling tool, which provides the computation of LOL, position in time of the evacuating people, building and vehicles destruction.

- The Red Kenue tool attends to the graphic visualization of LSM2D results, providing the time variation, graphics and animations.

Four main types of outputs are produced by LSM:

- Weighted loss of life estimate;

- Descriptive event statistics;

- Detailed event histories and time series;

- Visualizations.

Together with the Red Kenue software, this provides comprehensive outputs for analysing the whole flood event, making use of static GIS maps, or visualization of the wave progress and when and where the fatalities took place.

# Chapter 13

# Performing and testing the British Columbia Life Safety Model

As stated before, in order to assess an evacuation model, a deep knowledge of the examinated area must be developed. In the present work, the pilot sites that have been involved in the analysis are the same for which the tidal and the hydrodynamic models have been developed.

### 13.0.3 LSME input Data

The Life safety model is a really detailed model, that allows to recreate the environment of the studied area with great details. This could be useful in terms of detailed analysis, but requires a great data processing behind, that has implied to code a series of sub programs to process the building and the population data. Furthermore, the data processing implies to have a good skills in programming with GIS interfaces and with the digital mapping. In fact, Life safety model is a particularly complicated model, mainly characterized by a "data hanger" that requires to analyze data coming from different fonts. In fact, all of the social texture of the area must be introduced in the model in order to asses the people world details, as the age, the physical condition and to describe the family situations. The characteristics of the buildings, then, must be analyzed in order to introduce to the model the building resilience in case of flood. Finally, the flood itself needs to be add to the model, to assess the hydrodynamic scenario that is linked with the movement of people and the state of the buildings. The data used here are the Census data coming from Office of the Deputy Prime Minister and the Properties data, provided by the cadastre.

### Properties data

The properties data give back a quite clear picture of the usage of each flat, but not allow us to understand the construction characteristics of the structures, in order to predict the resilience itself to the incoming flood. For that, the better way to set up the model is certainly to perform a deep analysis of the recent history of the area, and to verify the data collected by means of site visits. The site visit, together with the historical analysis, is necessary to set up the buildings' parameters. Those parameters are needed to state whether the building is standing or which is its resilience to the flood. In fact, the building is considered to be destroyed if the parameter is below a certain threshold. This parameter depends on the type and the age of the building. Furthermore, the building parameter decreases with a velocity/time relationship, that means that the building is getting more vulnerable if it has to withstand a continuous flood.

Another programming work has been done in this thesis in order to give back some tools to set up the properties data. In fact, the properties has been grouped per building (recognising the properties belonging to the same building by means of a tool that cluster the properties basing on the coordinates and assigning that to the relative building), and for each building the number of apartments has been computed, detecting and counting the building usage in the same building. This is important to distribute the population to the different buildings, that will be the "‘starting points"’ for the evacuation simulation. The program accepts as input fixed types of properties. For that, it has been important to cluster the buildings that has been previously identified by means the properties usage features. The properties types are:

- Hospital / visiting
- Just Work
- MFD (Multiple Family Dwelling)
- Organized recreation
- Religious
- Retail services
- School

In this thesis, another routine has been written in order to assign each building to a specified census point. For each building the distances between every census point have been calculated by means of geometrical distance between the building coordinates and census point coordinates and each building has been assigned to the nearest census area "centroid".

### Social analysis - population data

The model assessment requires first of all a deep study of the area of interest. While in the previous chapters, the hydraulic and morphological aspect of the area has been mainly considered, in the evacuation planning one of the focal element is the social aspect. In fact the main issue on planning an evacuation, is actually to understand and focalize which is the target of the plan, that is vital for the succeed of the entire operation. For that, the main reference for a planner, must be the local population data, such as the census and the properties data. Only giving a picture of the age distribution plus the knowledge of the properties data, we already know the practical motorial capability of the targeting people and the willness of the people to leave the house, the tendency in the choice of the way to escape, and so on. The properties data are really useful also to practically allocate the people in the different time of the day and in the different day of the week or the year. Furthermore, the economical data coming from the authorities statistics and from the census analysis, could give back a picture of the actual level of awareness of the people, the willingness in listen on the authorities advice and to leave behind goods and homes.

Some assumptions have been made to divide the population in the groups that are needed for the model. Some statitistical analyse have been carried on to define the percentage of various groups. The groups and the relative percentages have been calculated based on the rate of adults in each group from the total adults per each census area. Those rates are shown in the table 13.1.

| Population Group | Percentage Rate of Total Adult per Group |
|---|---|
| Couples (2 adults) | 13 % |
| Couples with 1 child (2 adults, 1 child) | 10 % |
| Couples with 2 children (2 adults, 2 children) | 4 % |
| Couples with 3 children (2 adults, 3 children) | 1 % |
| Single with 1 child (1 adults, 1 child) | 10 % |
| Single with 2 child (1 adults, 2 child) | 5 % |
| Single with 3 child | 3 % |
| Single (1 adult) | 26 % |
| Live with Parents (3 adults) | 6 % |
| Group 4 adults (roomies) | 14 % |
| Seniors living with family (2 adults 1 senior) | 8 % |
| Couple Seniors (2 seniors) | 0 % - based on remaining seniors |

Figure 13.1: The identified groups in which is divided the population of the Thamesmead

After definition of group, a routine has been realized to divide the population of each census point in the various population families, and to calculate the number of family per each family group.

After assigning the number of groups and the buildings belonging to each census area, and after defining each building use, according with the properties information, the data input for the LSM Environment has been completed.

**Running LSME programme** After completing the input data, LSME programme needs to have the "simulation time", the hydrodynamic model, to create a possible time percentage distribution for each "person-whereabout" (child, adult, senior), that is the probability for each people group to stay in every place at the time of simulation (defined by "simulation time"). After that, it is required to create the "people world" by means of load the prepared data files, to define the distribution probability curves to assign the health and building indexes, to define the escape methods (car, foot), the probability curves for the places, people average status, pedestrian probability densities, vehicles types and vehicles probability densities. Then, to finish the People World creation, it is needed to compute the Building, Peoples, People counting and balance word and assign places. After that the user needs to define the global parameters that are the simulation start time, the simulation duration, the simulation time step and save step, the exponent of velocity-depth products and the reduction factors of PARUs and Buildings parameters, the default time of first awareness, the depth that triggers awareness in pedestrian, the depth that triggers awareness in building occupants and which triggers awareness in vehicles occupants, the distance betweens PARUs that make them aware if they are not, the safe elevation, the minimum distance allowed between vehicles and the Greenshield parameters. Then, the user can create scenarios and save the file that is needed as input to LSM2D model. It is also possible to run the LSM2d into the LSME programme, to save results files and to load these files to compute the weighted LOL. Actually the LSM Environment has some problems for huge population data, giving back an overflow problem. The BC Hydro People are currently facing on that problem. For that, a further preprocessing has been done in this thesis in order to provide a small tool to supply the organization of the model environment.

### Hydrodynamic data

The Hydrodynamic models has been set up as shown in chapter 8, by means of a Finite Difference model. The data in output from this hydrodynamic model are not compatible with the data needed in the evacuation model. In fact, the data gave back from TUFLOW Hydrodynamic Simulation programme are .dat data. This format is basically a binary data file in which the data are arranged in rectangular format. LSM2D compatible Hydrodynamic file are .t3s and .t3v data files. This file formats are typical for some Hydrodynamic modelling tool, such as Telemac2d. The three (3) in t3s stands for 3-node triangles, the simplest of finite element grids. The 's' in t3s indicates that the data in the file are scalar and the 'v' in t3v indicates that the data in the file are vector. The data contained in a triangular mesh file is divided in two parts: the first part lists the coordinates and the data attributes of the mesh points, and the second part lists the nodes of the elements. A triangular mesh has only one data attribute associated with each node. Both t3s and t3v files that contain time-varying data are always stored in a binary format. Non-varying files may be stored in either BINARY or ASCII. The data contained in that triangular mesh file are split in two parts, in which in the first the coordinates and the data attributes of the mesh points are listed, and the second part which contains nodes of the elements. To convert the .dat files in .t3s files the conversion of the first files in ASCII format has been done. The .dat Free Surface, Depth and Velocity files are time dependent. The obtained ASCII converted files are one file for each time step, each file being a matrix (grid) file (like a DTM but with the depth or velocity for each point). As long as the ASCII converted files are rectangular, it is easier to convert that in a rectangular LSM2D compatible format. The rectangular LSM2D formats are .r2s and .r2v files. The 's' in r2s indicates scalar data and similarly, the 'v' in r2v indicates vector data. Both r2s and r2v files that contain time varying data are always stored in a binary format. Non time varying files may be saved in ASCII or Binary. The .r2s time-varying files, which are in binary format, have one row for each time step. Each row contains the values of the feature of the rectangular grid points, ordered from the bottom left, so just one file containing all the time step values is needed. For that, to convert the ASCII files in the required .r2s file a program has been written. That program is provided to rearrange the data by means of assigning the number (counter) to each point start from the bottom left of the grid, organize each point in a same row and take the value for one time step in the same row for each ASCII files. The vector time-varying data (such as velocity file) are in a different format than the scalar data files (depth and free surface files). In fact, being a vector data, each point has an x and y coordinates, that are not given back in the ASCII format. For that, the .dat file has been convert in a .mif/.mid formats, which contain the points of the arrows and the length. Using the .mif/.mid files it could be possible to take the x and y coordinates from the .mid file, compute the direction of the arrow, and, starting from the arrow length provided by the .mif files, compute the the x and y directions and put that in the right rectangular format. The .r2v vector files have one row for each time step as in the .r2s files. The difference is that in .r2v files each row contains first the values of the x component and then the value of y component of the rectangular grid points, ordered from the bottom left, being each row for each time step. Once the .r2s and .r2v files has been created, it is possible to convert time varying r2s file to a time varying t3s file without loosing the time-dependency. This data conversion work has required a deep study of the data format, the vectorial type, the time-dependency and the binary formats. Furthermore, this work has required a big effort in programming for the conversion itself. This work has been therefore interesting to understand the importance of the data standardization between the models, specially if we analyze the hydrodynamical models. In fact, model as TUflow, Telemac2D, DYNHYD, LISFlood that are some of the most used one, does not provide sufficient requirements of data compatibility.

### 13.0.4 Life Safety Model 2D (LSM2D) tool

The LSM2D (Life Safety Model 2D) tool is properly the modelling tool, which provides the computation of LOL, position in time of the evacuating people, building and vehicles destruction, using the spatial references for each objects and events. The LSM2D included in the BC Hydro Life Safety Modelling is written in (Visual) C++ and it has to be used by means of the classic DOS interface.

This program is written to merge the Hydraulic simulation results (that means velocity/time/position, free surface/time/position, depth/time/position and bathymetry/position files), with objects position and conditions.

#### Objects

There are three kinds of objects included in LSM2D which are People objects, Vehicles objects and Buildings objects.

People objects have proper identity status, which could be, for example, the gender or some other classification user-defined. This is the single-person object, called PARU (People At Risk Unit). Furthermore, the people are grouped in a higher level that means that they have a further classification based on their time position-activities. This latter classification is called here PARG (People At Risk Group). For example, a PARG could be made of people working in the same shop building that likely escape together in case of evacuation - that is an example of Separable PARG - or people that believably stay together in case of escape. Family PARG are in any case considered as inseparable PARGs. Vehicles objects are not set in advance from the user, which only gives to the program the reliable way to escape for each PARU. For user-defined vehicle escaping PARUs or for usually vehicle moving PARUs a vehicle is generate in the model (or just one vehicle for PARG if PARU belong to a small PARG or to a family PARG). Before starting the extreme event, the vehicle could be moving (if the people inside are already moving at beginning of the simulation) or parked. The program generates a proper number of vehicles at the beginning of simulation. The vehicles are directly related with PARUs inside. The positions for moving vehicles are given by means of random moving up and down the vehicles. People and vehicle objects are moving objects so as they could change their xyz coordinate references. Building objects are obviously a non-moving object (even if in some flooding situation it could be happen at all) and they are directly related with the PARUs staying in. At beginning of the simulation they are Standing.

**Decision algorithms for the "objects"** The program analyses step by step the object condition. At each time step it interpolates the water depth and velocity from the hydraulic triangular grid for each object. Then, for each object it update the condition parameters that depend on time, flow velocity and water depth. For that, one or more buildings that are set up to be are warning centers, start to "disseminate the warning" end then, basing on the warning rate, the people and the vehicles whose state is set on "Aware" start to evacuate, changing their status o "Aware and Evacuating". Pedestrian people could be Drowned (depending on the water depth and velocity product $h * v$ or just if $h$ exceed the user-defined limit), Toppled (the could not move anymore) and then, after a time given by health curve, they could be Exhausted, Deceased in Collapsed Building (a building could collapse for impact $h*v$, reaching the $h$ limit or for fatigue - stability curve), or Decease in Toppled vehicle (a vehicle is toppled when $h * v$ is higher then critical). The vehicles could also be floating, and in this case the vehicle occupants become pedestrian.

