Report Phase B

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MANAGING THE RISK IN THE COASTAL ZONE

FLOODING RISK IN COASTAL AREAS - TECHNIQUES AND MODELS FOR PREDICTION

1. Introduction - The Conceptual Model

Flood risk is defined as the combination of the probability of a flood event and of the potential adverse consequences to human health, the environment and economic activity associated with a flood event. For understanding the physical system of flooding, it is useful to consider the commonly adopted Source-Pathway-Receptor-Consequence (S-P-R-C) conceptual model. This is a conceptual tool for representing systems and processes that lead to a particular consequence. For a risk to arise there must be a hazard that consists of a source or initiating event; a receptor (person or property); and a pathway that links the receptor to the source. In the context of coastal flooding these terms are identified in Figure 1.

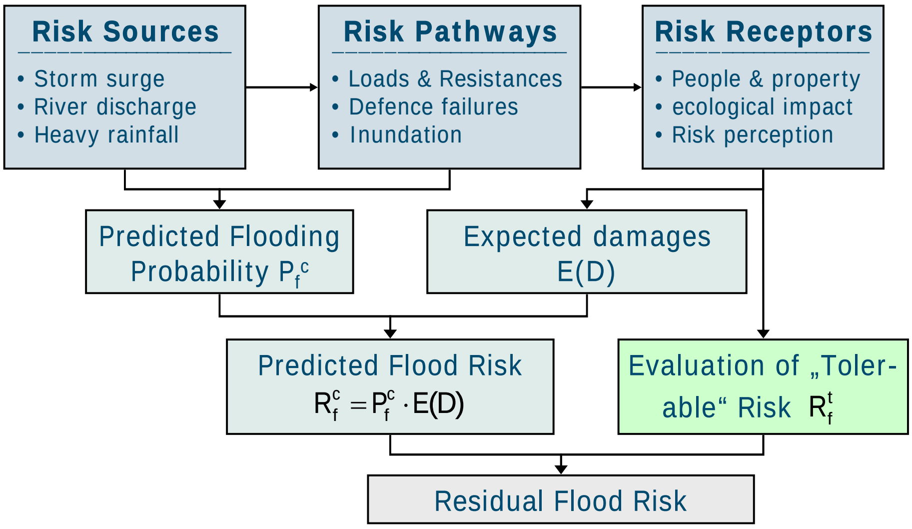


Figure1. Conceptual model and methodology of calculating flood risk

These elements of the flood system can be described as:

Sources- High wave conditions and high sea levels (tide and surge), offshore and transformed to nearshore are typically considered as the source of coastal flooding.

Pathways- Flood defence responses such as overtopping or breaching, and flood inundation and propagation are considered as the pathways of coastal flooding.

Receptors- The receptors of coastal flooding are considered as property, people and the environment.

Consequences- Loss of life, stress, material damage and environmental degradation are considered the consequences of coastal flooding.

In Figure 1, P_f^c is the predicted overall flooding probability and E(D) is the expected economic and non-economic damages in the flood prone areas. The predicted flood risk probability is defined as: $R_f^c = P_f^c \cdot E(D)$ and R_f^t is the tolerable risk by the receptors of risk.

The physical processes dominating the sources of coastal flooding vary from the large scale oceanic environment, through the regional scale coastal environment and into the pathway environment of coastal defences and flood plain areas. As the dominant physical processes change, the modeling methods that have been developed to simulate them have also changed. With these dominant physical processes in mind, it is useful to describe the physical system as interconnected but distinct zones. For the purposes of this study these zones have been defined as given below in Figure 2.

- Sources
  - Offshore waves and water levels (including processes of wave generation and the interaction of waves with each other)
  - Nearshore waves and water levels (loosely defined as the zone in which the seabed influences wave propagation and includes shallow water effects such as shoaling, depth refraction, interaction with currents and depth induced wave breaking).

- Pathways
  - Shoreline response (including response of beaches and defences to waves, wave structure interaction, overtopping, overflowing and breaching)
  - Flood inundation (including flow of flood water over the flood plain area).

Although, for ease of understanding, the physical system has been characterized as four separate zones, it is important to note the boundaries of these zones are “blurred” and certain models may simulate physical processes over two or more of the defined zones.

For calculating the risk of flooding the following should be examined: (a) storm classification, (b) analysis of extreme events and estimation of return levels, (c) modeling methods, (d) techniques-models.

2. Storm Classification

The impacts of storms on coastal areas induce a range of potential hazards for the natural as much as for the human environment. Phenomena such as beach and dune erosion, overwash, inundation, even infrastructure damages in developed coasts, affect systematically and dynamically the modulation of prevailing conditions in coastal areas. Therefore, storm classification is deemed to be essential in the framework of Integrated Coastal Zone Management and of the aforementioned phenomena’s scientific study, rendering -at the same time- their impacts’ investigation easier.

The identification and further study of storms, is achieved through the collection and statistical analysis of wind (wind speed and duration, frequency of occurrence) and wave (wave height, wave period, sea level rise) measurements’ data. Mendoza and Jimenez (2006) defined storms as events exceeding a minimum significant wave height (SWH) of 2.0m and with a minimum duration of 6h, while Hill et al. (2004) instead of the duration criterion proposed that that storms should have a maximum horizontal scalar speed that is more than twice the background variability of the surrounding data.

The storm classification scales presented in this chapter are frequently cited in relevant bibliography.

The Saffir-Simpson scale (Saffir and Simpson, 1971) based on hurricane intensity, is used to identify their destructive potential and constituted the qualitative basis for every posterior classification attempt. The scale, as presented in Table 1, comprises five categories characterized by various wind speed, atmospheric pressure and storm surge ranges. Each hurricane category is considered to cause damages of different extent (ascending from the 1st to the 5th category) to both natural environment and infrastructures.

