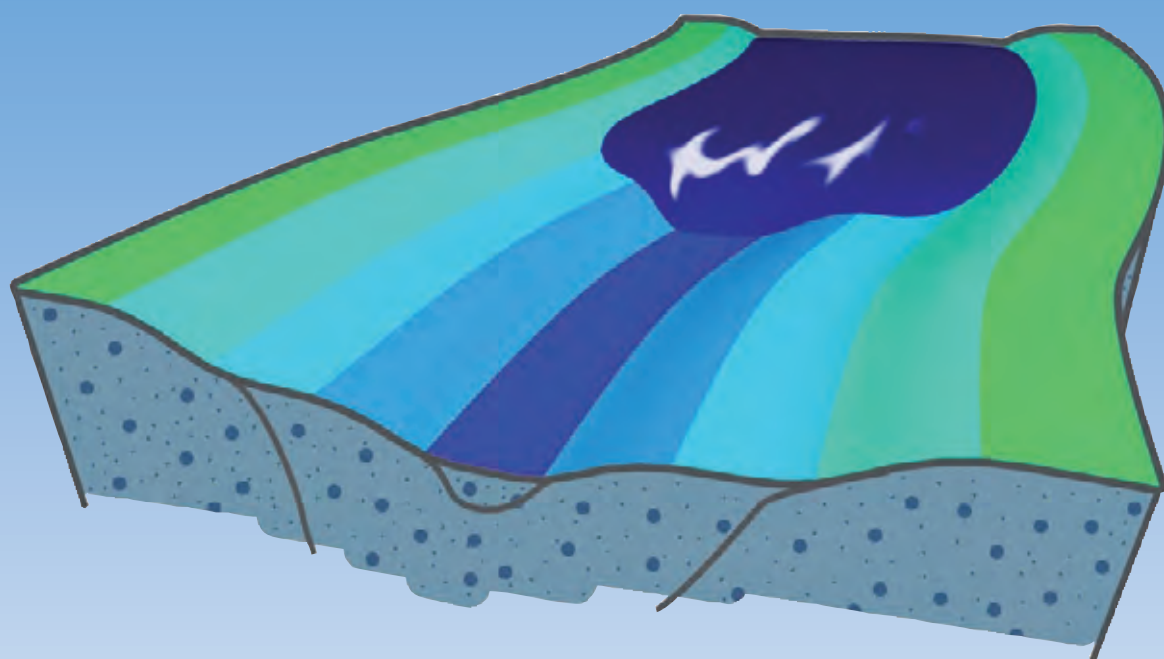


# A Handbook on Flood Hazard Mapping Methodologies



GOBIERNO  
DE ESPAÑA

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Instituto Geológico  
y Minero de España

# **A Handbook on Flood Hazard Mapping Methodologies**

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**GEOLOGICAL SURVEY OF SPAIN**  
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# INTRODUCTION

Floods are the natural disasters with the greatest socio-economic impact after droughts, both globally and in Spain itself. Suffice it to recall the consequences of the floods which have in recent decades affected countries like Mozambique, the Philippines, China, Venezuela, the United States and Myanmar (Burma), to cite a few events which have received wide media coverage. In Europe, the great floods which took place in the centre of the continent in 2002 were an inflection point in the level of concern of European institutions with respect to this problem. In Spain, according to a study carried out by the Spanish Geological Survey (IGME) in collaboration with the Consortium of Insurance Compensation<sup>1</sup> in 2004, the direct economic losses resulting from floods during the period 1987-2002 reached nearly EUR 12 billion, that is to say, the equivalent of 0.1% of GDP. In addition, nearly EUR 26 billion in losses are predicted over the next 30 years. If we speak of the cost in terms of human life, there is a steady flow of victims each year (over 200 mortal victims in the past decade) due to events which have sparked profound social alarm. The floods in Biescas, with 86 mortal victims, Badajoz, with 21 victims, or Yebra (Guadalajara), with 10 victims, are proof of the latter point.