The evacuation decisions taken from peoples are determined by:

- The awareness of people: if people are aware, it escapes according to their pre-defined evacuation-decision time plus building-escaping time (if in building) or car-evacuation time (if in a flooded car).
- Then, even if they escape by car or by foot (user-defined option), the model calculate path using "shortest path" algorithm (see "Traffic

and positioning algorithms" in the following paragraph) for every Safe Heaven and choose the shortest path. Then address the vehicle for that path. If the road condition change (e.g. the road in which the object is going to go is flooded) the model calculates a new path.

- People who reach the Safe Heaven are considered "safe" and no more involved in simulation

Practically, the model calculates the indexes for any object, and then compares the obtained value with the threshold critical values, user defined or time-velocity-depth dependent. The object status indexes are uploaded every time step by means of simple curves functions of time, velocity and/or depth. The varying indexes for the population units (PARU) are shown in the table 13.2. The Equations for the Population At Risk Groups (PARG) indexes are simply the weighted means of the PARU indexes. The Buildings state indexes equations are shown in table 13.3.

| *Index* | *Description* | I*Equation* |
|---|---|---|
| PPC | *Physical condition* (if PPC<PPCC, where PPCC is the Critical Physical Condition then dead) | $PPC(t+1) + PPC(t)\left(1 - \frac{dv(t)+dv(t+1)}{2}\Delta t \cdot \frac{1}{PCDVM}\right)$ |
| PLTD | *Lowest toppling depth* (LTD) metres - PLTDA is the Initial Lowest toppling depth | $PLDT(t) = PPC(t) \cdot PLDA$ |
| PHSD | *Highest safe depth* (HSD) metres - PHSDA is the Initial Highest safe dept | $PHSD(t) = PPC(t) \cdot PHSDA$ |
| PDVTC | Critical dv for *toppling* person (m2/s) m2/sec - PDVTCA is the Initial Critical dv for toppling person | $PDVCT(t) = PPC(t) \cdot PDVCTA$ |
| PDVDC | Critical dv for *drowning* person (m2/s) m2/sec – PDVDCA is the Initial Critical dv for drowning person | $PDVC(t) = PPC(t) \cdot PDVCA$ |
| PS | *Escape speed* on foot (km/hr) km/hr - PSA is the Initial Escape speed on foot | $PS(t) = PPC(t) \cdot PS$ |
| PDEU | Delay before *evacuating building* seconds – PDEUA is the Initial Delay before evacuating building | $PDEU(t) = \frac{1}{PPC(t)} \cdot PDEUA$ |
| PDEV | Initial Delay before *evacuating vehicle* seconds – PDEVA is the Initial Delay before evacuating vehicle | $PDEV(t) = \frac{1}{PPC(t)} \cdot PDEVA$ |
| PCDVM | Cumulative dv resulting in complete exhaustion $m^2$/sec – RPCDVM is the Reduction factor and it is a positive realnumber. If it is set to 0.0 therate of decline in PPC does not change, if it is set to 1.0, the rate ofdecline in PCDVM is directly proportional to dv(t) | *Constant Value* |

Figure 13.2: Population AT Risk Unities (PARU) indexes

| Index | Description | IEquation |
|---|---|---|
| BSS | *Structural condition of the building.* - BSSC The critical value for structural condition (if BSS < BSSC the building is destroyed) | $BSS(t+1) = BSS(t)\left(1 - \frac{dv(t) + dv(t+1)}{2}\Delta t \cdot \frac{1}{BCDVM}\right)$ |
| BCDVM | Building's capability to withstand continuous damage from the flood wave flood wave | $BCDVM(t+1) = BCDVM(t) - RBCDVM(dv(t) \cdot \Delta t)$ |
| RBCDVM | Reduction of BCDVM. If it is set to 0.0 the rate of decline in BSS does not change. If it is set to 1.0, the rate of decline in BCDVM is directly proportional to dv(t). | *Constant Value* |
| BDCVC | Critical dv for destroying building m2/sec – BDVCA is the Initial Critical dv for destroying building | $BDCVC(t) = BSS(t) \cdot BDVCA$ |

Figure 13.3: Indexes and equations for the buildings

The decision about Object status is taken comparing the indexes values with reference critical values for each time step and for each object (that is PARU, PARG, Building, Vehicle). The PARU and PARG statuses are also influenced by the Building and the Vehicles conditions. It could be noted that there is obviously a strong relationship between the indexes and the flood features.

**Traffic and positioning algorithms** The moving objects of the model are the Vehicles, the PARUs and the PARGs, that could move in the model as pedestrians. While the status of that objects is computed by means of the equations above, the object positions are decided considering two aspects of the event. The moving object position of unaware objects (which are already on the road at the beginning of the simulation) is determined randomly in the model domain. While they are located in a randomly chosen road, they continue to move back and forth in the same lane while their awareness status changes. Once they become Aware - by meeting aware objects, by means of coming across the predefined awareness water depth, by entering in the Warning Centers Ray of Awareness - they start the evacuation. The evacuation routes are chosen by the model by means one of the wildness used routing algorithms that is the Shortest Path algorithm, in the modified form.

The Shortest Path, SP, problem is one of the most simple but crucial among the network flows optimization problems. We refer to a graph $G = (N, A)$ where $N$ is the set of nodes and $A$ is the set of arcs. The graph is supposed directed, i.e. the flow on arc is allowed in only one direction. If flow is allowed in either direction a pair of direct arcs in opposite direction is associated to the arc. A direct path between two nodes, $r$ and $t$, is a sequence of distinct consecutive directed arcs, connecting these nodes, in such a way that the flow from $r$ can reach node $t$. A path that begins and ends at the same node is called a cycle. A tree is a graph with no cycle, such that a path exists connecting each pair of nodes. A spanning tree associated with a graph is a tree connecting all the nodes in the graph. Associated with each arc is a nonnegative "cost" that represents the length of the arc, sometime in terms of time necessary to run along it. For each path $P$, its cost $C(P)$ is given by the sum of arc costs included in it. Given an origin node r and a destination node $t$, the objective of the $SP$ problem is to find the oriented path with the minimal total distance from $r$ to $t$, i.e. with the minimum cost $C(P)$. If $P_{rt}$ represents the set of all direct path connecting $r$ and $t$, the shortest path $P*$ is the solution of the following problem:

$$C(P*) = minC(P) : P \in P_{rt} \tag{13.1}$$

The SP problem can be expressed in a general form in terms of finding the shortest path from the origin r to all nodes of the graph. The reason why the this general form is considered is that to solve the SP problem from r to t in practice, it is necessary to explore all nodes $i \in r$ and then determine the minimal distance from $r$ to all other nodes. The process does not stop until all shortest paths are determined. As a result all the paths form a spanning tree. Therefore the problem is, really, to find the spanning tree with a minimal total cost (length) of the arcs. This problem can be solved in a very straightforward way with a "greedy" approach, following the Dijkstra algorithm. The first stage of the algorithm, starting from origin connects it to the nearest distinct node. The second stage identifies the unconnected node that is closest to a connected node, and connect these two nodes. This processes is repeated until all nodes have been connected. This algorithm can produce the solution very efficiently by computational point of view even if applied to graphs with a huge number of nodes and arcs such is the network in this study where the graph reproduce the lane system where source nodes represent the starting point of the people or the vehicles and destination nodes represent the safe heavens. The cost associated to the arcs can be simply the length of the lane or a more sophisticated parameter including, e.g. probability of congestion due to physical or environmental features. Tanks to the efficiency of this procedure, it is possible to solve efficiently the routing problems nested in the overall problem.

One the path has been chosen, the object could cover it only if the traffic density of the lane is less than the user defined Maximum traffic density. The traffic velocity is determined by means of Greenshields Equation (1935):

$$V = V_r(1 - \frac{u}{u_r}) \tag{13.2}$$

Were $u_{max}$ is the free flow traffic density (maximum traffic density in vehicles/km/lane) that is user-defined, $u$ is the actual density and $V_r$ is the free flow speed.

### 13.0.5 Sensitivity analysis

A sensitivity analysis has been carried out for the LSM2D, by means of the increasing or the decreasing percentage of the people health parameter (PPC). The PPC curves are simply shifted up linearly. For that, the time series of the PPC that has been computed by the model has been linearly shifted up, as it has been verified for some significant examples (see figures 13.4 and 13.5). In this test, the initial values of PPC for the population have been shifted by adding 3 different values (see figures 13.4). As result of that, the time-varying values of PPC in output has been observed for different samples of PARUs (figure 13.5). In fact, the value of health index varies depending of the hydrodynamic condition (water height and velocity) that the PARU encounters in the simulation. For that, shifting the initial values of the PPC, the time-series of the PPC itself must shift by the same order of magnitude, to assure the stability of the model. This stability has been observed for all of the samples of PARU analyzed, as it is shown in figure 13.5.

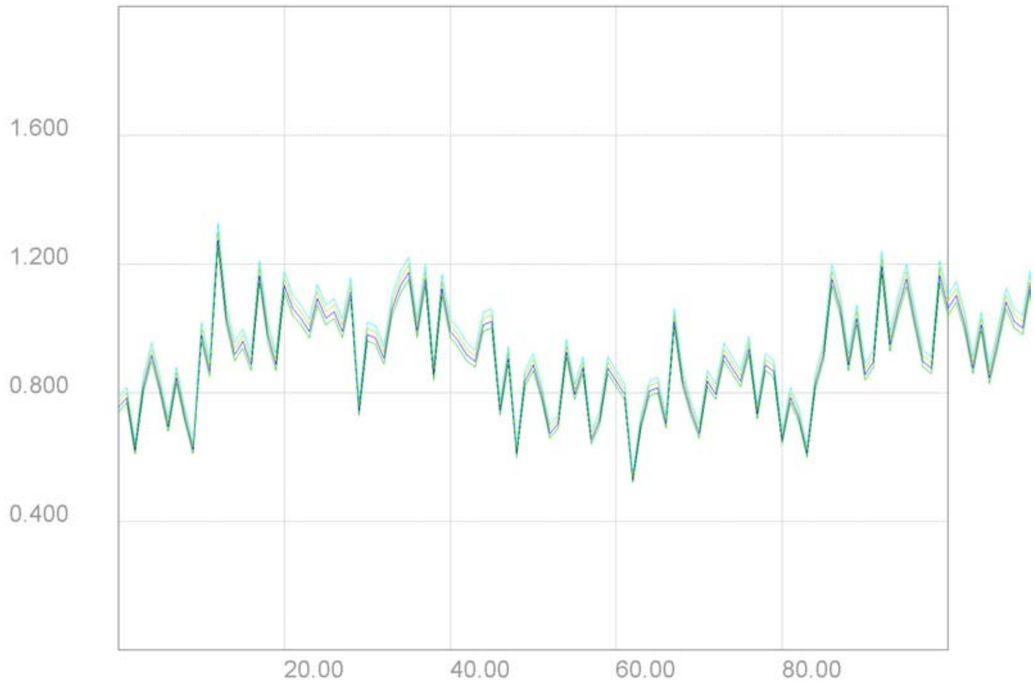


Figure 13.4: Used PPC shifted curves for every PARUS

The deceased people results obtained are shown in figure 13.6.

The number of People Deceased by Building Collapse decreases with increasing PPC. This could be apparently strange, because the strength index of buildings is not influenced by PPC. In effect, while the "building behaviour" is not influenced by PPC, the "people in the building" behaviour is influenced by the people health condition, because the initial delay in the evacuation of buildings and vehicles is function of PPC(t). In fact, this initial delay is function of PPC(t) by means of PDEU and PDEV index, that are linearly inversely proportional to PPC(t). For that, increasing the PPC index, the number of people who die in building collapse decrease as expected,

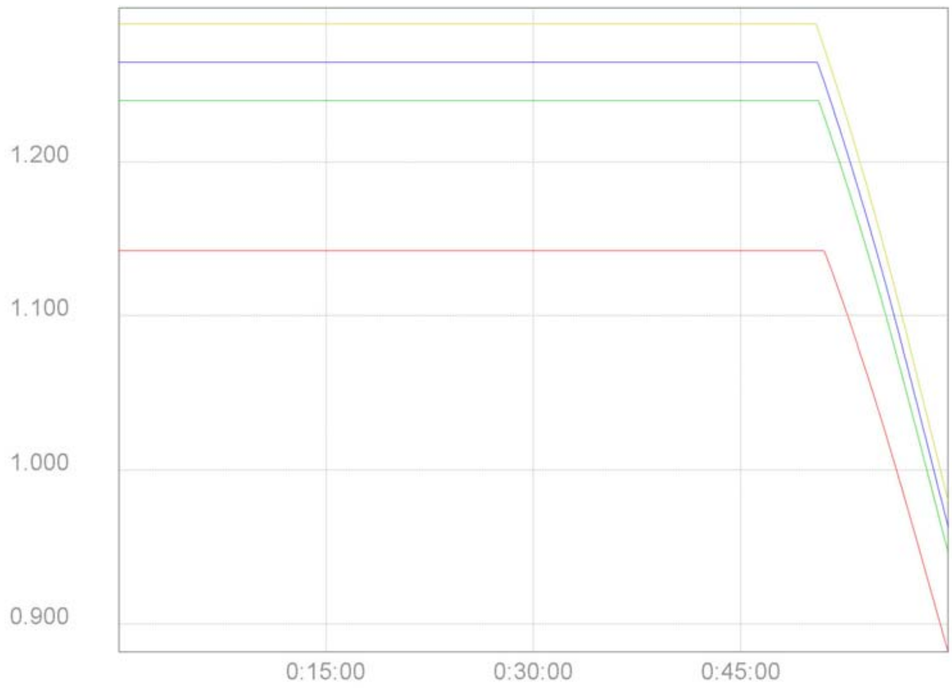


Figure 13.5: Time series shifted curves for one significant sample PARU

because the people in the buildings are more "‘healthy"’ and they are able to start the evacuation earlier than people with a lower PPC. On the contrary, the Drowned people results differ than expected. In fact, the people who die for drowning increase with PPC increase, and it is a clear contradiction in PPC significance, because the drowning people index is directly proportional to PPC(t) values.