Table 1: The Saffir-Simpson scale (Saffir and Simpson, 1971)

Category	Wind Speed [km/h]	Atmospheric Pressure [mb]	Storm Surge [m]	Damage Level
1	119-153	> 980	1-2	Minimal
2	154-177	965-979	2-3	Moderate
3	178-209	945-964	3-4	Extensive
4	210-249	920-944	4-6	Extreme
5	> 250	< 919	> 6	Catastrophic

University of Virginia researchers Dolan, R. and Davis, R., invented and publicized in 1992 (Dolan and Davis, 1992) a classification scale resulted from wave height and duration data analysis of 1347 north-eastern originated storm events (also known as “northeasters”) along the North Carolina coast, over a period of 42 years (1942-1984). The storms were classified according to their peak wave height and duration, parameters also used in the calculation of each event’s “relative storm power”. The scale, as presented in Table 2, comprises five categories of ascending destructive potential, for which the frequency of occurrence and the return interval are additionally quoted.

Table 2: The Dolan-Davis scale (Dolan and Davis, 1992)

Category	Frequency of Occurrence [%]	Average Return Interval	Peak Wave Height [m]	Average Duration [h]	Damage Level
1	49.7	3 days	6.6	8	Minimal
2	25.2	1 month	6.2	18	Moderate
3	22.1	9 months	10.8	34	Extensive
4	2.4	11 years	16.4	63	Extreme
5	0.1	100 years	23.0	95	Catastrophic

A classification scale similar to that of Dolan and Davis, was presented in 2004 by Mendoza, E. and Jimenez, J. (Mendoza and Jimenez, 2004), based on a 14-year long (1990-2004) time series of wind and wave data along the Catalonian coast. To characterize each storm's intensity Mendoza and Jimenez used the term of "energy content", parameterized as:

$$E = \int_{t1}^{t2} H_s^2 \cdot dt \tag{1}$$

where t_1 and t_2 define the duration of the storm and H_s is the significant wave height. They modified their scale in 2006 (Mendoza and Jimenez, 2006), due to their changing the minimum significant wave height criterion for defining an event as storm, from 1.5m to 2.0m. The scale, as presented in Table 3, adopts the rationale of Saffir–Simpson and Dolan–Davis scales and comprises five storm categories as well. Each category is associated with the maximum meteorological tide "ξ" registered during the storm.

Table 3. The Mendoza–Jimenez "energy content" scale (Mendoza and Jimenez, 2006)

Category	**Maximum Significant Wave Height [m]**	**Duration [h]**	**Peak Period [sec]**	**Energy [m^{2}h]**	**ξ [cm]**
I	2.6	13	7.3	57.2	18
II	3.1	32	8.3	175.1	17
III	3.4	56	8.2	342.6	14
IV	4.3	76	9.9	634.1	27
V	6.0	161	11.1	1368.9	53

Also in 2006, Mendoza and Jimenez (Mendoza and Jimenez, 2006) introduced a second scale based on the erosive potential of each storm category. This scale's innovation consists in the diversion from the classification attempts based on the storm characteristics, to those based on its consequences, quantitative and not just qualitative as well. In this particular approach, the coastal response to storms is defined by two parameters: beach retreat "ΔX" and eroded volume "ΔV". These parameters were calculated using the computational model SBEACH ("beach profile model") as well as various predictors. Table 4 shows the aforementioned parameters' values for reflective beaches.

Table 4. The Mendoza–Jimenez "erosive potential" scale (Mendoza and Jimenez, 2006)

Category	**ΔV [m^3/m]**	**ΔX [m] (z=+3.8m)**	**ΔX [m] (z=+2.0m)**	**ΔX [m] (z=0.0m)**
I	-16.8	-5.0	-3.8	-1.4
II	-22.0	-6.5	-5.4	-2.4

III	-35.9	-10.1	-8.8	-4.8
IV	-51.7	-11.0	-11.7	-9.0
V	-91.9	-24.2	-22.0	-15.3

* where z is the elevation above the mean sea level at which ΔX was calculated

In 2001 MacClenahan et al. (MacClenahan et al, 2001), presented a storm classification scale based on a totally different rationale, resulted from the analysis of wind data time series along the western Irish coast (weather stations at Malin, Head and Valencia and data from the time periods 1956-1998, 1956-1998 and 1940-1998 respectively). The classification criterion used by these researchers was the threshold exceedance for a trinity of storm parameters (wind speed, storm duration and duration gap between successive storms). These thresholds were calculated using a numerical model developed in the framework of the specific study. The proposed scale, as presented in Table 5, comprises seven categories without correlating them with storm-induced impacts on the coastal area.

Table 5. The MacClenahan et al. scale

Category	E1	E1	E2	E2	E3	M1	M2
Thresholds	60,1,1	60,1,1 50,5,1	50,1,1	50,1,1 40,5,1	30,48,1	40,24,1	40,5,1

* the digit trinity refers to: wind speed threshold [knots], storm duration threshold [h] and duration gap between successive storms [h]

3. Analysis of extreme events and estimation of return levels

Risk is a combination of the chance of a particular event, with the impact that the event would cause if it occurred. Thus, risk includes two components: the probability of an event occurring and the consequences associated with the event. Consequences can either be desirable or undesirable. When considering floods, risk is typically concerned with the likelihood of undesirable consequences. All risks should be considered in terms of source, path, receptor and consequence model. In order to assess risk, spatial and temporal variability of both likelihood and consequence should be considered. A simple measure of risk may be calculated by: Risk = Probability * Consequence.