Bearing this in mind, the action taken by public administrations must be steered towards adequate management of flood-related risks in an attempt to minimize them and mitigate their consequences. To achieve this, there are three traditional groups of measures: predictive, preventative and corrective. The predictive measures and techniques for floods are still in their incipient stages of development and include, among others, meteorological tracking of convective cells, or real-time hydrologic information systems. As regards the adoption of corrective measures, that is, post-catastrophe actions, or the financial assistance expressed through disaster zone declarations, it is clear that mere adoption per se unaccompanied any other type of measures logically results in social dissatisfaction. This is why most public administrations in developed countries have chosen, for decades, to focus their action on what we call preventative measures, which encompass those traditionally defined as 'non-structural': spatial planning, assurance systems, civil protection and risk education.

To be implemented, all of the measures, particularly non-structural preventative ones, require, as a preliminary and fundamental step in management, that a flood risk analysis be carried out, which involves a conducting detailed study of the risk elements (hazard, exposure and vulnerability). In this context, flood hazard mapping is a basic component in flood risk analysis studies as it permits the effective evaluation of the spatial distribution of the various elements of severity (such as water surface level, flow velocity, sediment transport, or characteristic times) and frequency (return periods or exceedance probability) of the flood phenomenon. Furthermore, they offer the utility of being able to link the maps and their associated databases to exposure and vulnerability maps in order to analyse and predict risk in an integrated manner using such tools as geographic information systems (GIS).

In order for the production and publishing of these maps to fulfil the functions of accurate mapping and practical utility, it is desirable to harmonise the methodologies used to make them, standardize the criteria and arrive at a consensus on which elements to represent and legends. To that end, a basic starting point in preventing risk would be to draw up methodological guides which provide an inventory of the data-gathering and representation methods, map scales, zoning criteria and available computer programs. It is in this context that the publication of IGME's "A handbook on flood hazard mapping methodologies" takes on its fullest meaning.

**José Pedro Calvo Sorando**

*Director General of the Geological Survey of Spain*

<sup>1</sup> Consorcio de Compensación de Seguros.



# FOREWORD

In the past few decades, numerous plans, programmes, projects and systems for analyzing and mapping flood hazards have been implemented in Spain and in the rest of the developed countries. To cite a few examples in the international arena: the National Flood Insurance Program (NFIP) maps in the United States, the Flood Risk Prevention Plans in France<sup>2</sup>, or the recent European Community Directive 2007/60/EC on the assessment and management of flood risks, which lays down in its Chapter III the need to prepare flood hazard maps and flood risk maps for specific hydrographic areas by the year 2013.

In Spain, the different public administrations at the government, Autonomous Region, county and local levels have implemented various initiatives, such as the National Flood Zone Mapping System<sup>3</sup>, promoted by the Directorate-General of Water<sup>4</sup> (Ministry of the Environment and Rural and Marine Affairs<sup>5</sup>), Autonomous Region master plan maps focused on spatial planning (PATRICOVA and Region of Murcia) and civil protection (Inun-cat, RICAM, Inunbal, Inungal), the compulsory natural risk maps in the environmental sustainability reports provided for in the Land Law (8/2007)<sup>6</sup>; in addition to other experiences in which potential flood-prone zones were mapped for different return periods (100 and 500 years), such as the LINDE and PICHRA programmes, the flood hazard studies by the River Basin Authorities for the protection of the public water domain<sup>7</sup>, etc.

However, almost all of these initiatives lack clear and concise methodological handbooks making it possible to harmonise the resulting maps and thereby avoid inconsistencies and discrepancies in the administrative boundaries for which they were carried out. For this reason, what is lacking is an element of standardization, similar to the role played by the EXCIMAP exchange group in preparing the maps associated with the above-mentioned European Directive.

Moreover, the Earth Sciences play an indispensable role in studying the origins and consequences of flash flood and flood inundation events. It is in this line of thought that the recent modification was made to the Royal Decree on the Regulations on the Public Water Domain<sup>8</sup> (RD 9/2008 of 11 January, Official Gazette<sup>9</sup> No. 14 of 16 January 2008) which considers all of the methods valid with respect to delimitations since no priorities are established on this matter.