This behaviour could not be explained thinking about the randomness of the positions of pedestrian and vehicles: in fact, reiterating the model, the results are exactly the same. This could be an interesting aspect for a more exhaustive study, but it has not been able to satisfactory explain in this study.

Similar apparently contradictions are shown in the sensitivity analysis of the building index (BSS). In fact, while the index of delay in building evacuation is definitely influenced by the PPC, and that could explain the decreasing in people died in building collapse while PPC linearly increase, the BSS index seems do not influence peoples’ behaviour, except for the people who die in building collapse. I can not explain the results in BSS sensitivity

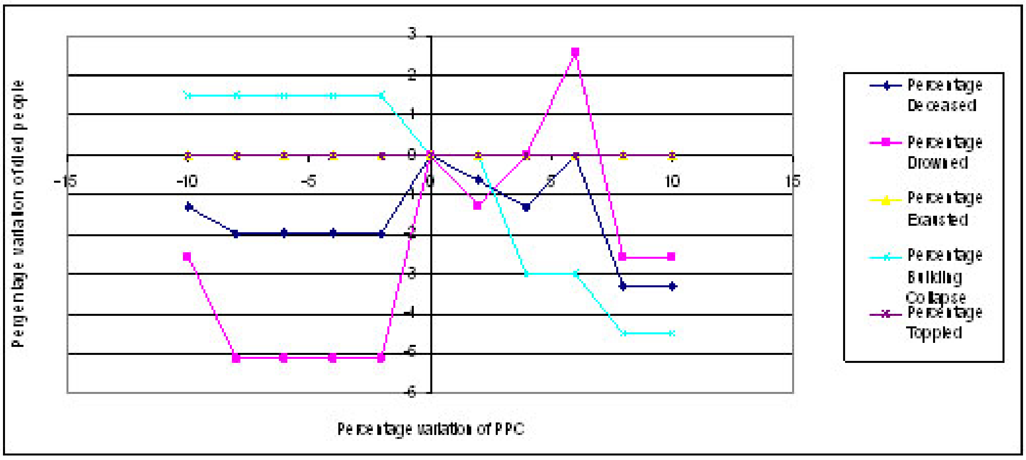


Figure 13.6: Died people variation (percentage) vs PPC variation (percentage). Percentage of 0% corresponds to the reference value

analysis shown in figure 13.7, in which the variation in died people due to BSS linear variation is due to variation in drowned people, while the other variables remain constant. While increasing the BSS index the Deceased people number remains constant after 4%, the strange behaviour of results could be explained as floating spike due to some particular conditions. All of these issues has been reported to the developer of the model, and by now are still object of study and development for the next version of the model itself.

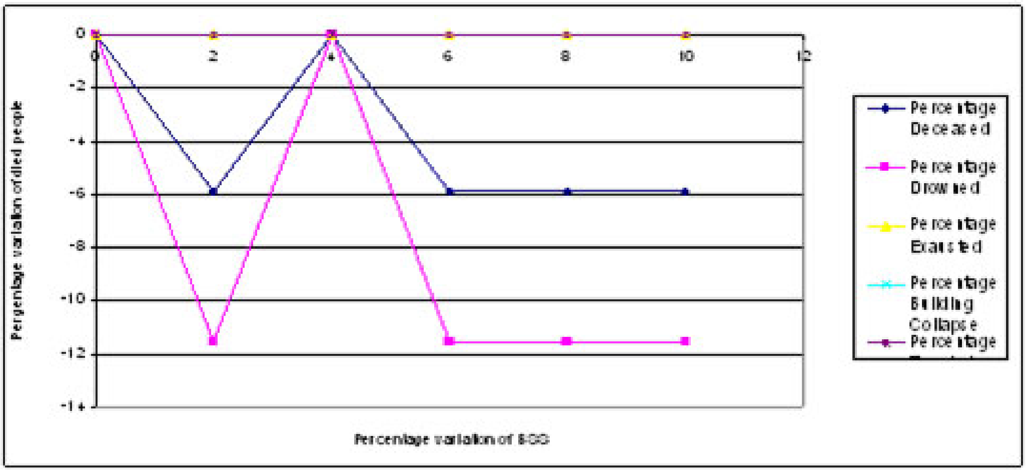


Figure 13.7: BSS variation (percentage) vs Died people variation (percentage). Percentage of 0% correspond to the reference value

## 13.1 Model results

The Life Safety Model has been tested for the two pilot sites individuated in the European Union project FLOODsite, that is a wide project that involves 35 partners in 37 different tasks [52]. Seven Pilot Study Sites have been established within FLOODsite that include river, estuary and coastal locations with some of the river locations being subject to flash floods. As detailed before, the selected pilot sites for the evacuation modelling testing are both situated in the Thames Estuary, and are London district of Thamesmead and the sub-urban area of Canvey Island. Both of the areas have revealed to be very interesting from the hydrodynamic point of view, being situated in a particular morphological environment and subjected to really important tidal phenomena. Furthermore, the data analysis that has been necessary to set up the evacuation model, has revealed that the areas are even more interesting from both the socio-economical point of view and the architetonical aspects.

### 13.1.1 Thamesmead

The area of Thamesmead as it appears today, has been developed starting from 1967 fully advertised as a new "‘luxury development"’. The first family, the Gooches, moved into their "‘luxury, three-bedroomed maisonette"’ in June 1968, but problems had already been encountered with the new housing and no more residents moved in until the following year. In fact, many people were desperate to move to the new town partly as a result of the publicity. Many were lured by the GLC’s glossy brochures featuring lakes with yachts and colorful artists’ impressions of tree-lined canals coupled with ultra modern accommodation. In fact, Thamesmead benefited from its central location. In addition, excellent transport facilities meant it was very easy to get to and from central London. Surveys have revealed that 47 per cent of residents in the town worked in Central London, emphasising this point. The plan for Thamesmead was that it should be a self-contained, balanced community with facilities for such things as recreation, housing and education fully provided for within the town itself. However, by the end of the development of Stage III Greenwhich Council, in which a large number of building had been developed, were finding it hard to fill vacancies in the high-rise blocks and accusations of the dumping of anti-social tenants in Thamesmead by other councils were already beginning to surface. By 1980 these empty dwellings were becoming a serious problem and vandalism and graffiti were becoming rife. The GLC tried several offers to fill this housing to single people or groups of single people willing to share or on a first-come, first-served basis to people willing to take on a property in need of repair. These had some success, as have the efforts by Thamesmead Town Ltd in attracting people, but they have inevitably compromised the initial vision for the community. Thamesmead was developed and managed by the Greater London Council up until the abolition of the GLC in 1986. A referendum was held in October 1985 to find out how local residents wanted Thamesmead to be run after the council's abolition. The majority of voters wanted the area to be managed by a private company run by residents, so in March 1986 Thamesmead became the first residential estate in the country to be run by a private company controlled entirely by residents. Thamesmead Town is a company limited by guarantee, it has no share capital and is non-profit distributing. The board of 12 manages not only the residential development but also the commercial areas, open spaces, recreational facilities and industrial estates ([43], [28], [15]).

**Population** The area of Thamesmead is characterized by a low-average income per person. While the area was thought as a upper class residential area, it knew a decadence period in the early 80s, while now the area itself seems to know a great increasing in the population rate, due to the vicinity with London and to the quality of the area. Thamesmead Town now has about 45,000 residents and there are ambitious plans for the development of a proper town center and also riverside housing development. The population of Thamesmead, in fact, is distributed mainly in the lower age bands, as it is shown in figure 13.8, due to the high appeal of the area's new developments.

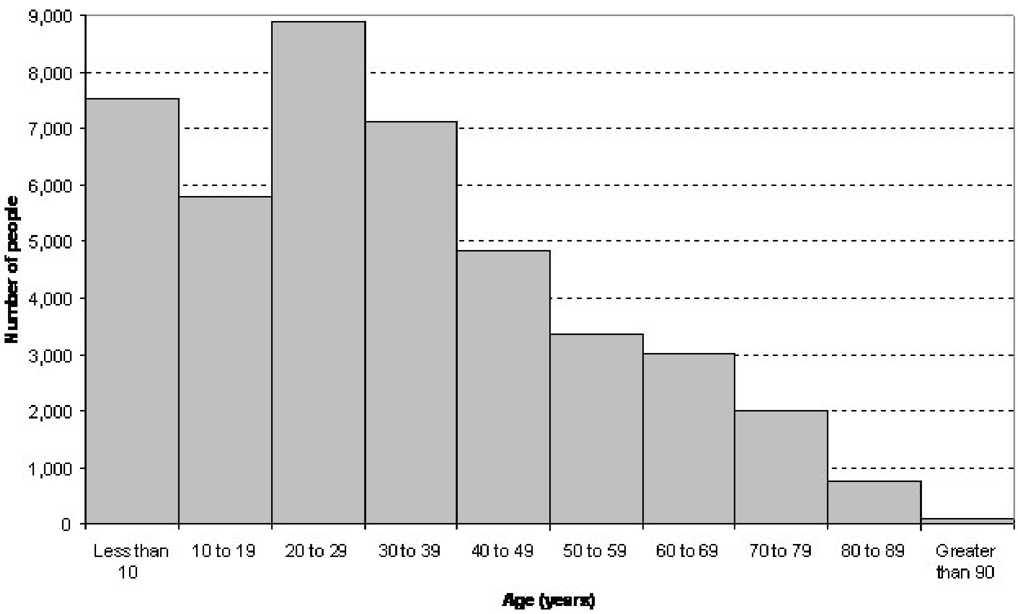


Figure 13.8: Age distribution of the Thamesmead population

**Buildings** Although Thamesmead was a "‘new town"’ and built on the scale of the early post-war towns, it was a new town built within a capital city. It may seem hard to believe it today, but when Thamesmead was built and even long after the first families had arrived, coach loads of professional visitors would descend on the area to consider the architectural and sociological aspects of the development. The site visits in the area have highlighted that the Thamesmead houses are meanly recent brick and concrete buildings and modern apartments, as shown in the figure 13.9, with two or more floors.

Figure 13.9: Thamesmead new development

### Evacuation modelling results

The Thamesmead evacuation model results are revealed to be quite critical, due to the high population concentration of the area and the high density of the buildings 13.10.


Figure 13.10: Thamesmead evacuation model: building distribution

While the building itself has revealed to have a good resilience, giving back on average a percentage of $5-7\%$ of destroyed buildings, the population has revealed to be particularly at risk, with a damage close to the 4% for the population and to the 10% for the vehicles. The damage is given by the vulnerability and the element at risk therms. For the population element a risk, the vulnerability has been taken in account in terms of loss of lifes and toppling, that means the attitude of the people to be knocked over by the flow. The sum of the percentages of people deceased and toppled has been considered to give a measure of the damage for the population. In figure 13.11, the poulation state after the first stage of the flood is shown, where the flags indicate the state of the people: 0 - Unaware; 1 - Aware; 2 - Aware and evacuating; 3 - Safe; 4 - Toppled; 5 - Deceased.

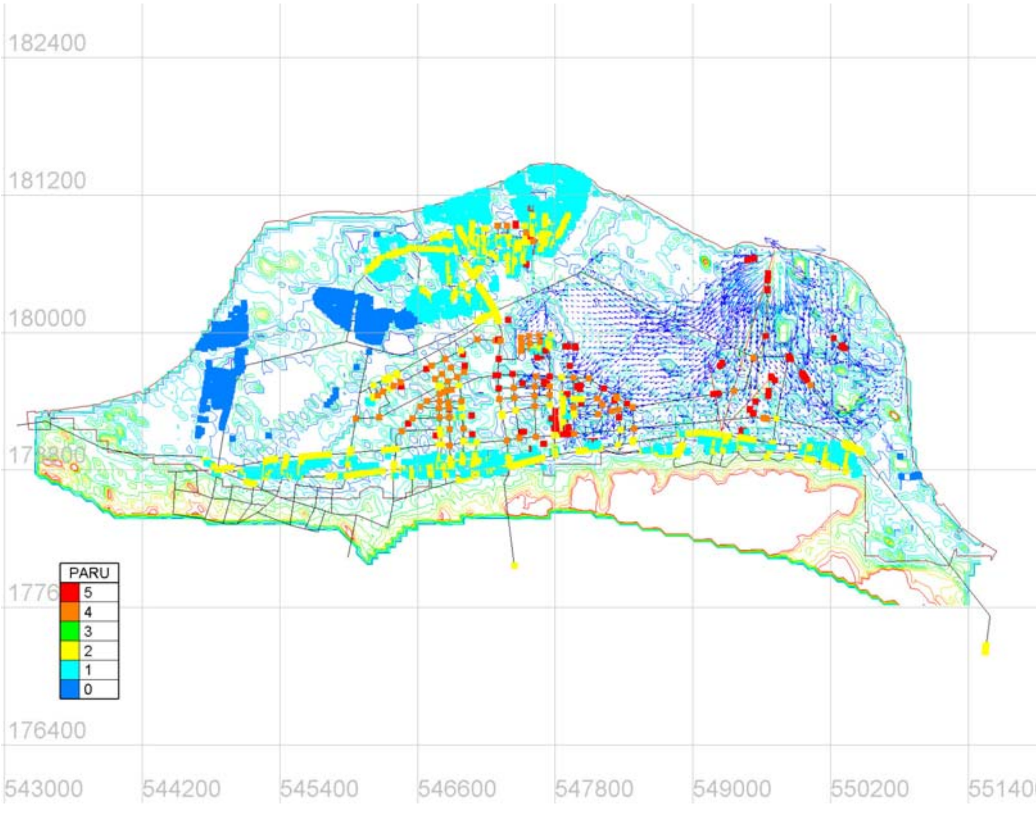


Figure 13.11: Thamesmead evacuation model: state of the people close to the end of the simulation: 0 - Unaware; 1 - Aware; 2 - Aware and evacuating; 3 - Safe; 4 - Toppled; 5 - Deceased.