Risk analysis is characterized by uncertainty. Two different categories of uncertainty are considered: the inherent uncertainty that represents randomness in samples both in space and time and uncertainties that are caused by lack of knowledge on particular physical systems or by the lack of sufficient data. While the first category of uncertainty cannot be reduced, the second one can decline, increasing the understanding of physical processes and the amount of data to be analyzed.

Units of risk are defined according to the units of its components: likelihood and consequences. Likelihood is generally expressed as a probability or frequency. Frequency defines the expected number of occurrences of a particular event within a specific time frame. Probability may be defined as the chance of occurrence of one event compared to the population of all events. It is often expressed with reference to a time period, for example annual exceedance probability. As mentioned earlier, probability is more frequently utilized in risk calculation.

The fact that engineering works need to be designed for extreme conditions requires special attention to be paid to singular values, more than to regular (mean) ones. Block maxima and exceedances over high thresholds are used, according to data availability, to extract design values for different structures.

Extreme value methods are powerful statistical methods for drawing inference about the extremes of a process, using only data on relatively extreme values of the process. Extreme value methods are usually utilized for the purpose of extrapolation to levels more extreme than those which have been observed. The statistical methodology is motivated by a well- established mathematical theory (Extreme Value Theory), which relies on the assumption that the limiting models suggested by the asymptotic theory continue to hold at finite but extreme levels. Nevertheless, a crucial assumption in fitting distribution functions to data is that the data are independent and identically distributed (iid).

It is supposed that $X_1, X_2, \dots X_n$ is a series of independent and identically distributed variables with a common distribution function F and that $M_n = \max(X_1, X_2, \dots, X_n)$. We assume that there are sequences of normalising constants $a_n > 0$ and b_n that:

$$P\left(\frac{M_n - b_n}{a_n} \leq z\right) \rightarrow G(z) \text{ as } n \rightarrow \infty \qquad (2)$$

for all $z \epsilon [z_-, z_+]$, where G is a non degenerate function supported in the interval $[z_-, z_+]$.

The two classic results in Extreme Value Theory state that:

a) G has a Generalised Extreme Value (GEV) distribution with distribution function

$$G(z) = \exp\left[-\left\{1 + \xi\left(\frac{z - \mu}{\sigma}\right)\right\}_+^{-1/\xi}\right] \qquad (3)$$

where μ, $\sigma > 0$ and ξ are location, scale and shape parameters respectively (G is defined by continuity when $\xi = 0$).

b) The conditional distribution of exceedances $(X_i - u) | (X_i > u)$, converges to a Generalised Pareto distribution (GPD) with distribution function

$$H(z) = 1 - \left(1 + \frac{\xi \cdot z}{\hat{\sigma}}\right)^{-1/\xi} \qquad (4)$$

as $n \rightarrow \infty$, where $\hat{\sigma} = \sigma + \xi(u - \mu)$. The two results can be unified within a broader probabilistic framework by considering the limit of the sequences of point processes $N_n = \{(i/(n+1)), (X_i - b_n)/a_n\}$ on IR^2. Specifically, it can be shown that as $n \rightarrow \infty$ the sequence N_n converges on intervals of the form $[0, 1] x [u, \infty]$, for any threshold $u > z_-$, to a Poisson process N with intensity measure on $A = [t_1, t_2] \, x [z, z_+]$:

$$\Lambda(A) = (t_2 - t_1)\left[1 + \xi\left(\frac{z - \mu}{\sigma}\right)\right]^{-1/\xi} \qquad (5)$$

Use of the block maximum model for statistical applications seems to have started in the 1950’s. Gumbel promoted the methodology of using the Generalised Extreme Value (GEV) distribution to model componentwise maxima. Tawn (1992) applied the methodology to oceanographic data, while Walshaw & Anderson (2000) used it for wind field modeling. The statistical attributes of the approach of the problem of analysing extreme values using thresholds were studied in detail by Davison (1984), Smith (1984), Davison and Smith (1990), Walshaw (1994) and Fitgerald (1989). The "POT" method is rather common today and it is considered, under conditions of course, advantageous in comparison to other techniques of analysis. The use of point processes in the analysis of extreme values is allocated to Pickands (1971). Smith (1989), Coles and Tawn (1996) and Coles and Casson (1999) contributed considerably to the use of the model in various applications. Coles (2001) introduces shortly the mathematical foundation of the model, while more details are given by Leadbetter and al. (1983).

An important drawback of using annual maxima is that it can be wasteful of data, due to the fact that such approaches use only one observation per block and therefore tend to be inefficient. An important reason for which a point process, namely the Poisson process is preferred, is that it gives an interpretation of the behaviour of the extreme values which unifies asymptotic models, as well as the fact that it leads to the creation of a likelihood which allows a more natural and simpler mode of incorporating non- stationarity in exceedances of a particular threshold, in relation for instance to the Pareto distribution. It was proven that owing to similarity between both approaches presented above, any conclusions from the use of the Poisson process can be extracted from a threshold excess model.

The threshold used in the Pareto distribution, as well as in the Poisson process, must be appropriately chosen, so that the distribution of the chosen extreme values converges to the asymptotic distribution GPD. The choice of the threshold resembles to the one of choosing the length of the block in the approach of maximums of blocks, implicating a balance between bias and variance. In this case, a very low threshold will violate the asymptotic basis of the model, leading to bias while a very high threshold will not produce enough excesses with which the model can be estimated, causing a rather high variance. The most known methods which are helpful in choosing an appropriate threshold according to Coles (2001) are: (a) the mean residual life plot and (b) the diagrams of the parameters of the model ($\hat{\sigma}$ and ξ) with a variety of possible threshold values. The parameters of the applied model are estimated using different methods. Methods that are commonly used are the Maximum Likelihood Estimation (MLE) and the Bayesian approach.