In light of the above, this methodological handbook written by IGME on preparing flash flood and flood inundation hazard maps comes at an opportune moment as it provides methods and criteria pertinent to all of the abovementioned master plans and projects, as well as those to come in the short and middle term.

**Vicente Gabaldón López**

*Director of the Department of Geoscientific Research and Prospective*

<sup>2</sup> *Plan de prévention des risques d'inondation (PPRI).*

<sup>3</sup> *Sistema Nacional de Cartografía de Zonas Inundables (SNCZI).*

<sup>4</sup> *Dirección General del Agua (DGA).*

<sup>5</sup> *Ministerio de Medio Ambiente, Medio Rural y Marino.*

<sup>6</sup> *Ley del Suelo.*

<sup>7</sup> *Dominio Público Hidráulico (DPH).*

<sup>8</sup> *Real Decreto del Reglamento del dominio público hidráulico.*

<sup>9</sup> *BOE (Boletín Oficial del Estado).*





# ABSTRACT

Natural disasters caused by flood inundations are among those which cause the most casualties and economic loss in Spain. Accordingly, there is a variety of European, Spanish, and Autonomous Region legislation relating to the management and mapping of flood-prone areas.

Since floods may stem from various origins, there are different types of floods (natural/artificial, inland/coastal, flash floods/rising periods, *in-situ* flooding), and the effects of some may be aggravated by human activities (deforestation, earthworks, urbanization). Floods in Spain can be grouped into four broad risk areas: flash floods in the Mediterranean catchment basin, torrential floods in the mountain ranges, rising periods in the middle and lower reaches of big mainland rivers, and waterlogging in flat and endorheic areas in the central part of big basins.

Following are some of the effects and impacts of floods: water depth and residence time, flow velocity, erosive capacity, sediment transport and deposition, and other associated geological phenomena (landslides, piping, etc.).

There is a variety of existing national and international projects which can be used as references and examples for mapping risk and hazard of floods. There are also multiple sources of information: mapping (topographical, thematic, photographic), alphanumeric (hydrometeorological and socioeconomic) and fieldwork. As regards the surveying methods, flood hazard analysis techniques can be divided into three broad groups: historical-palaeohydrological, geological-geomorphological and hydrologic-hydraulic. The ideal approach is to use all of them in an integrated, calibrated fashion in which they complement one another. There is a wide range of elements which can be represented on the maps and a variety of systems for graphically representing them. Whether or not they are included depends on the map scale, mapping method used and the map's intended purpose. Hazard can be mapped in three zones (high, medium, and low) for which boundaries and usage restrictions must be established. Likewise, different tools may be used to prepare these maps, both for hazard analysis and integrating risk factors.

To conclude, risk mitigation measures may comprise predictive, preventative and corrective strategies. The ideal approach involves the use of spatial planning as a non-structural preventive measure.





# RESUMEN

Las catástrofes naturales ocurridas como consecuencia de las inundaciones se encuentran entre las que han generado un mayor número de víctimas mortales y pérdidas económicas en España. Por ello, existe diversa legislación aplicable a la gestión y cartografía de áreas inundables, tanto en el ámbito europeo y estatal, como en el autonómico.

Las inundaciones tienen variados orígenes, lo que determina la existencia de diferentes tipos de inundaciones (naturales-artificiales, terrestres-costeras, avenidas-crecidas, riadas-*in situ*), algunas de las cuales pueden ver sus efectos agravados por determinadas actuaciones humanas (deforestación, movimiento de tierras, urbanización). Las diversas manifestaciones de las inundaciones en España permiten diferenciar cuatro grandes zonas de riesgo en nuestro país, asociadas a las avenidas súbitas en la vertiente mediterránea; a las avenidas torrenciales en los sistemas montañosos; a las crecidas en los tramos medios y bajos de los grandes ríos peninsulares; y al encharcamiento en zonas llanas y endorreicas en los sectores centrales de las grandes cuencas.