In the figure 13.12 the results for some of the simulation scenarios has been shown, revealing the difference in the results due to the closure of different roads.

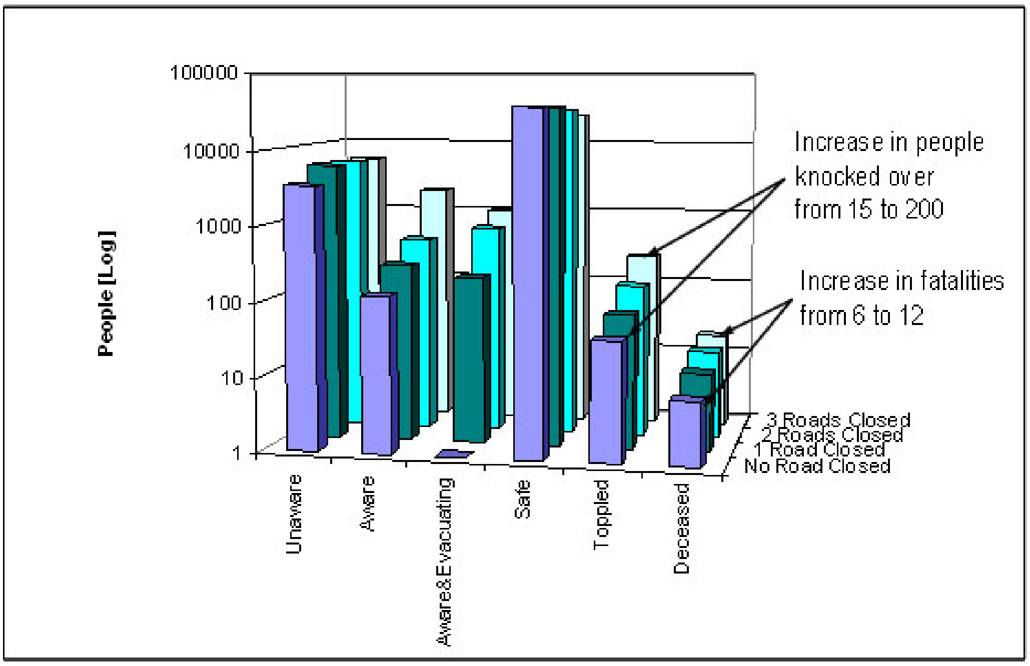


Figure 13.12: Thamesmead evacuation model results for road closures scenarios

### 13.1.2 Canvey Island

The Canvey Island is a really peculiar area in the Thames estuary. This island reveals a definite identity that makes it different from the closest urban development. While the average per capita income is nearly lower than the east England in the island population, as is shown in one of the statistics of the National Statistics office (see figure 13.13), the area is characterized by a strong community and by a remarkable singularity in the architectonical shapes, that makes this area a really interesting and different environment from different point of view.

| Income Support Claimants, August 2006 | | | | | | |
|---|---|---|---|---|---|---|
| | | | | Castle Point | East of England | England |
| | | | | Non-Metropolitan District | Region | Country |
| Claimants Aged 16-24 | Percentage | Persons | Aug06 | 13 | 14 | 14 |
| Claimants Aged 25-49 | Percentage | Persons | Aug06 | 64 | 67 | 66 |
| Claimants Aged 50-59 | Percentage | Persons | Aug06 | 22 | 19 | 20 |
| Claimants Aged 60 and Over | Percentage | Persons | Aug06 | 0 | 0 | 0 |
| Male | Percentage | Persons | Aug06 | 32 | 34 | 35 |
| Female | Percentage | Persons | Aug06 | 68 | 66 | 65 |
| Single | Percentage | Persons | Aug06 | 86 | 87 | 87 |
| Working Age Statistical Group; Incapacity Benefits | Percentage | Persons | Aug06 | 50 | 53 | 55 |
| Working Age Statistical Group; Lone Parent | Percentage | Persons | Aug06 | 44 | 41 | 38 |
| Working Age Statistical Group; Carers and Others | Percentage | Persons | Aug06 | 7 | 7 | 7 |

Figure 13.13: Canvey Island district Income Support Claimants, August 2006 (National Statistics): percentages of claimants persons in August 2006 divided by age and working status for the Castle Point district, compared with the percentage of the East of England and with the ones of the whole England

**Population** The population of Canvey Island is middle ages on average, therefore with a considerable grown up young population, as is shown in the figure 13.14.

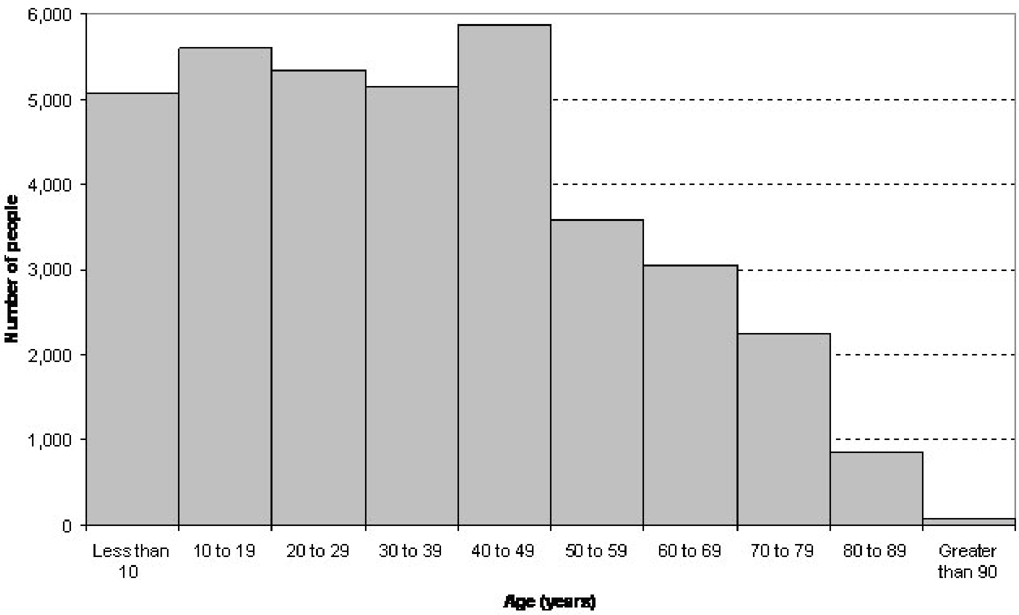


Figure 13.14: Population distribution in Canvey Island for 2006 (National Statistics)

**Buildings** Concerning the architectonical point of view of Canvey Island, it has been estimated that approximately 91% of dwellings are houses and 9% flats. Most properties have two storeys, and have a mean floor level 0.3 m above the surrounding ground levels. Thirty percent of properties are bungalows and 45% of flats are situated at ground floor level, there is thus a large risk to life and property with limited opportunities to temporarily move to a higher level. It is possible that a majority of the island would be inundated if a major storm surge occurred and led to major overtopping of defences. However, this is still considered to be a very rare event. The failure or breaching of a seawall is a more likely option and would involve more localised severe flooding depending on the exact breach scenario that occurred.

The site visits have allowed to understand the typology of the buildings in both areas. Canvey Island has shown types of buildings that are mainly made of bricks and wood (see figure 13.15), that are mainly one floor detached houses.

Figure 13.15: Typical houses in Canvey Island

Furthermore, during the last site visit a new development not even in the recent OS maps has been noticed, see figure 13.16. This urban development has revealed to be quite important in terms of evacuation planning, due to the fact that the population is increased, that it is built very close to the defenses and that all the houses are simile precasted small swellings, to be considered highly vulnerable.

Figure 13.16: The new urban development in Canvey Island

### Evacuation modelling results

Th evacuation modelling of the Canvey Island has been set up with great care of the buildings parameters and disposition (see figure 13.17), due to the fact that the buildings themselves have been revealed a high vulnerability.


Figure 13.17: Model of the buildings in Canvey Island

The model has been set up as delineated before, by means of the census and the properties data, plus the historical and bibliographical data. The two warning centers has been set up to be one close to one of the breach location (west) and the other one in the urban center. The results of the modelling have revealed a great sensitivity in the buildings, as expected, while the concentration of the population close to the center, and tho the main roads is probably peculiar to not give back a high number of fatalities, around the $1-2\%$. The results for all the object in the model are shown in figure 13.18

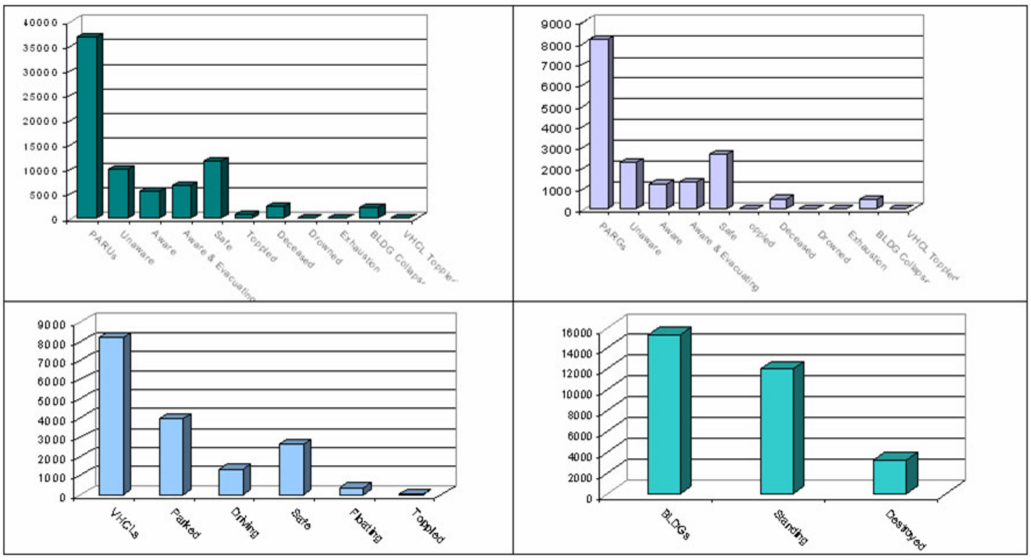


Figure 13.18: Results for the vulnerable objects in Canvey Island. Clockwise, from the top left: People at risk units (PARU), People at risk groups (PARG), Buildings (BLDG) and Vehicles (VHCL)

## 13.2 Modelling of the 1953 flood event

As already explained in the section 8, the 1953 flood event on Canvey Island was modelled. In order to validate the BC Hydro LSM model the 1953 flood event that occurred in Canvey Island was reconstructed. During the 1953 flood, which occurred at night, the flood defences in Canvey Island were breached in a number of locations. It is estimated that on Canvey Island alone 58 people died and that 10,000 had to be evacuated. Starting from the hydrodynamic model, the evacuation model of this event has been performed in order to validate the BC Hydro LSM model. The population data of the 1953 has been reconstructed by means of the census data. Even if the property data was not available for the 1950s, the historical maps has been used to reconstruct the building distribution. A comparison of the building density between 1953 and 2001 for Canvey Island is shown in figure 13.19.