Among others, Coles (2001) uses the approach of Maximum Likelihood to estimate the parameters of the distribution of extreme values for maritime data, rain as well as financial data. The likelihood function is given with respond to acquired observations, and parameters $\theta = (\mu, \sigma, \xi)$:

$$L(\boldsymbol{\theta}, x)= \prod f(x_i, \boldsymbol{\theta}) \qquad (6)$$

and L (or, for numerical advantage logL) is maximized with regard to parameters μ, σ and ξ. Method ML gives unbiased estimates of parameters and from all unbiased estimators it has the smallest mean square error (Van Gelder, 1999). The maximization of L (**θ**, x), with regard to all parameters θ, is numerically direct and allows easily the numerical calculation of standard errors and confidence intervales (Coles et al., 2003).

In the Bayesian frame, parameters $\theta = (\mu, \sigma, \xi)$ are treated as random variables and their prior distributions are intended to represent beliefs of the extreme values, previous to data availability. The specification of information in the form of a prior distribution is alternately considered to be the strongest advantage and the main pitfall of the Bayesian inference (Coles, on 2001). Because of data scarcity, advantages of including other sources of information by a prior distribution are obvious, but since different analysts specify different prior distribution, conclusions become subjective.

The adaptability of the distribution of extreme values to the data is controlled by four diagnostic diagrams: a) the probability plot (p-p plot), v) the quantile plot (q-q contact), c) the return level plot and d) the density plot. The probability plot aims at the comparison of the empirical distribution (x-coordinate of points) and of the one adapted to the data (y-coordinate of points). The quantile plot aims at the comparison of the distribution adapted to data (x-coordinate of points) and of the empirical distribution (y-coordinate of points). This plot is often more useful than the probability plot, since it utilizes the physical scale of data instead of the probability scale [0,1] (Castillo and al., 2005). The return level plot constitutes of all points: $\{(m, \hat{x}_m)\}$, where $\hat{x}_m$ is the return level of the m observation, for large values of m. The x-coordinate of the plot is the return period in a logarithmic scale and the y-coordinate is the return level. Finally, the density plot compares the density f(x) of the model adapted to a histogram of extreme values.

The estimate of extreme quantities, which correspond to a small probability of exceedance is a critical subject in the analysis of risk of hydraulic structures. The analysis of extreme values using the Bayesian methodology is usually preferred owing to the general lack of data and the easiness that it offers to include other sources of information in the analysis, via different prior distributions of parameters of the distribution function.

Non-stationary processes have characteristics which change systematically with time. In the context of environmental processes, this phenomenon is often obvious because of seasonal effects, perhaps owing to climatic differences in different months, or in form of trends, perhaps owing to the long-term climatic changes. In this case, it is ordinary to adopt a pragmatic approach of using standard models of extremes values, as fundamental size which can be ameliorated by statistical modeling.

One of the main objectives of the analysis of the extreme values is also the estimate of the T-year return level u(T). This is fixed as the threshold u(T), for which the medium number of exceedances during a time length T, is equal to unity. If X_1, X_2, …, X_T are variables with common distribution function F, u(T) is the resolution of equation:

$$u(T) = F^{-1}(1-1/T) \tag{7}$$

therefore it is the (1-1/T) quantity of the distribution function F. It can be noted that:

$$P\{X_1 > u(T)\} = 1 - F(u(T)) = 1/T \tag{8}$$

and also the probability of exceedance of the return level u(T) by the observation given during the period considered, is equal to 1/T.

Caution is demanded in the interpretation of the inferences of return level, especially for return levels associated with long return periods. It should be noted that their estimates and their measurements of precision are founded in a hypothesis that the model of extreme values is correct. Although the distribution of extreme values is supported by mathematical argument, their use in the domain of extrapolation is founded on a non-verifiable hypothesis and the measurements of uncertainty of return levels should be correctly considered as the lowest limits, which could be much higher if the uncertainty because of the accuracy of the model was considered.

4. Modeling Methods

The purpose of this section is to identify and categorize currently available methods for forecasting variables relating to coastal flooding.

Some aspects of the modeling of coastal sources and pathways, such as wave modeling and overtopping, are mature and there is a proliferation of available methods. Other aspects, such as defence breaching, however, are poorly understood and modeling techniques remain in their infancy. The large range of available methods (in certain aspects) and lack of formal guidance procedures for developing coastal flood forecasting systems, has led to the development of disparate and ad hoc approaches. This section therefore seeks to provide a more structured approach to the selection of appropriate flood forecasting tools that :

- Facilitates consideration of a range of available methods that may be appropriate for carrying out a specific task
- Facilitates consideration of the specific physical characteristics
- Considers costs of developing and maintaining models
- Considers the overall function of the system.

As there are many models that have a similar primary function, but differ in the basic manner in which the processes are represented, it is sometimes difficult to determine the most appropriate modeling solution. It can therefore be useful to define categories of models. Carried out in a meaningful manner, categorization can relieve the burden of memorizing the purpose and function of every available model and assist in the selection of the most appropriate approach.

When developing a categorization system it is important first to identify the intended use and function of the system. The primary function of the categorization system is to assist in the selection of the forecast modeling approach at a particular site. More specifically, the system should assist in the development of a consistent, appropriate and transparent approach to model selection.