Entre los efectos e impactos de las inundaciones están: la profundidad del agua, su permanencia temporal, la velocidad de la corriente, la capacidad erosiva, el arrastre de sólidos y su depósito, y otros fenómenos geológicos asociados (movimientos de ladera, sufusión).

Para la elaboración de mapas de riesgos y de peligrosidad por inundaciones existen diversos antecedentes internacionales y nacionales que pueden usarse como referencia y ejemplo, así como diferentes fuentes de información cartográfica (básica, temática, fotográfica), alfanumérica (hidrometeorológica y socioeconómica) y adquisición en campo. Entre los métodos de reconocimiento destacan tres grandes grupos de técnicas para el análisis de la peligrosidad de inundaciones: históricos y palaeohidrológicos; geológicos y geomorfológicos; e hidrológicos e hidráulicos. Lo ideal es utilizar todos ellos de forma integrada, calibrada y complementaria. En cuanto a los elementos a representar en los mapas, pueden ser múltiples y diversos, al igual que los sistemas de representación; su inclusión dependerá de las escalas de trabajo, del método utilizado y de la finalidad o aplicación del mapa. La peligrosidad puede cartografiarse en tres zonas (alta, media y baja) en las que deben establecerse limitaciones y restricciones de uso. Igualmente, para la elaboración de estos mapas pueden utilizarse diversas herramientas, tanto en el análisis de la peligrosidad como para integrar los factores del riesgo.

Finalmente, entre las medidas de mitigación del riesgo existen las estrategias predictivas, preventivas y correctoras, destacando como idóneo el empleo de la ordenación del territorio como medida preventiva de carácter no estructural.



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## INTRODUCTION AND PURPOSE

The idea of drawing up and publishing a handbook on flood hazard mapping methodologies is an old ambition of IGME. In fact, there have been several projects in the last quarter century, if not before that.

Since IGME's creation in 1849 as the *Commission Charged with the Geological Mapping of Madrid and the Kingdom of Spain*<sup>10</sup>, flooding and flood mapping have been the driving themes behind all IGME activities and publications (Díez and Laín, 1998; Llorente *et al.*, 2006; Figure 1).

trajeron los rios. Los habitantes de la provincia de Segovia en todo lo que va del siglo no habian sufrido una avenida tan fuerte como la que tuvo lugar el 24 de mayo del presente año. El rio Prádena, que pasa por el pueblo del mismo nombre y por los de Castroserna y Sebúrcol, y se une al Duraton cerca de San Miguel de Neguera, atravesando antes el terreno de arenas, arrastró tal cantidad de ellas, que en Burgo Millodo, donde el rio sale de una profunda hoz, arrojó una parte de las mismas sobre la orilla derecha, que allí se halla bastante baja, cubriéndola en 1 y 2 metros de altura, con no poca admiracion de las gentes, que, reducido el rio á su cauce, se hallaron con aquella novedad. Es de advertir que no habia memoria de que hubiese sucedido allí una cosa igual anteriormente. Sin embargo, se cree que el mismo rio que las trajo podrá en otra avenida arrastrarlas hácia adelante, dejando el campo restituido á su anterior fecundidad.

En el diluvium de la provincia de Segovia no se ha encontrado fo-

**Figure 1.** Extract from the text of Prado (1853) describing a flood in the province of Segovia and its geological effects.

<sup>10</sup> Comisión encargada de elaborar la carta geológica de Madrid y general del Reino.

But it was in the early 1980's when a small group of experts (Elízaga, Ayala, Durán, Pernía...) began spearheading map production in this field, publishing pioneering maps and reports in Spain. Efforts were already being made to standardize these maps; the first attempts to unify guides, regulations and map legends came about. The publication of the book "Geology and the Prevention of Damage Caused by Floods" (Ayala, 1985)<sup>11</sup>, as well as the appearance of homogeneous mapping series, such as "Forecast Maps of Flood Risks in Population Centres" (Ayala *et al.*, 1986)<sup>12</sup>, represent a milestone in these attempts at standardization (Figure 2).