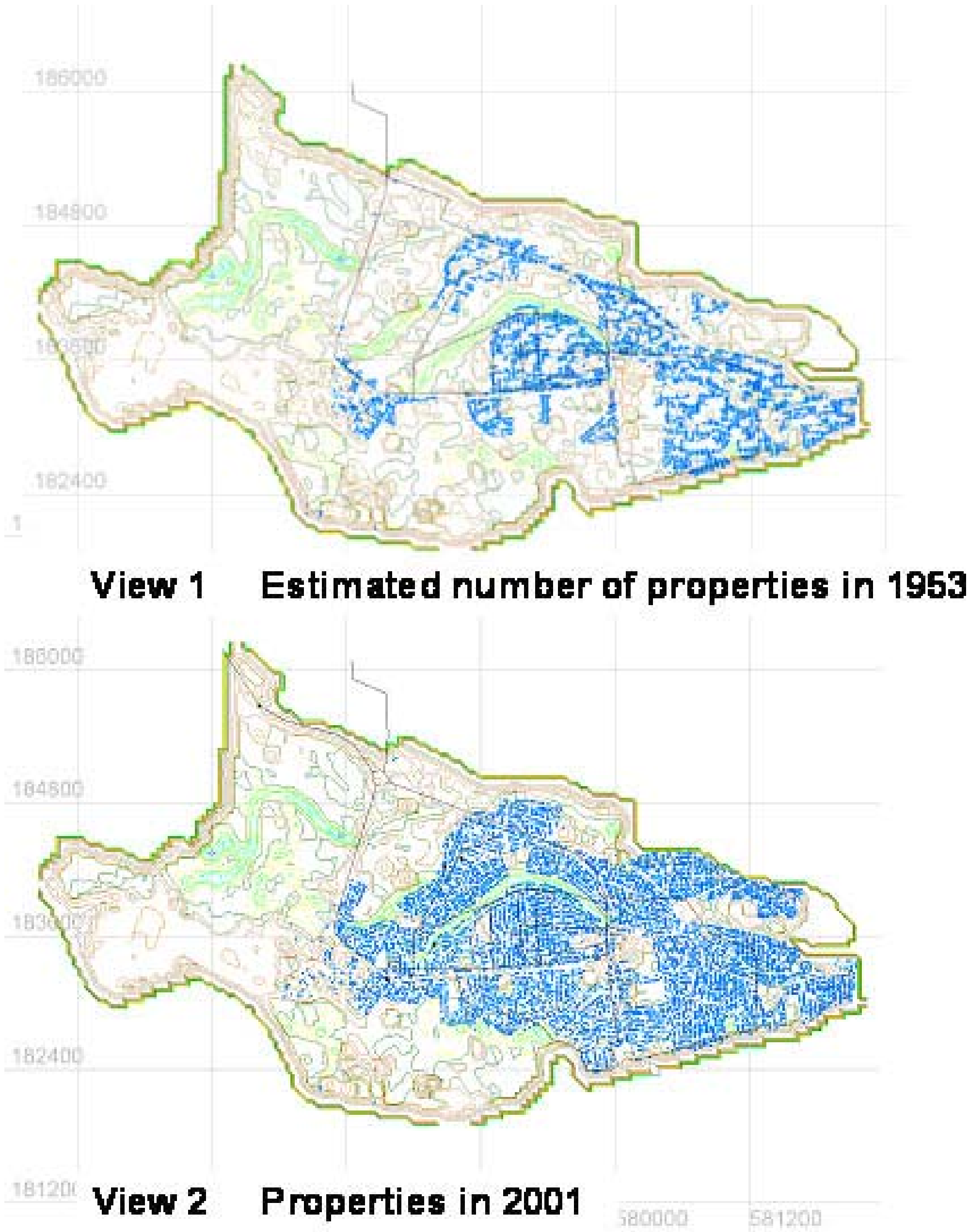


Figure 13.19: Comparison of the number of properties on Canvey Island in 1953 and 2001

### 13.2.1 Results

The results of the re-creation of the 1953 flood event agreed well with historical data. The BC Hydro LSM model indicated that 100 fatalities had occurred during the 1953 event. This number is dependent on the "resilience factors" applied to both people and buildings. The actual number of people that died in 1953 was 58. The number of buildings estimated to be destroyed during event by the model was definitely bigger than the one that could be (very poorly) estimated from the historical fonts. This remarks one of the most important drawback of the model, that consists in the vulnerability analysis evaluation, that could definitely be improved. The results of the modelling are shown in figure 13.20.

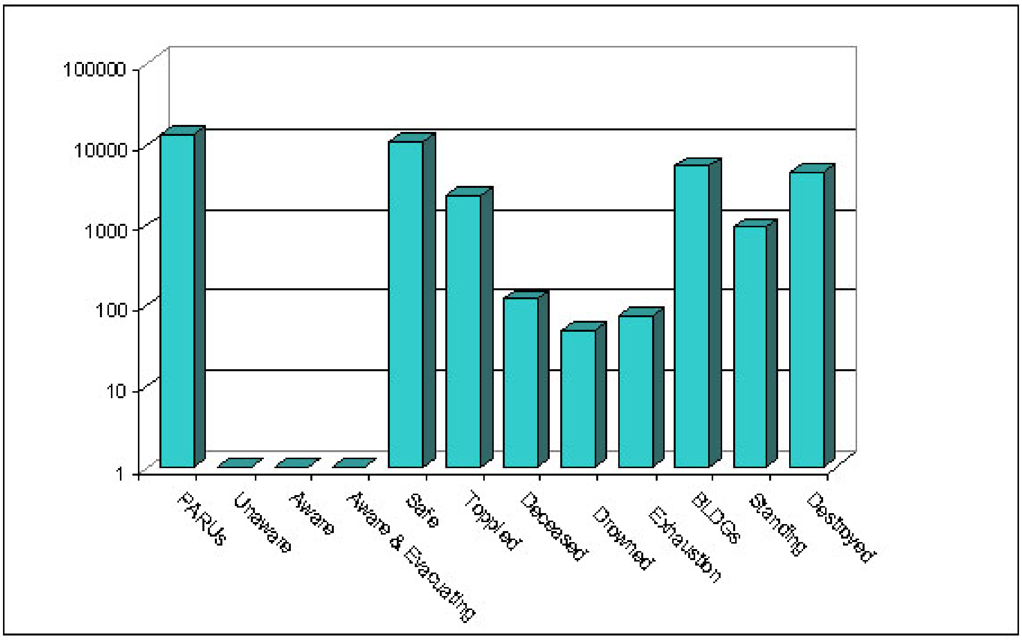


Figure 13.20: Results of the loss of life model for the 1953 flood for Canvey Island

# Conclusions

This part has presented a new approach to asses and evacuation planning, new philosophy of evacuation modelling and decision making for the evacuation itself. First, the policies and the legislative issues has been analyzed in order to set up some guidance and the schedule for assessing an evacuation plan. Than, a new model developed from the British Columbia Hydro has been tested for the fist time in a densely populated area for a breach inundation scenario. The testing has taken in account the sensitivity of the model and the data requirements from a technical point of view. The results has shown how this model can be implemented, which kind of analysis needs to be done to set up the input data, which are the output, and how they can be red.

# Part IV

# Decision criteria technique for a quantitative assessment of the modelled evacuation scenarios

# Introduction

The Life Safety Model simulated scenarios could be a good picture on the actual situation in case of breach, to analyze the direct consequences in case of a similar situation occurs, assuming different measures for the evacuation management, such as the number of safe heavens, the rate of warning dissemination and the closure of the road. This could be useful in terms of an immediate cost-benefit analysis, but could be really subjective and dispersive in case of comparing a high number of scenarios. Furthermore, in order to assure to the interlocutor that a chosen evacuation scenario is effectively one of the best and to give back a formal justification of the taken decision, a rigorous method is needed. For that, the results of the LSM Thamesmead scenario have been processed in order to give back an objective decision device for the decision makers. Four techniques have been tested: an Utility method, a Clustering method, a method based on the decision tree technique and a method based on the Markov decision criteria.

# Chapter 14

# Sensitivity analysis

The decision criteria must been developed in order to give back an instrument to evaluate or choose among different scenario, those producing different consequences to the element at risk in the system [25]. The variable selection, in fact, is one of the most crucial features in the multicriteria analysis, because of the importance of choosing really meaningful variable, being clear which is the sensitivity of the solution to each variable and remember that not always greater is the number of variables, better is the result (usually is exactly the other way round) [9]. In fact, each scenario variable has a strong impact in terms of economic analysis, due to the different cost of each scenario itself. This impact is due both to the different costs of the variables themselves, (i.e. the variation in number of safe havens or in the velocity of warning dissemination has a strong impact in the evaluation of cost), and to the differences in economic losses due to choose different variables (i.e. the costs in terms of loss of life or damage in vehicles) [18].

## 14.1 The consequences

The first analysis here developed is the one concerning the selection of the consequences that could been considered more important from the risk analysis point of view. For that, the human life, that is the most vulnerable element in the system is immediately taken in account. The direct consequences on this element are the *loss of life*, that are considered as the first element to monitorize the consequences. As second element, it has been considered the vehicles. The *losses of vehicles* are included in the evacuation model as number of toppled vehicles, considering any vehicles toppled as lost or partially damaged. Finally, another element has been considered, that is important having a direct consequence in the people exposure, that is the *time that the 60% of people needs to reach the safe heavens.* In fact the time of evacuation, has a great importance in evaluating an evacuation scenario, giving back a strong indication of evacuation scenario value [30].

## 14.2 The variables

The further analysis concerned the study of the system sensitivity to the different environmental conditions, and which are the differences in the response of the model due to the different rates of change in that conditions. A small change in a certain environment condition that causes a change in the consequences with the same or bigger order of magnitudo means that the system is particularly sensitive to that condition, that has to be taken in account for the scenario analysis. This study is carried on by means of modeling different scenarios that are set up by means of varying the degree of freedom in constructing the models. These degree of freedom are:

1. The number of safe heavens
2. The number of road closed
3. The boolean variable concerning the decision to close the road in relation to a certain water depth
4. The velocity in warning dissemination
5. The number of waning centers

Concerning the first point, the model has shown to be quite sensitive to this parameter, specially concerning the loss of life: a variation in this parameter of 200%, causes a model answer consisting in decreasing in the loss of life of 30%. This is clearly shown in the figure 14.1

This parameter either influences the time of people evacuation, that has revealed to be quite sensitive to the number of safe heaven. A variation of 100% in this parameter causes a difference in the percentage of people reaching the safe heaven of 10% in the average (see figure 14.2).

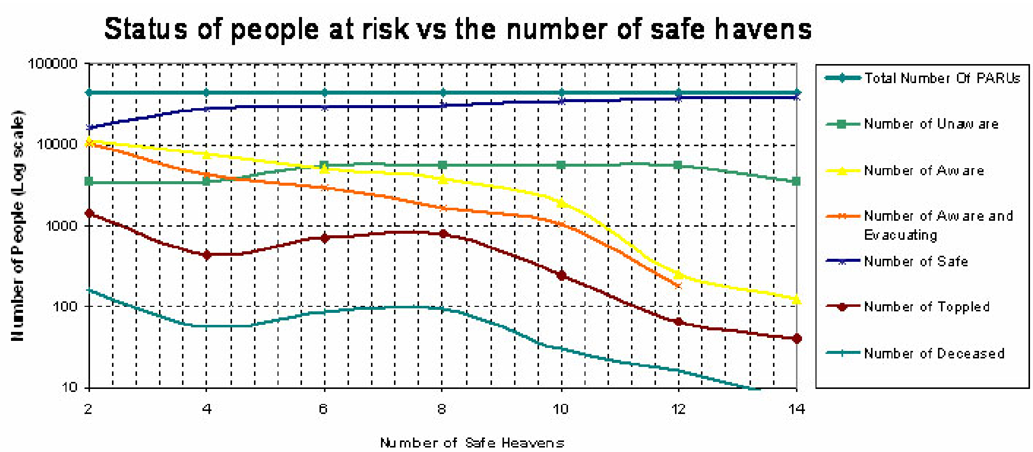


Figure 14.1: The effects of the number of safe havens on the status of people


Figure 14.2: The effects of the number of safe havens on the percentage of people reaching safety

## 14.3 Conclusion of the sensitivity analysis

While the model do not seem to be really sensitive to the number of warning centers, parameter influence the model depending on the position of the warning center itself on respect to the position of the breach. Otherwise the model seems to be more sensitive to the velocity of warning dissemination. Furthermore, neither the closure of certain roads could be considered as a generalizable sensitive characteristic, that is too dependent on the position of the closed road. As consequence of this fact, the model has revealed a good sensitivity on the boolean variable that states the closure of the road occurring a certain water depth. This variable causes a difference in the results in a range of $5 - 20\%$ in the loss of life, while the difference goes from 10 to 30% if we look at the number of vehicles toppled. For that, the parameter that has been chosen for building the different scenarios are:

1. The number of safe heavens
2. The boolean variable concerning the decision to close the road in relation to a certain water depth
3. The velocity in warning dissemination
4. The number of waning centers

even if the last parameter does not seem to influence the model so far. 60 scenarios has been then set up and implemented, for the Thamesmead pilot site. The results for these scenarios provided the data set that is needed to test different decision techniques. The implemented scenarios are schematically explained in the table 14.3

| Number of safe havens | 2 | 4 | 6 | 8 | 10 |
|---|---|---|---|---|---|
| Road closures (Rd) | 2Rd | 4Rd | 6Rd | 8Rd | 10Rd |
| Decreased rate of warning (RoW) | 2RoW1 | 4RoW1 | 6 RoW1 | 8 RoW1 | 10 RoW1 |
| Road closure and decreased RoW | 2RdRoW1 | 4RdRoW1 | 6RdRoW1 | 8RdRoW1 | 10RdRoW1 |
| Additional warning centre (wc2) | 2wc2 | 4wc2 | 6wc2 | 8wc2 | 10wc2 |
| wc2 and Rd closure | 2Rdwc2 | 4Rdwc2 | 6Rdwc2 | 8Rdwc2 | 10Rdwc2 |
| wc2 and decreased in RoW in wc1 | 2RoW1wc2 | 4RoW1wc2 | 6RoW1wc2 | 8RoW1wc2 | 10RoW1wc2 |
| wc2 decreased RoW in wc2 | 2RoW2wc2 | 4RoW2wc2 | 6RoW2wc2 | 8RoW2wc2 | 10RoW2wc2 |
| Wc2 and decreased RoW in wc1 and in wc2 | 2RoW1RoW2wc2 | 4RoW1RoW2wc2 | 6RoW1RoW2wc2 | 8RoW1RoW2wc2 | 10RoW1RoW2wc2 |
| Wc2 and decreased RoW in wc1 and Rd closure | 2RdRoW1wc2 | 4RdRoW1wc2 | 6RdRoW1wc2 | 8RdRoW1wc2 | 10RdRoW1wc2 |
| wc2 and decreased RoW in wc2 and Rd closure | 2RdRoW2wc2 | 4RdRoW2wc2 | 6RdRoW2wc2 | 8RdRoW2wc2 | 10RdRoW2wc2 |
| wc2 and decreased RoW in wc1 and wc2 and Rd closure | 2RdRoW1RoW2wc2 | 4RdRoW1RoW2wc2 | 6RdRoW1RoW2wc2 | 8RdRoW1RoW2wc2 | 10RdRoW1RoW2wc2 |

Figure 14.3: Schematization of the 60 assessed scenarios: Rd means that the closure of the road has been modelled, RoW1 stays for Rate of Warning (the number one, $0.65m/s$, in this case), wc2 means that in the scenario two warning centers have been modelled

# Chapter 15

# Utility method

## 15.1 Introduction

The first decision criteria sets up for evaluating the scenario results concerns the idea of weighting-based voting technique. The concept of Utility has been adopted in terms of evaluating the goodness of each scenario [49]. The Utility has a simple and conceptually powerful importance, because gives back an easy to calculate, univoque for a given "universe" but strictly adaptable to the changing in the "universe" itself (such as the changing in the market, the political choices and so on). The importance in the utility criterion is to choose the criteria to be used, the weights and to formulate a feasible formalization to calculate the utility itself. In this sense, the utility is the evaluation of the chosen variable assessment from the post-evacuation results point of view. In effect the concept of utility has been adapted to the present case and an algorithm has been newly assessed. This algorithm follows the logic of DSS methodology developers. This logic aims to allow one to compute the utility factor by means of realization of a conceptual model. This model tries to reconstruct the Decision Maker mental processes [10], taking in account the criteria and the alternatives followed by an human mental process.

## 15.2 The weighting criteria

As shown before, different criteria by which the "success" of different emergency management plans has been chosen. These include criteria such as:

- Minimising the loss of life;
- Minimising the number of vehicles that are damaged;

- Minimising the time required for 60% of the population to reach a safe haven.

The importance of each of the above criteria has been given a weight as shown in table 15.1.

| Emergency management objective | Weighting |
|---|---|
| Minimising the loss of life | 0.7 |
| Minimising the number of vehicles that are damaged | 0.1 |
| Minimising the time required for 60% of the population to reach a safe haven | 0.2 |

Table 15.1: Costing weightings to assess different emergency planning options

A "cost" has been allocated to each alternative as shown in table 15.2.

| Scenario | Cost option |
|---|---|
| Two safe havens (2sh) | 0.2 |
| Four safe havens (4sh) | 0.4 |
| Eight safe havens (8sh) | 0.8 |
| Ten safe havens (10sh) | 1.0 |
| Ten safe havens with road closures when the water level reaches $0.6m$ (10SHRC0.6) | 1.0 |
| Ten safe havens with a delayed rate of warning (10shRoW0.5) | 0.8 |

Table 15.2: Costing weightings to assess different emergency planning options

It should be noted that the weightings and costs in table 15.1 and table 15.2 have been chosen purely to illustrate how decision makers can do a quantitative assessment of the modelled scenarios. In fact they depend on the particular socio-economical environment, to the contingent cost of each alternative and to the particular political choices.

## 15.3 Formalization of the utility factor

After defining the weighting criteria, the scenarios' utilities has been calculated. For that, a simple equation that takes in account the sum of the weight for each alternative, related to the analyzed criterion has been set up. This

utility gives back a numerical score for each alternative, giving the decision maker a way to make decisions in a quantitative manner. The scenario utility is based on the following equation:
$u_k = \sum_{i \in N_{criteria}} 1 - g_i(\alpha_k)$
Where:
$u_k$ is the utility of the kth alternative $k$
$g_i$ is the normalized weighted value of the $i-th$ criterion

## 15.4 Application of the methodology and results

Using this method for the six options shown in table 15.2 the following utility scores shown in figure 15.1 where calculated. Figure 15.1 shows that among the six emergency planning options considered, the option with four safe havens has the highest utility score. Figure 15.2 shows the results of the 60 scenarios detailed in table 15.1.

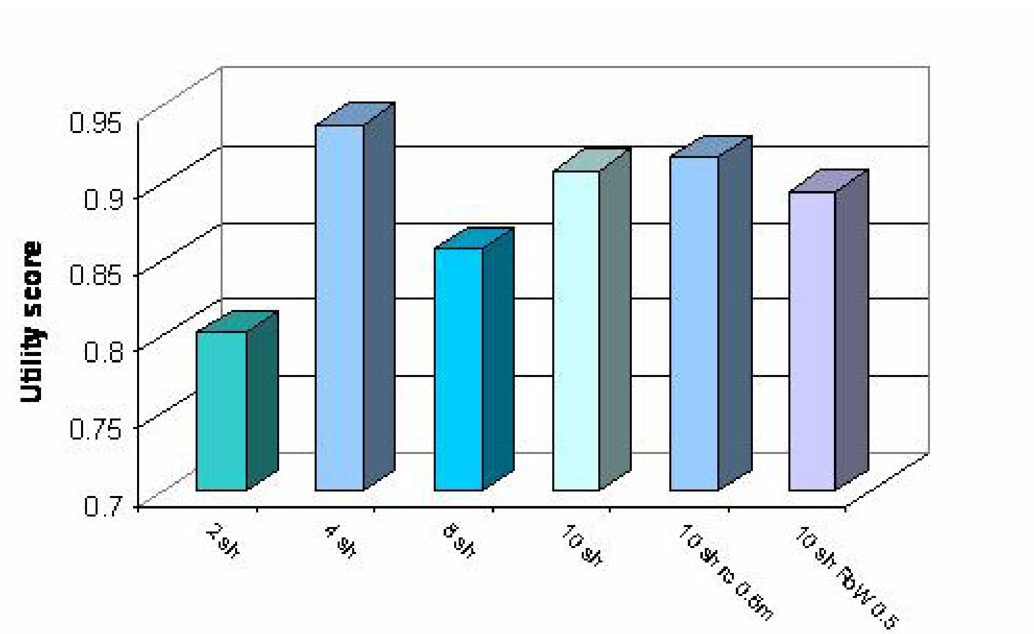


Figure 15.1: Assessment of six emergency planning options using the scenarios utility

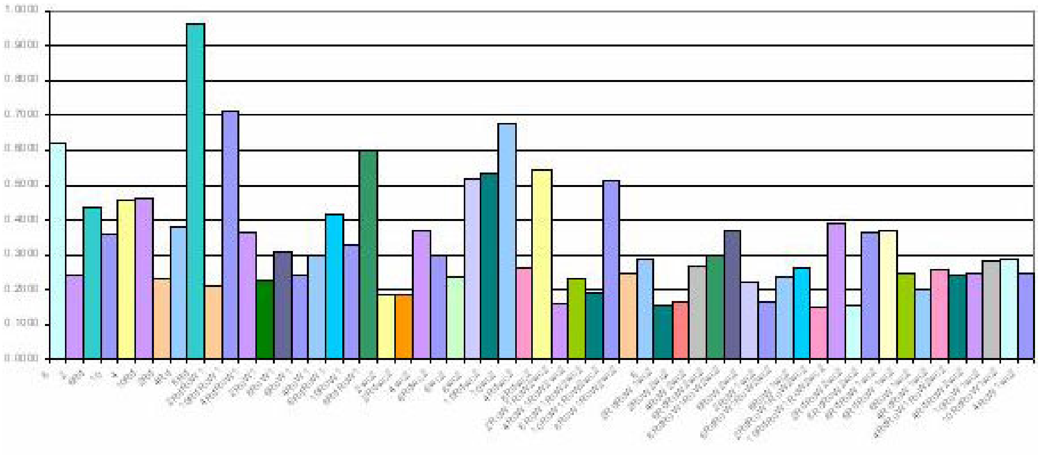


Figure 15.2: Assessment of 60 emergency planning options using the scenarios utility

# Chapter 16

# Clustering method

The decision techniques must be assessed in order to analyze the relationship between the changing in the scenarios assessment and the consequences of this changes. For that, it is important to explore the space of the consequences to find an objective way to evaluate the different scenarios. In order to evaluate the results of the scenarios, a clustering method has been applied. The first step in a clustering analysis consists of the selection of the important features. In this case, the sensitivity analysis presented before, and the social-political consideration of the importances of the different consequences in a flood disaster have driven to choose the features below:

- The weighted normalize percentage of people that have reached the safe heaven after 5 hours
- The weighted normalized percentage of people who loose their life
- The weighted normalize percentage of vehicle losses

The normalization and the weighting of this features has been done as in the utility methodology. In this case, the evaluation of the scenario based on the selected features has been made trying to find a natural spatial disposition of the data that could lead to which is the group of solution having the better behaviour in general. While the first feature needs to be maximized, for the other two a minimization is needed. The clustering analysis applied here is the K-means methodology.

## 16.1 K-means clustering

K-means [26] is one of the simplest unsupervised learning algorithms that solve the well known clustering problem. The procedure follows a simple and easy way to classify a given data set through a certain number of clusters (assume k clusters) fixed a priori. The main idea is to define k centroids, one for each cluster. These centroids should be placed in a cunning way because of different location causes different result. So, the better choice is to place them as much as possible far away from each other. The next step is to take each point belonging to a given data set and associate it to the nearest centroid. When no point is pending, the first step is completed and an early clustering is done. At this point we need to re-calculate k new centroids as barycenter of the clusters resulting from the previous step. After we have these k new centroids, a new binding has to be done between the same data set points and the nearest new centroid. A loop has been generated. As a result of this loop we may notice that the k centroids change their location step by step until no more changes are done. In other words centroids do not move any more. Finally, this algorithm aims at minimizing an , in this case a squared error function. The objective function

$$J = \sum \sum \|x_i^{(j)} - c_j\|^2 \tag{16.1}$$

where $\|x_i^{(j)} - c_j\|$ is a chosen distance measure between a data point $x_i^{(j)}$ and the cluster center $c_j$, and it is an indicator of the distance of the n data points from their respective cluster centers.

The algorithm is composed of the following steps:

1. Place k points into the space represented by the objects that are being clustered. These points represent initial group centroids.

2. Assign each object to the group that has the closest centroid.

3. When all objects have been assigned, recalculate the positions of the K centroids.

4. Repeat Steps 2 and 3 until the centroids no longer move. This produces a separation of the objects into groups from which the metric to be minimized can be calculated.

Although it can be proved that the procedure will always terminate, the k-means algorithm does not necessarily find the most optimal configuration, corresponding to the global objective function minimum. The algorithm is also significantly sensitive to the initial randomly selected cluster centers. The k-means algorithm can be run multiple times to reduce this effect. k-means is a simple algorithm that has been adapted to many problem domains.

## 16.2 Application of the methodology and results

In this case, following the k-means clustering, the clustered space of the consequences has been divided in five class.