The underlying basis for the categorization system described here, is the level of complexity of the model. The level of complexity has been defined to be dependent on: a) Data Requirements, b) Resolution, c) Physical Processes and d) Characteristics of the underlying equations.

The categorization of models has two primary functions. First it divides the four physical zones of Offshore, Nearshore, Shoreline Response and Flood Inundation. Secondly it uses the information regarding model properties to arrange a series of categories of increasing complexity. To aid understanding, a common and consistent terminology has been used to describe the range of categories for each physical zone. In order of increasing complexity these categories are:

- **Judgement**- Defined as a non-mathematical approach relying on intuition and experience
- **Empirical**- Defined as a model that does not attempt to simulate physical processes but relates observations or measurements of inputs such as wave conditions and water levels directly to outcomes such as overtopping rates
- **First Generation**- Attempts to model explicitly the physical processes, usually involving a number of simplified assumptions
- **Second Generation**- More sophisticated attempts to model the physical processes, involving more advanced (less simplified) methods than First Generation methods
- **Third Generation**- Advanced methods that attempt to model the physical processes that include few simplifying assumptions.

The categorization system is shown in Figure 3. Characteristics of the models of the last 3 categories (First, Second and Third Generation) are presented in the following paragraphs.

For offshore wave prediction, First Generation models provide predictions at a single point. They consider wave generation and energy dissipation by white capping. The Second Generation models are 2DH models providing results over the grid area. They solve the energy balance equation and their distinguishing feature is the parametric description of the wave spectrum. The Third Generation models are like the Second Generation ones, but include an explicit presentation of the primary wave-wave interactions.

For offshore/ nearshore water level predictions (tide and surge), the First Generation models are 2DH models providing results of tide and surge components across a given area. They solve the non linear shallow water equations and use inputs of wind fields and atmospheric pressure over the modelled area. More advanced models include the effects of breaking waves, causing set-up of water levels in nearshore areas. The Second Generation models are 3D models that include the effects of temperature and salinity, in addition to the characteristics of First Generation models.

For nearshore wave prediction there are phase resolving and phase averaging models. The First Generation models of the former category (e.g. “mild slope” models) are 2DH models which provide instantaneous surface elevations over a given area. They include a linear representation of refraction, mild shoaling and an approximate representation of diffraction. The Second Generation models (Boussinesq models) are 2DH models which include non-linear representation of diffraction, refraction and mild shoaling. The First Generation models of the latter category are 2DH wave tracing models that provide results at a point or in an area and they have a linear representation of refraction and shoaling. The Second Generation models are 2DH models which provide averaged results of tide and surge components across a given area. The Third Generation models are like the Second Generation ones but include an explicit representation of the non-linear transfer of energy resulting from the primary wave-wave interaction frequencies.

For nearshore water level prediction the models include all the fundamental processes included in the models for predicting offshore water levels. The distinguishing feature is the increased spatial resolution required to resolve coastline features.

For wave overtopping prediction, First Generation models are 1D and 2DH models, which provide results for a profile or length of the defence. They include a non linear representation of: propagation of broken waves, run-up and overtopping. Second Generation models are 2DV or 3D, which provide results for a profile or length of defence. They include a non-linear phase resolving representation of: propagation and breaking of waves on structures, vertical resolution of velocities and pressures and full representation of the free surface. For breach prediction First Generation models include a physically based representation of the breach growth, while Second Generation models include physically based representation of the breach (location, initiation, growth). Third Generation models are 3D hydrodynamic models which simulate the evolution of a breach.

For flood inundation, First Generation models are 1D models that include unidirectional flow over and through control structures and between flood cells. Second Generation models include hybrid models that combine 1D and 2DH modeling approaches that allow more rapid estimation of flood depths in flood plains. These models provide both depth and velocity that enables the representation of multi-directional propagating flood water. Third Generation models are nested with 3D breaching models to ensure accurate hydrodynamics as the breach changes.

5. Techniques - Models

The successful confrontation of erosion and inundation risks, consists a priority for countries with long coastlines and highly developed coastal zones. Confrontation of course, is the last stage in the procedure of understanding and successfully quantifying the phenomena taking place in the marine environment, the sea-shore interface and the inner coastal zone. These phenomena are studied using various techniques, with numerical forecasting models' role being that of the foremost importance.

Wind and wave action, coastal erosion and impacts on coastal areas (overtopping, breaching, flooding), can neither be standardized nor be precisely represented using simple mathematic formulae. The multiformity of coastal fields and the complexity of the aforementioned processes, "condemned" the attempts to simplify and uniquely describe them via analytical solutions to mediocrity, at least in terms of efficiency. The advance in computer technology in combination with various numerical solution methods (finite elements, finite differences, finite volumes) led to the development of forecasting models which nowadays constitute the main operational research tools.

Considering the natural environment to be a system of interactive but discrete areas/zones, numerical models can be categorized according to the one they describe. Ergo, there are:

- **offshore models**, which describe wave generation and water level setup under wind, current and tide (astronomical and meteorological) action
- **nearshore models**, which describe wave shoaling, refraction, diffraction and breaking
- **beach evolution models**, which describe cross-shore and longshore transport and consequently, the change of coastal morphology
- **shoreline overtopping and breaching models**, which describe the natural obstacles' and technical structures' response to water flow
- **flood inundation models**, which, combined with digital terrain models, describe the processes taking place in the flood plain

During research's historical march, for every one of the above categories, there have been developed from simple **descriptive** (non-mathematical approaches based on experience) and **empirical** (direct correlation of observations and measurements with the studied outcome) **models,** to last generation **three dimensional models** of great input and output parameters' range.