After a nearly decade-long hiatus in which flood mapping came to a slight halt at IGME, the impetus of the "golden decade" resumed in 2005 with the launch of the Plan for Geological Risk Mapping (PRIGEO)<sup>13</sup>. As a first step, the initiative's action plan for the first few years called for the creation of handbooks on hazard mapping methodologies for the different geological phenomena considered (landslides, flooding, volcanism, seismicity and tsunamis, and coastal dynamics).

Since the presentation of PRIGEO in June 2005 at a public event at the National Civil Protection School (Rivas Vaciamadrid, Madrid)<sup>14</sup>, many of the projects and activities of the then Geological Risks "Unit" (currently, the Geological Risk and Hazard Research Area<sup>15</sup>) were part of an effort to attain the objective of producing a methodological handbook and elaborating the pilot experiences necessary to calibrate and validate the methods proposed therein. Therefore, research projects such as Georiada and Dendro-Avenidas, as well as technical development projects such as Mapping-Flood-Hazards<sup>16</sup>, PRIGEO-floods<sup>17</sup>, Albuñol, Posets-Maladeta, etc., are the starting point of the information contained in this handbook and excellent 'touchstones' for putting the methodologies to the test.

The organization of the Congress on Flood Hazard Maps (INUNMAP 2006)<sup>18</sup> by IGME in collaboration with the Consortium of Insurance Compensation was what definitively triggered the materialisation of the methodological handbook. This Congress, which took place in three days, in May 2006, was a clear success, both for the quantity and quality of speakers and for the participation of those present (more than 225 persons), including the significant quantity of documentation that was generated and published, such as the book "Flood hazard maps. Methods, experiences and application" (Díez *et al.*, 2006)<sup>19</sup>, in which renowned foreign and national experts made available to IGME key information about their experiences and methods, or the "Technical Experiences" brochure (Llorente *et al.*, 2006b)<sup>20</sup>, which contains over 30 abstracts of the papers submitted to the Congress by more than 80 scientists and experts, whose posters were exhibited during the Congress.

Since the INUNMAP 2006 Congress, and following a brief period of functional restructuring associated with the modification of the IGME Statute, the demand various public bodies have expressed for tools such as this handbook prompted IGME Management Direction to decide to relaunch its publication within the editorial programme of the first six months of 2008.

Therefore, the main objective of this handbook on flood hazard mapping is to act as a reference for those interested in creating, reviewing, authorising or interpreting these maps for any of the fields of application being focused on. As such, the definition of "handbook" in Merriam-Webster's unabridged dictionary applies: "A concise reference book covering a particular subject or field of knowledge". In other words, it is not an exhaustive treatise or compendium of all the methodologies and techniques of flood hazard analysis and representation, but rather a practical selection of those which are most useful and frequently used, approached from a technical perspective and not a scientific one. Nor is it meant to be a book of recipes, in the sense of a code of con-

<sup>11</sup> *Geología y prevención de daños por inundaciones.*

<sup>12</sup> *Mapas previsores del riesgo de inundaciones en núcleos de población.*