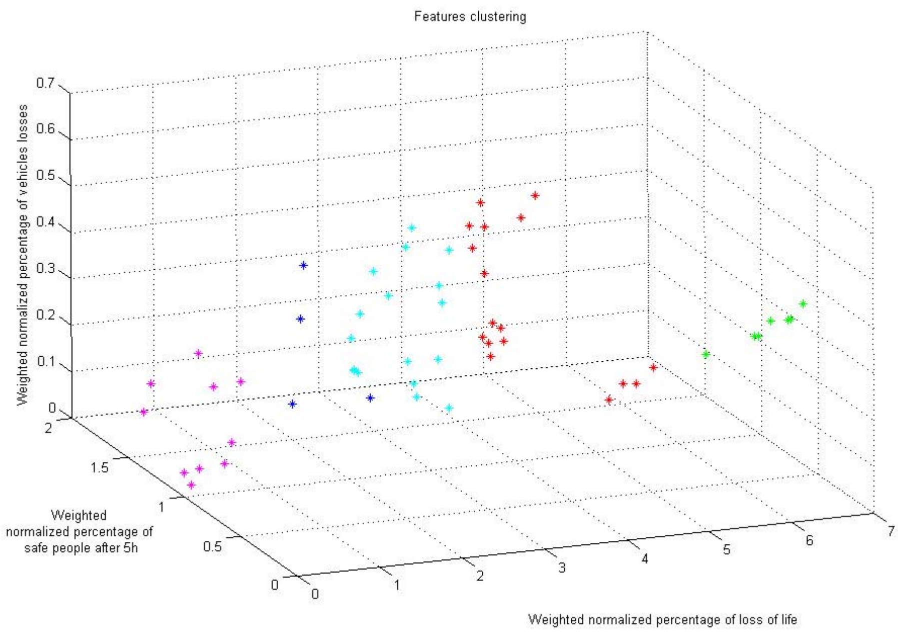


Figure 16.1: Results of the clusterization of the scenarios in five classes

For this class, the one that has been recognized to be the most likely one is the fourth class, that is the purple in figure 16.1, that contains the following scenarios:

- 4 (four safe heavens)
- 6 Rd (six safe heavens and the closure of the roads)
- 8 Rd (eight safe heavens and the closure of the roads)
- 10 RdRow1 (ten safe heavens, the closure of the roads and the rate of warning number one)
- 10 wc2 (ten safe heavens and two warning centers)

- 8 Rdwc2 (eight safe heavens, the closure of the roads and two warning centers)
- 10 RoW1RoW2wc2 (ten safe heavens, the closure of the roads, the rate of warning number one and two warning centers)

This result is the one corresponding to the minimisation of the two features that have to be minimized and the exploration of the wide range of the third feature. In fact, if we reduce the choice at the inferior limit of the results, this domain is the closest one to the Pareto's solution, in terms of multiobjective modelling [13]. while the solution is clearly defined in this case, it could be difficult to discern it in case of a large number of scenarios. Furthermore, the methodology allows us to have the measure of the distance between the different classes' centroids, that give an idea of the degree of belongness of each scenario to a particular class. The bigger the distance, the fewer is the belongness, that states that the scenario could be swooped with one of the other neighbour class, in therm of advantages/disadvantages.

# Chapter 17

# Method based on a decision tree technique

In order to explore the different alternatives and the different scenarios, a decision tree technique has been tested. Decision Trees are a class of techniques for helping to choose between several courses of action. They provide a highly effective structure within which it is possible to lay out options and investigate the possible outcomes of choosing those options. They also help the decision maker to form a balanced picture of the risks and rewards associated with each possible course of action, due to the value of each decision branches.

## 17.1 The decision tree

In operations research, specifically in decision analysis, a decision tree (or tree diagram) is a decision support tool that uses a graph or model of decisions and their possible consequences, including chance event outcomes, resource costs, and utility. A decision tree is used to identify the strategy most likely to reach a goal.

In this case, the decision tree has been developed as shown in figure 17.1 The upper branches A and B refer to the two hydraulic scenarios chosen for the evacuation modelling. The weight on these branches is due to the probabilities of occurrence that is related to the probabilities of failure of the defense related to the particular scenario. The lower branches refer to the number of safe heavens (second level), the choice to close or not the roads (third level) and the rate of warning dissemination (fourth and last level). The weight for these branches has been calculated basing on the real improvement of the branches choices that have been observed in the simulated scenarios.

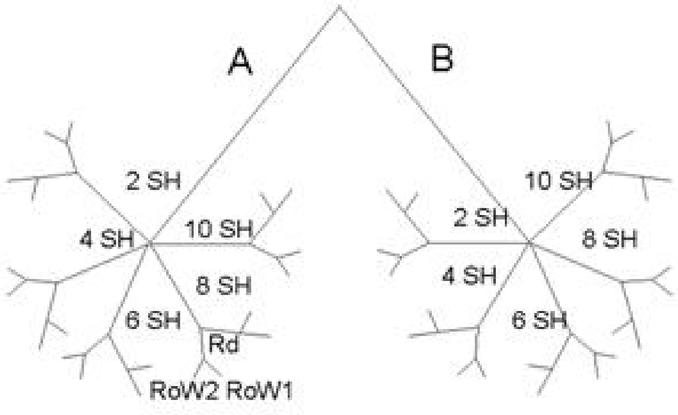


Figure 17.1: Decision Tree for the evacuation scenarios

## 17.2 The model

The best path from the root to a leaf of the tree corresponds to the best chosen intervention. It can be determined by solving an optimization model where boolean variables $x(i, l)$ are equal to 1 if the branch $i$ at level $l$ is included in the solution and 0 otherwise. The weight $w_i$, described in the previous section, is associated to each branch. The aim of the model is to identify the path that minimize the global cost of the alternatives. The model can be formulated as follows:

$$Min \sum_i w_i l_1 + \sum_j w_j l_2 + \sum_k w_k l_3 \quad (17.1)$$

subject to:

$$\sum_i l_1 \leq 1 \quad (17.2)$$

$$\sum_j l_2 \leq 1 \quad (17.3)$$

$$\sum_k l_1 \leq 1 \quad (17.4)$$

$$x_{il} \in 0, 1 \quad (17.5)$$

Constraints 17.2 - 17.5 require that at each level only one branch is selected. This model can be solved by a generalized shortest path algorithm [1] or by a branch&bound technique like that described in chapter 19.

## 17.3 Results

The models has converged in one iteration, given back that the chosen path is the one corresponding to the scenario with 4 safe heaven, with the road closure options and with the rate of warning dissemination 1.5. The path in the tree is schematized in figure 17.2

This technique is particularly useful because allows to not recalculate and re-run the whole evacuation model. In fact, once the branches of the three has been calibrated, new possible scenarios could be explored.

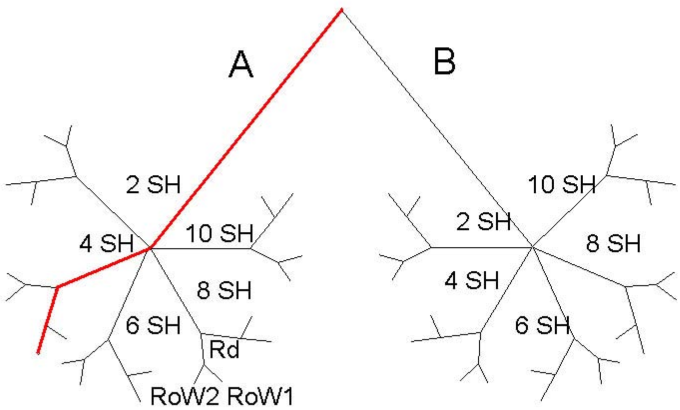


Figure 17.2: Chosen path in the decision tree

# Chapter 18

# Markov decision chain

Another decision technique tested here is the Markov decision technique. A Markov Decision Process (MDP) is just like a Markov Chain, except that the transition matrix depends on the action taken by the decision maker (agent) at each time step. The agent receives a reward, which depends on the action and the state. The goal is to find a function, called a policy, which specifies which action to take in each state, so as to maximize some function (e.g., the mean or expected discounted sum) of the sequence of rewards [42].

## 18.1 Markov decision process

A Markov Decision Process is a discrete time stochastic control process characterized by a set of states; in each state there are several actions from which the decision maker must choose. For a state $s$ and an action $a$, a state transition function $P(a(s))$ determines the transition probabilities to the next state. The decision maker earns a reward for each state visited. The states of an MDP possess the Markov property. This means that, if the current state of the MDP at time $t$ is known, transitions to a new state at time $t+1$ are independent of all previous states. For the present case, the transition probabilities are calculated by means of the transition mechanism empirically observed in the modeled scenarios. The transition between one state and the other gives a score to the choice, due to the actual advantage/disadvantage brought to the system as consequence of the choice.

## 18.2 Application and results

The results of this analysis are shown in the table 18.1, in which the total rewards for each scenario has been shown. While in the decision tree, the cost of each branch has been calculated basing on the average ameliorament brought from the particular action to the system, in this case, the transition matrix has been calculated basing on the consequences of the transition between a state to another. This analysis states that the the best scenario, in this case, is the one with 6 safe heavens, the road closure and the the rate of warning dissemination 1.5.

| | nRD_nRow | RD_nrow | RD_Row |
|---|---|---|---|
| 2 | 0 | 0.063104 | -0.0601 |
| 4 | 0 | -0.5961 | -0.7193 |
| 6 | 0 | 0.655662 | 0.532463 |
| 8 | 0 | 0.303359 | 0.18016 |
| 10 | 0 | 0.090959 | -0.03224 |

Figure 18.1: Transition rewards between the states

# Chapter 19

# Planning the evacuation: developing an optimization model for evacuation planning direction and time calculation

Despite of the goodness and the accuracy of the BC Life Safety Model, it would be quite time consuming concerning the data collection and the setting up. For a first analysis it could be useful to have a quick and simple instrument to compute the evacuation scenarios, by means of a model that even if does not require a great amount of input data, could be strongly rigorous anyhow. For that, an evacuation model based on the linear integer optimisation programming has been implemented. This model practically takes in account the road network, considering the different kinds of road, everyone having a characteristic capacity in terms of vehicles/km/lane that give back the time that each vehicle needs to wait "stacked" in a traffic jam.

## 19.1 The model formulation

Referring to the Graph G=(N;A), as defined in chapter 19, section 19.0.4, the mathematical model can be formulated in terms of a linear integer model as follows: Data
$t_{ij}$ : "cost" associate to each arc $(i, j) \in A$ $T \subset N$: set of destination (heavens) nodes $b_i$ : number of vehicles starting from each node $i \in N - T$ $u_{ij}$ : estimated upper capacity of each arc $(i, j) \in A$ Variables $x_{ij}$ : integer nonnegative variable representing the number of vehicles on each arc $(i, j) \in A$ $y_{ij}$ : binary decision variable equal to 1 if arc $(i, j)$ is part of solution, 0

otherwise

The objective function can be expressed in terms of minimizing the global travel time, instead of global distance, and $t_{ij}$ represent the estimate travel time of arc $(i, j)$. While the computation of distances is straightforward, the estimation of travel times is often difficult. A rough evaluation of the travel time along a road segment can be obtained by dividing road (lane) length by the average speed at which the road segment can normally be traversed. This method results accurate enough for inter-city roads but less performing for intra-city lanes. In such a case, average travel times can be estimated by making recourse to a regression method. A regression equation can be used to forecast the average travel time as a function of factors mainly affecting the travel time along a lane. The most relevant factors are the number of lanes, street width, whether the street is one-way or two-way, traffic volume and the quality of the road surface. The objective function can then be expressed as:

$$Min\{\sum_{(i,j)\in A} t_{ij}y_{ij}\} \tag{19.1}$$

Constraints can be formulated as follows:

$$\sum_{j\in S(i)} x_{ij} - \sum_{j\in P(i)} x_{ji} = b_i \tag{19.2}$$

for each node $i \in N - T$

Where $S(i)$ is the set of successors and $P(i)$ the set of predecessors of node $i$. This is the balance constraints expressing that, in each node, the number of vehicles coming in the node plus the number of vehicles, $b_i$, starting from that node must be equal to the number of vehicles leaving the node (no vehicles can stop in a node).

$$x_{ij} < u_{ij}y_{ij} \tag{19.3}$$

for each arc $(i, j) \in A$

This state that if the arc $(i, j)$ is used $(y_{ij} = 1)$ then the number of vehicles cannot be greater the estimated capacity of the lane. Otherwise, if the arc $(i, j)$ is not used $(y_{ij} = 0)$ then no vehicles can travel along that arc.

$$\sum_{k\in T} \sum_{i\in P(s_k)} x_{ik} = b_i \tag{19.4}$$

This state that all vehicles have to reach the safe heavens

Finally

$x_{ij} \in I^+ + 0$ state that vehicles number must be nonnegative integer and
$y_{ij} \in 0, 1$ state that this decision variable must be boolean.

In this scenario, 2 safe heavens are set up. The people in the vehicles need to reach the safe heaven to complete the evacuation. Starting from this assumptions, the model optimize the number of vehicles passing through each road segment, minimizing the time that is needed to arrive to the safe heaven and choosing which is the optimal safe heaven to address each vehicle. In this model, for simplicity, only the vehicles have been modelled, but it could have been possible to add an overlapped network for the pedestrian. This is a problem involving the nonlinear programming, as long as the time is non linearly dependent on the number of vehicles. The non linearity is in only the objective function and not in the constrains. The variable in the problem are the number of car for each road arch, that is an integer continuous variable, and the variable that says whether the road arch is covered or not, that is a Boolean variable.

## 19.2 The solving technique

The model solving is based on the Branch and Bound method, that is a systematic method for solving optimization problems that applies where the greedy method and dynamic programming fail. The general idea of B&B is a breadth-first like search, a graph search algorithm that begins at the root node and explores all the neighboring nodes, for the optimal solution, in which not all nodes get expanded. Rather, a carefully selected criterion determines which node to expand and when, and another criterion tells the algorithm when an optimal solution has been found.