As for the spatial aspect of the field characteristics and the equations used, there can be identified: **one-dimensional (1-D) models** (e.g. beach profile models), **two-dimensional (2-D) models** which describe the phenomena either in the two horizontal dimensions assuming condition uniformity in the vertical one (two-dimensional horizontal models "2-DH"), or in one horizontal and the vertical dimension assuming condition uniformity in the second horizontal (two-dimensional vertical models "2-DV") and **three-dimensional (3-D) models** which are more accurate but also more complicated, and for this reason being confined to the study of smaller areas.

Further model classification can be made according to the implemented solution techniques/methods. In particular, there exist:

- **linear models**, in which the phenomena are represented by simplified first-order forms of the basic equations used (e.g. equation of forces equilibrium or mass conservation) and **non linear models** which comprise second or higher order terms and correlation between the variables
- models based on **finite element, finite difference** and **finite volume** schemes
- **phase-averaging models** through which the time-averaged effect of a process can be found (e.g. offshore and coastal wave models) and **phase-resolving models** which provide a simulation of the instantaneous environment for every model time step (e.g. swash zone and wave overtopping models)
- **coupled models** with one-way or two-way data transfer between two different models
- **nested models** with one-way data transfer from large area to small area models. In particular, the first model's output is used as an input for the second model which has a finer spatial discretization.

Table 6 presents some widely used models, classified for better supervision under the most important of the categories mentioned in the present chapter (Defra, 2003).

In this study Democritus University of Thrace is going to use simple models for beach evolution and wave run-up (e.g. SBeach, Oneline, Genesis), while IACM-

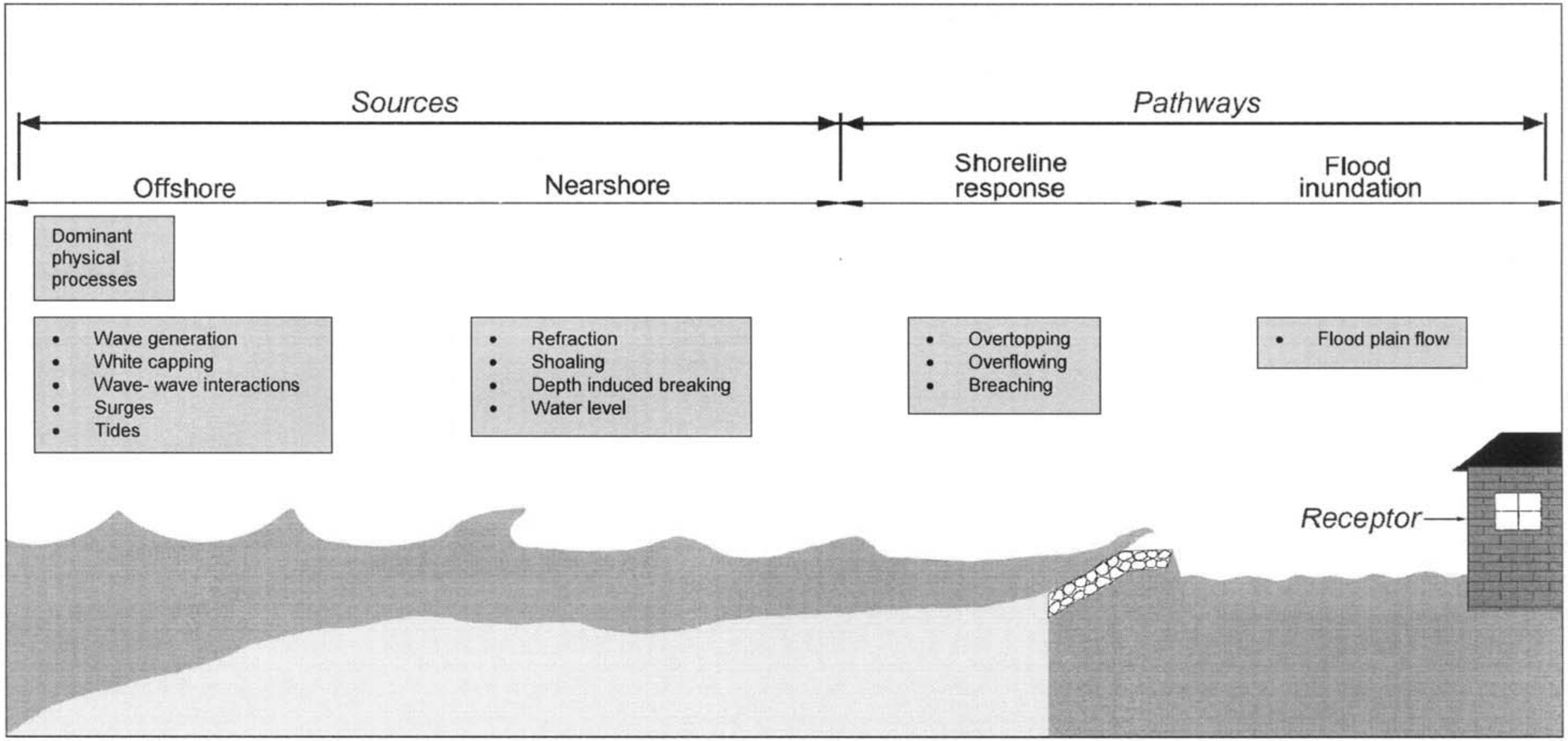
FORTH is going to use more advanced models for calculating wave run-up, based on the Navier-Stokes equations.