<sup>13</sup> *Plan de Riesgos Geológicos (PRIGEO).*

<sup>14</sup> *Escuela Nacional de Protección Civil.*

<sup>15</sup> *Área de Investigación en Peligrosidad y Riesgos Geológicos.*

<sup>16</sup> *Cartografía-Peligrosidad-Inundaciones.*

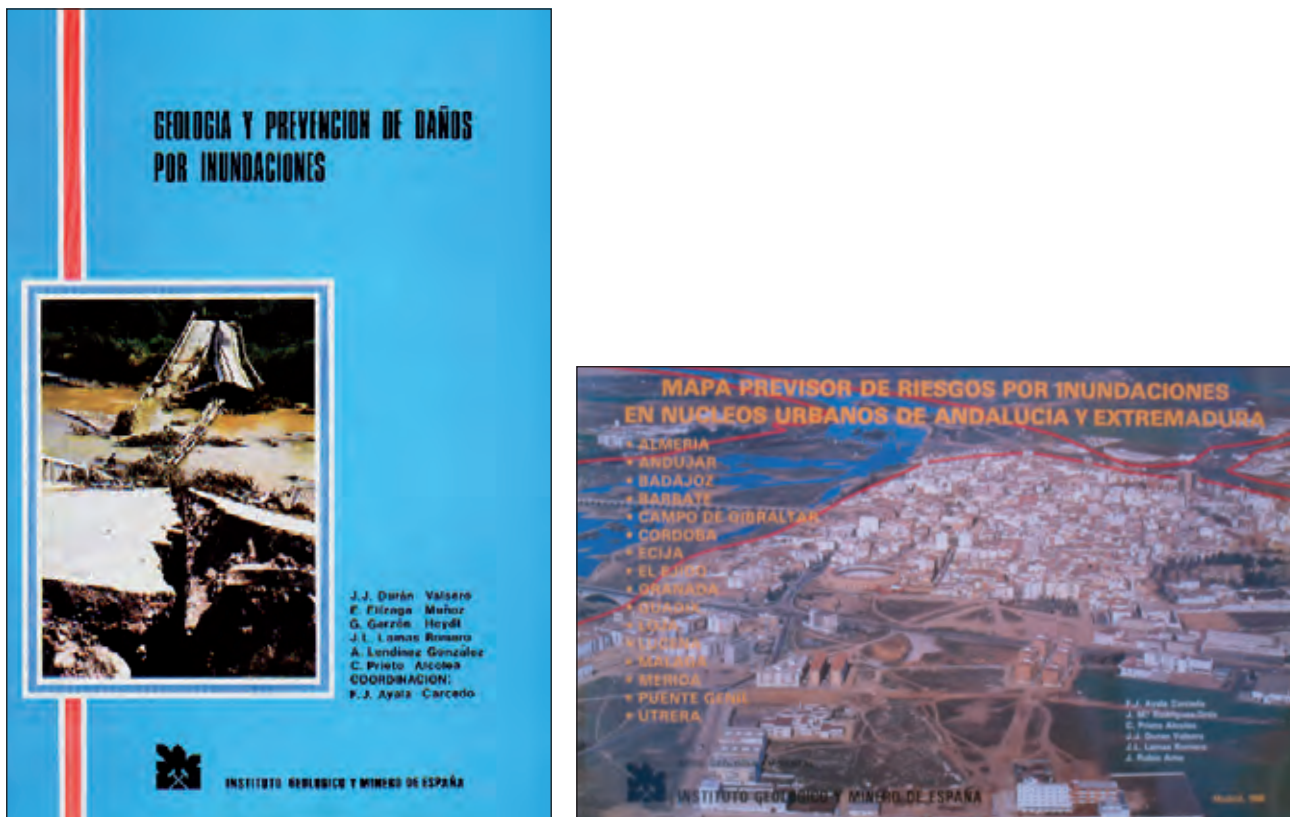
<sup>17</sup> *PRIGEO-avenidas.*

<sup>18</sup> *Jornadas Técnicas sobre Cartografía de Peligrosidad de Inundaciones.*

<sup>19</sup> *Mapas de peligrosidad de avenidas e inundaciones. Métodos, experiencias y aplicación.*

<sup>20</sup> *"Experiencias Técnicas".*





**Figure 2.** Front covers of two reference works from IGME's past involvement in flood risk studies: Ayala (1985) and Ayala et al. (1986).

duct that instructs the user to adhere to a fixed procedure set in stone. Instead, it is meant to be a compilation presenting a number options and alternatives of methods and techniques.

Among the handbook's potential users are all experts in charge of creating flood hazard maps, both in public administrations (ministerial bodies, ministries in regional governments, county councils, city councils, town councils) and in the sphere of private enterprises (engineering consultancies, insurance companies, town planning offices), as well as the academic world (universities, centres of secondary education, postgraduate schools) and the scientific community (public research organizations, research centres). The handbook's target audience may also include those who, although not charged with preparing such maps, are responsible for supervising, reviewing and authorising them, such as professional associations, technical offices, quality control companies, technical auditors, etc. Last but not least, this handbook can be a fundamental tool for the end users of maps in various fields of application for predictive measures (design of early warning and hydro-meteorological information systems and networks), preventative measures (design of construction works, spatial planning, insurance systems, civil protection, risk education), and corrective measures (resource planning in emergencies, implementing aid systems for victims, declaring disaster areas).