## 19.3 Model results

This model gives back the optimal ways for the vehicles, the best distribution of the people between the n safe heavens and the time for each road to be crossed. Knowing that results, the calculation of the maximum time needed for the further group of people to reach the safe heaven is straightforward. Furthermore, a comparison between scenarios it could be done, moving the location of the safe heavens and analyzing scenarios having different number of safe heavens. The model testing has been done using a Thamesmead-based scenario, with a simplified road network explained in the table in 19.1 and with the population distributed in each nodes, basing on the actual closeness. The nodes-arches disposition is shown in and in table in 19.2 The model set up by means of choosing the nodes 3 and 8 as safe heaven is shown in the table in 19.3 and in the figure below. The time can be easily derived from the results.

| Arch | Length | Type of road | N of lanes |
|---|---|---|---|
| 2_3 | 600 | 2_lanes | 1 |
| 1_2 | 2600 | 4_lanes | 2 |
| 1_3 | 700 | small | 1 |
| 1_4 | 2000 | 2_lanes | 1 |
| 3_4 | 300 | small | 1 |
| 4_5 | 2000 | 2_lanes | 1 |
| 3_6 | 1800 | 2_lanes | 1 |
| 5_6 | 450 | 2_lanes | 1 |
| 6_7 | 800 | 2_lanes | 1 |
| 14_7 | 3400 | 2_lanes | 1 |
| 14_2 | 600 | 2_lanes | 1 |
| 7_8 | 800 | 2_lanes | 1 |
| 5_8 | 1400 | 2_lanes | 1 |
| 8_9 | 700 | 2_lanes | 1 |
| 9_12 | 1100 | small | 1 |
| 9_10 | 900 | 2_lanes | 1 |
| 10_11 | 2100 | 2_lanes | 1 |
| 11_15 | 1800 | 2_lanes | 1 |
| 6_8 | 900 | 4_lanes | 2 |
| 11_12 | 700 | small | 1 |
| 15_13 | 1400 | 2_lanes | 1 |
| 13_12 | 2000 | 2_lanes | 1 |
| 13_7 | 900 | 2_lanes | 1 |
| 13_14 | 3200 | 4_lanes | 2 |

Figure 19.1: Road network characteristic parameters

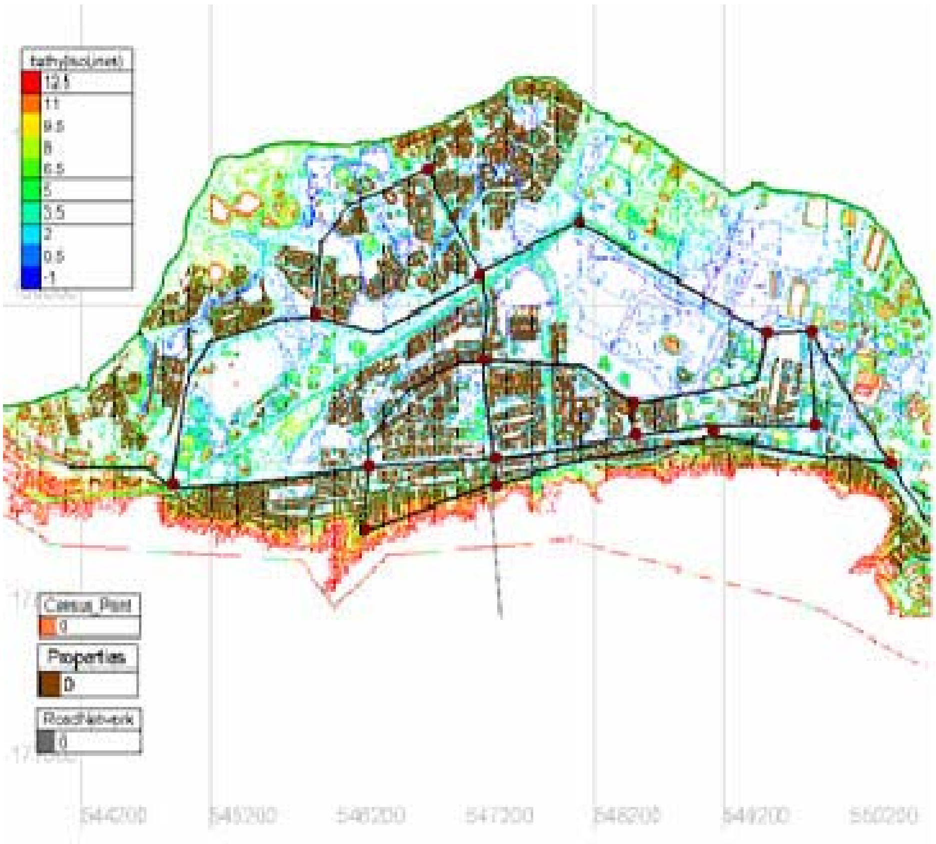


Figure 19.2: Node-arch model configuration

| Node | N of people starting from the node | Number of car starting from the node |
|---|---|---|
| 1 | 800 | 200 |
| 2 | 1400 | 350 |
| 3 | 2800 | 700 |
| 4 | 1600 | 400 |
| 5 | 4200 | 1050 |
| 6 | 5800 | 1450 |
| 7 | 4300 | 1075 |
| 8 | 5100 | 1275 |
| 9 | 2800 | 700 |
| 10 | 1900 | 475 |
| 11 | 3700 | 925 |
| 12 | 2800 | 700 |
| 13 | 2200 | 550 |
| 14 | 300 | 75 |
| 15 | 3600 | 900 |

Figure 19.3: Initial disposition of the people in each node

An example of the potentiality of the model has been set up by means of choosing two nodes as safe heavens and changing the position of that nodes, in order to have the different evacuation paths, that helps the decision maker in organizing the evacuation, and the optimum number of vehicles going through each road. In order to compare the different scenarios, the values of the objective function, that is the total cumulative time in the network, are shown in the table 19.4.

| Scenario | Total cumulative time |
|---|---|
| 5_7 | 29 |
| 6_15 | 27.8 |
| 3_8 | 30.5 |
| 5_9 | 30.1 |
| 2_4 | 27.6 |
| 6_9 | 28.1 |

Figure 19.4:

The six safe heaven disposition in the scenarios are shown in the figure 19.5.

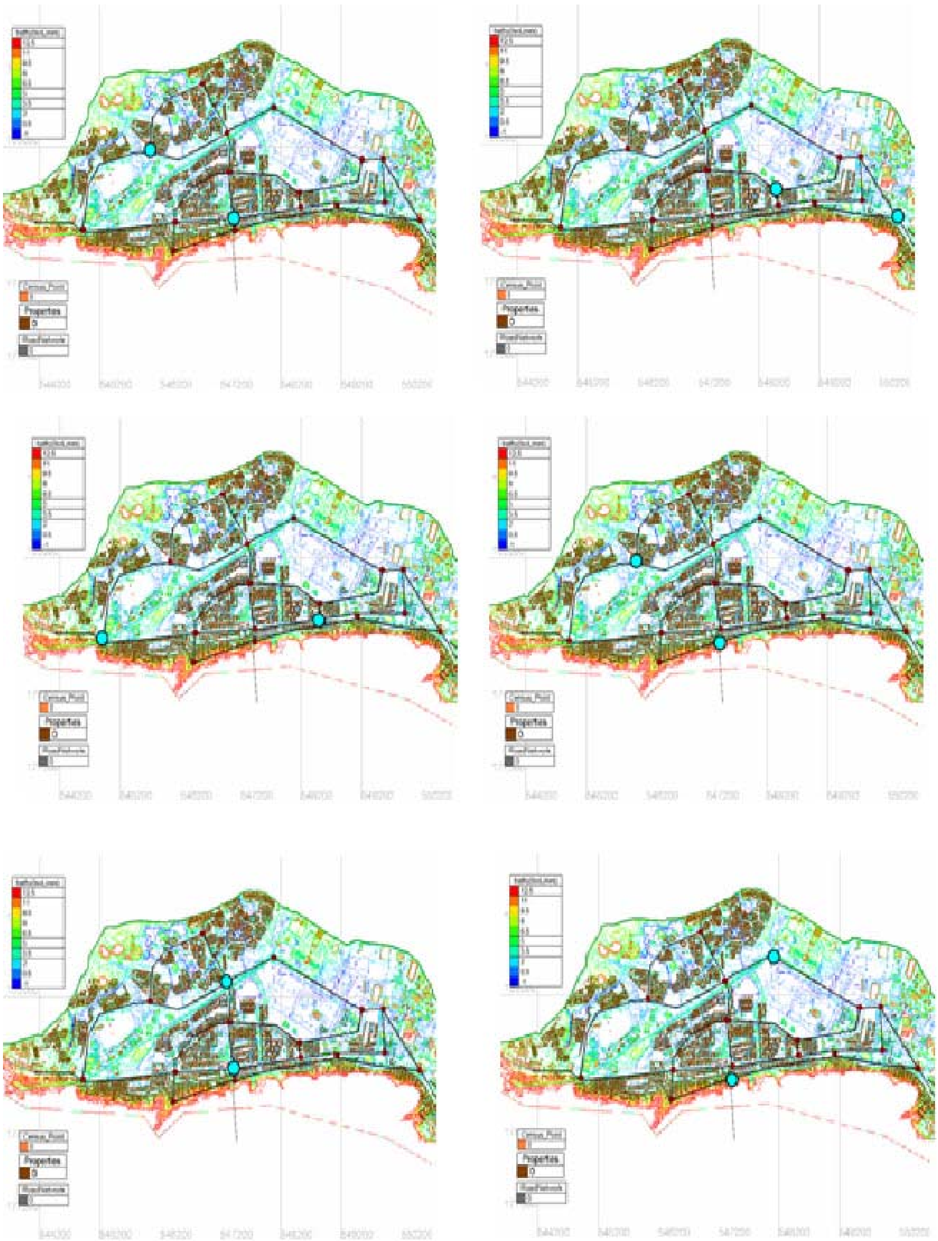

Figure 19.5: The six scenarios tested

# Conclusions

In this part, starting from the results of the evacuation model, several decision techniques have been developed, implemented and tested for one of the case study data. These techniques give back a powerful instrument that allows to quantify the importance of each choice, justify each decision taken from a objective point of view and give back in a short time a formal analysis of a high number of scenarios.
Furthermore, in this part, an example of how an evacuation model could be implemented has been presented, by means of setting up a model using the optimisation analysis. This model differs for the previous one because give back clear instructions for the evacuation planning, and not only a picture of the actual scenario. In fact, the output of this model consists in the optimal ways for the vehicles, the best distribution of the people between the n safe heavens and the time for each road to be crossed. The model has been tested for one of the pilot sites. The different approaches adopted give back a interesting picture of the problem of the evacuation assessment, presenting a relevant test case-based analysis for future decision making approaches.

# Part V

# Overall conclusions

In the present work, the scenario modelling that is needed to support the decision making in water risk scenario has been explored. Besides the work that has been done in order to make possible to understand the different methodologies and to give back a "final usable product", that is peculiar in the industrial research field, this thesis presents different original contribution to the research.

In order to develop the thesis, two mobility period have been done. The PhD student collaborated as visitor researcher with the Helmholtz-Zentrum für Umweltforschung UFZ in Leipzig, Saxony. Thanks to this collaboration, the first part of this thesis has been developed. The second mobility period has been performed in HR Wallingford Ltd, Oxfordshire, United Kingdom. This collaboration has been essential for the development of the second and third parts of this thesis. Besides the technical aspects of the research work here presented, the exchange periods have contributed to increase the study and the personal experiences of the student.

In the first part, new modelling techniques have been realized and implemented for the rain model, exploring the possibilities of using the Circulation Patterns in the model, without performing a GCM, that would introduce an increase of time and cost to the modelling. Therefore, with the approach delineated here, only the CP data and the basin precipitation data are needed. The testing has demonstrated that this approach increases the performance in the weather generator, if compared with some of the classical approaches, specially in estimating the maxima.

In the second part, the hydrodynamic modelling field has been explored and applied to assess the risk analysis in one vulnerable area, to perform all of the needed analysis and going through the multidisciplinary calculation. Furthermore, two main original contributions could be delineated. First, the modelling has been performed in an area that is an interesting test case for the hydrodynamic modelling for its morphologic aspect, for the particular exposition and from the social point of view. Second, the historical analysis to reconstruct and important flood event has been performed, exploring the

different font that have been available and study how to reconstruct the 1953 picture with the actual technologies.
In the third part, the main original contribution has been to explore a new approach to asses an evacuation planning, with a new philosophy of evacuation modelling and decision making for the evacuation itself. The model has been tested for the first time in a densely populated area for a breach inundation scenario. Furthermore, the testing has taken into account the sensitivity of the model and the data requirements from a technical point of view. The results have shown how this model can be implemented, which kind of analysis needs to be done to set up the input data, which are the output and how they can be red.
In the fourth part, starting from the results of the evacuation model, several decision techniques have been developed. The main originality in this work is that different techniques have not only explored, but also implemented and tested for the case study data. These techniques give back a powerful instrument that allows to quantify the importance of each choice, justify each decision taken from a objective point of view. Furthermore, they give back in a short time a formal analysis of a high number of scenarios without running again the evacuation modelling tool.
This thesis is a work that go trough different aspects of the modelling in order to produce and assess scenarios in the water risk field. The peculiarity of this work is to put together the research and the application to a practical case, that is peculiar from the industrial engineering point of view. Furthermore, a great work in bibliographic research has been done, and different methodologies coming from totally different aspects of the water risk discipline (and from outside) has been performed, explored and implemented. These aspects characterize this work by having a high level of multidisciplinarity, also showing how to use these instruments together to reach a common objective.

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