Table. 6. Classification of numerical prediction models

OFFSHORE		NEARSHORE		BEACH EVOLUTION		SHORELINE		FLOOD PLAIN
Waves	**Water Levels**	**Waves**		**Cross-shore**	**Longshore**	**Overtopping**	**Breaching**	
		Phase Resolving	**Phase Averaging**					
ADCIRC	ADCIRC	BOWAM 2D	AFDA	COSMOS	GENESIS	AMAZON-CC	BRDAM	HYDROF
TOMAWAK	CS3 (UKMO/POL)	CGWAVE	BOUSS-2D	CROSMOR	NMLong-CV	AMAZON-SC	BREACH	INFOWORKS
UKMO	HYDROF	FUNWAVE	COSMOS	DELFT 2D/3D	ONELINE	FAVOR	COSMOS	ISIS
UKMO UK	FEMA surge	HARES	COWADIS	LITCROSS		NEWMOTICS	FINEL 2D/3D	LISFLOOD-FP
WISWAVE	FINEL2D/3D	MIKE21 BW	ENDEC	SBEACH		OTT	HR BREACH	MIKE 21
WAVEWATCH III	FLOW 2D/3D	MIKE21 PMS	HISWA	SEDITEL		SKYLLA	NWS	TELEMAC 2D
	MECO	RCP-WAVE	MIKE21 EMS	UNIBEST-TC			SHINGLE	FINEL 2D/3D
	MIKE21 HD/HND	REF/DIF	MIKE21 NSW	WATAN 3				
	POLCOMS		NTUA					
	TABS RMA		RCPWAVE					
	TELEMAC-2D/3D		REFRAC					
	WAQUA		STORMS					
	WIMF		STWAVE					
			SWAN					
			TELURAY					
			TOMAWAC					
			WAM					
			WENDIS					

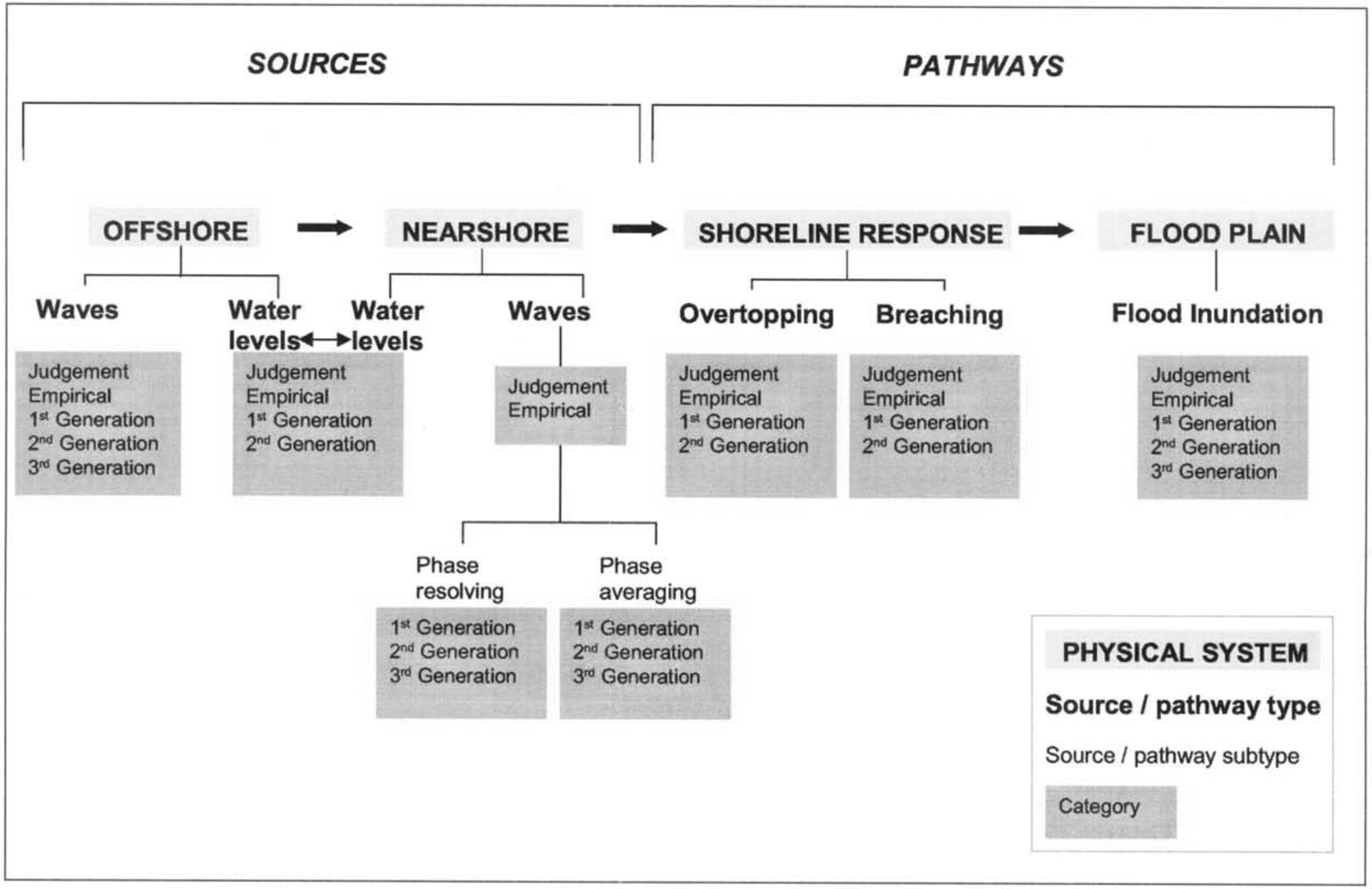
DEFRA/ Environment Agency Flood and Coastal Defence R&D Programme (2003) - Best practice in coastal flooding, *R&D Technical Report FD2206/TR1*, Workshop Version issued 24/09/03, HR Wallingford Report TR 132.