The authors would like to thank several individuals and institutions for their collaboration and assistance which made the preparation and publication of this handbook possible: the members of the Area of Research in Geological Risks and Hazards, Area of Geoscientific Mapping and Geoscientific Information Systems, all part of IGME; the Spanish Ministry of Education and Science (currently, Science and Innovation), for the economic aid awarded through a complementary action (No. CGL2006-26195-E/BTE); the Consortium of Insurance Compensation, and the other bodies, institutions, speakers that participated in the INUNMAP 2006 Congress; the IGME Working Group on Geoscientific Mapping, for the proposed table of contents which has served as a model.

We would also like to express our appreciation to those who have granted rights to or authorized the use of their



proprietary graphic material, such as Manuel López Chicano (University of Granada), Alejandro Gaona (ISEA)<sup>21</sup>, Gerardo Benito (CSIC)<sup>22</sup> and José Francisco Martín-Duque (Complutense University of Madrid).

The authors wish to dedicate this handbook to the memory of Francisco Javier Ayala Carcedo (Paco Ayala), a friend, teacher and example, who struggled so dearly for advances in geological risk studies in Spain.

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<sup>21</sup> ISEA, *Ingeniería, Arquitectura y Servicios* (Engineering, Architecture and Services).

<sup>22</sup> *Consejo Superior de Investigaciones Científicas* (Spanish National Research Council).



# METHODOLOGIES AND PROCEDURES FOR FLOOD HAZARD ANALYSIS

## *Floods and flood risks*

According to *Webster's unabridged dictionary*, **flood** signifies “a rising and spreading of water over land not usually submerged”. It is synonymous with **inundation**, from the Latin verb *inundare*<sup>23</sup>. The Spanish Basic Directive on Planning Civil Protection Against Flood Risks (MJI, 1995)<sup>24</sup> defines a flood as the temporary submersion of normally dry lands as a result of an unusual and more or less sudden flow of a quantity of water which exceeds a given zone's usual quantity. The Federal Emergency Management Agency (FEMA) in the United States further quantifies the surface subject to flooding in order to consider it a flood: “A general and temporary condition of partial or complete inundation of two or more acres (0.81 ha) of normally dry land area or of two or more properties”, that is, an excess of water (or mud) over land that is normally dry. The European Community Directive 2007/60/EC on the assessment and management of flood risks defines flooding as “the temporary covering by water of land not normally covered by water” (Article 2.1).

Despite the lack of specific definitions for terms such as “normally dry” or “are not normally covered by water”, what everyone can agree on is the exceptional character of floods as regards everyday human activities, and their innate character from the viewpoint of natural dynamics (Camarasa, 2002); even in ancient times, the first civilizations with close ties to the fertile valleys (the Euphrates, Tigris, Nile, Ganges) were aware of and utilized the beneficial aspects of floods, primarily for the natural fertilization of farm fields.

**Flood risk**, therefore, refers to the potential situation of loss or harm to persons, material belongings or services as a result of the covering of normally dry areas by floods, which are assigned a specific severity (intensity and magnitude) and frequency or probability of occurrence. The European Flood Directive defines it as the “combination of the probability of a flood's occurrence and the potential negative effects on human health, the environment, cultural heritage and economic activity associated with floods.” (Article 2.2).

<sup>23</sup> “flood.” *Webster's Third New International Dictionary, Unabridged*. Merriam-Webster, 2002. <http://unabridged.merriam-webster.com> (2 Apr. 2009); “inundation.” *Webster's Third New International Dictionary, Unabridged*. Merriam-Webster, 2002. <http://unabridged.merriam-webster.com> (2 Apr. 2009).