Figure 2. Characterization of the physical system



DEFRA/ Environment Agency Flood and Coastal Defence R&D Programme (2003) - Best practice in coastal flooding, *R&D Technical Report FD2206/TR1*, Workshop Version issued 24/09/03, HR Wallingford Report TR 132.

Figure 3. The categorization system



DEFRA/ Environment Agency Flood and Coastal Defence R&D Programme (2003) - Best practice in coastal flooding, *R&D Technical Report FD2206/TR1*, Workshop Version issued 24/09/03, HR Wallingford Report TR 132.

6. References

CASTILLO, E., HADI A. S., BALAKRISHNAN, N. and SARABIA J. M. (2005) - Extreme value and related models with applications in engineering and science, *Wiley Series in Probability and Statistics*.

COLES, S. G. and TAWN, J. A. (1996) - Modeling extremes of the areal rainfall process, *Journal of the Royal Statistical Society*, **B 58**: 329-347.

COLES, S. G. and CASSON, E. A. (1999) - Spatial regression models for extremes, *Extremes*, **1**: 449-468.

COLES, S. (2001) - An introduction to statistical modeling of extreme values, *Springer Series in Statistics*.

COLES, S., PERICCHI, L. R. and SISSON, S. (2003) -A fully probabilistic approach to extreme rainfall modeling, *Journal of Hydrology*, **273**: 35-50.

DABEES, M.A. (2000) - Efficient modeling of beach evolution, *Ph.D. Thesis*, Department of Civil Engineering, Queen’s University. Kingston, Ontario, Canada.

DAVISON, A. C. and SMITH, R. L. (1990) - Models for exceedances over high thresholds (with discussion), *Journal of the Royal Statistical Society*, **B 52**: 393-442.

DAVISON, A. C. (1984) – Modeling excesses over high thresholds, with an application. In Tiago de Oliveira, J., editor, Reidel, Dordrecht, *Statistical Extremes and Applications*: 461-482.

DEFRA/ Environment Agency Flood and Coastal Defence R&D Programme (2003) - Best practice in coastal flooding, *R&D Technical Report FD2206/TR1*, Workshop Version issued 24/09/03, HR Wallingford Report TR 132.

DOLAN, R. and DAVIS, R.E. (1992) -An intensity scale for Atlantic coast northeast storms, *Journal of Coastal Research*, **7(1)**: 53-84.

FITZGERALD, D. L. (1989) - Single station and regional analysis of daily rainfall extremes, *Stochastic Hydrology and Hydraulics*, **3**: 281-292.

HILL, H. W., KELLEY, J. T., BELKNAP, D. F. and DICKSON, S. M. (2004) -The effects of storms and storm-generated currents on sand beaches in Southern Maine, USA. *Marine Geology*, **210**: 149-168

HR WALLINGFORD (2004) - Best practice in coastal flood forecasting, *HR Wallingford Report TR 132*.

LEADBETTER, M. R., LINDGREN, G. and ROOTZEN, H. (1983) - Extremes and Related Properties of Random Sequences and Series, *Springer Verlag*, New York.

MENDOZA, E. T. and JIMENEZ, J. A. (2004) - Factors controlling vulnerability to storm impacts along the Catalonian coast, In J. Smith (Editor), *Proceedings of the 29th International Conference on Coastal Engineering*, Lisbon, Portugal.

MENDOZA, E. T. and JIMENEZ, J. A. (2006) - Storm-induced beach erosion potential in the Catalonian coast, *Journal of Coastal Research*, SI 48.

MACCLENAHAN, P., MCKENNA, J., COOPER, J. A. G. and O'KANE, B. (2001) - Identification of highest magnitude coastal storm events over western Ireland on the basis of wind speed and duration thresholds, *International Journal of Climatology*, **21** : 829-842.

PICKANDS, J. (1971) – The two-dimensional poisson process and extremal processes, *Journal of Applied Probability*, **8**: 745-756.

SAFFIR, H. S. and SIMPSON, R. H. (1971) - A proposed scale for ranking hurricanes by intensity *Minutes of the eight NOAA, NWS Hurricane Conference*, Miami, Florida.

SMITH, R. L. (1984) - Threshold methods for sample extremes. In Tiago de Oliveira, J., editor, Reidel, Dordrecht, *Statistical Extremes and Applications*: 621-638.

SMITH, R. L. (1989) - Extreme value analysis of environmental time series: an example based on ozone data (with discussion), *Statistical Science*, **4**: 367-393.

SORGEDRAGER, J.M. (2002) - Cross-shore sediment transport on the shoreface, Behaviour analysis of Unibest-TC sediment transport formulations, *Diploma Thesis*, Faculty of Civil Engineering, Delft University of Technology. Delft, Netherlands.

TAWN, J. A. (1992) - Estimating probabilities of extreme sea levels, *Applied Statistics*, **41**: 77-93.

VAN GELDER, P.H.A.J.M., (1999) - Statistical Methods for the Risk-Based Design of Civil Structures, *PhD Thesis*, Delft University of Technology.

WALSHAW, D. (1994) - Getting the most from your extreme wind data: a step by step guide, *Journal of Research of the National Institute of Standards and Technology*, 99: 399-411.

WALSHAW, D. and ANDERSON, C. W. (2000) -A model for extreme wind gusts, *Applied Statistics*, **49**: 499-508.

Sources in internet

UK Environment Agency. www.environment-agency.gov.uk

USACE, Coastal and Hydraulics Laboratory. chl.erdc.usace.army.mil