<sup>24</sup> Directriz Básica de Planificación de Protección Civil ante el Riesgo de Inundaciones.



## Types and origin of floods

There are essentially two **types** of natural floods (apart from those generated exclusively by human action, such as leakages and bursts in piping or storage) (Figure 3): surface flooding (“inland” flooding), in which fresh waters inundate areas of the inner parts of continents; and coastal flooding, in which seawaters or lake-marsh waters inundate the areas along the edge of surface regions. There are various combinations and intermediate situations between the two. Therefore, given this diversity of phenomena, it is more appropriate to use the plural form when referring to this type of risk, that is, risk of floods.

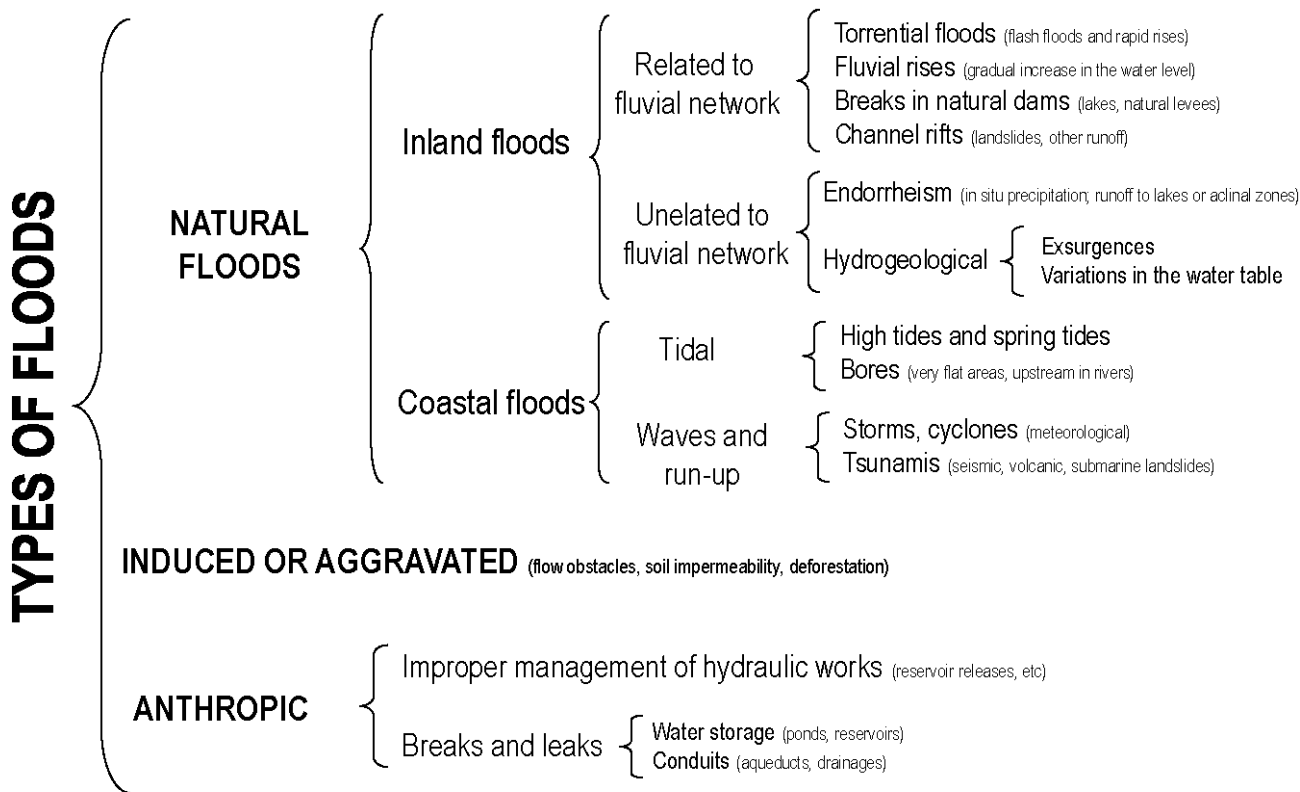


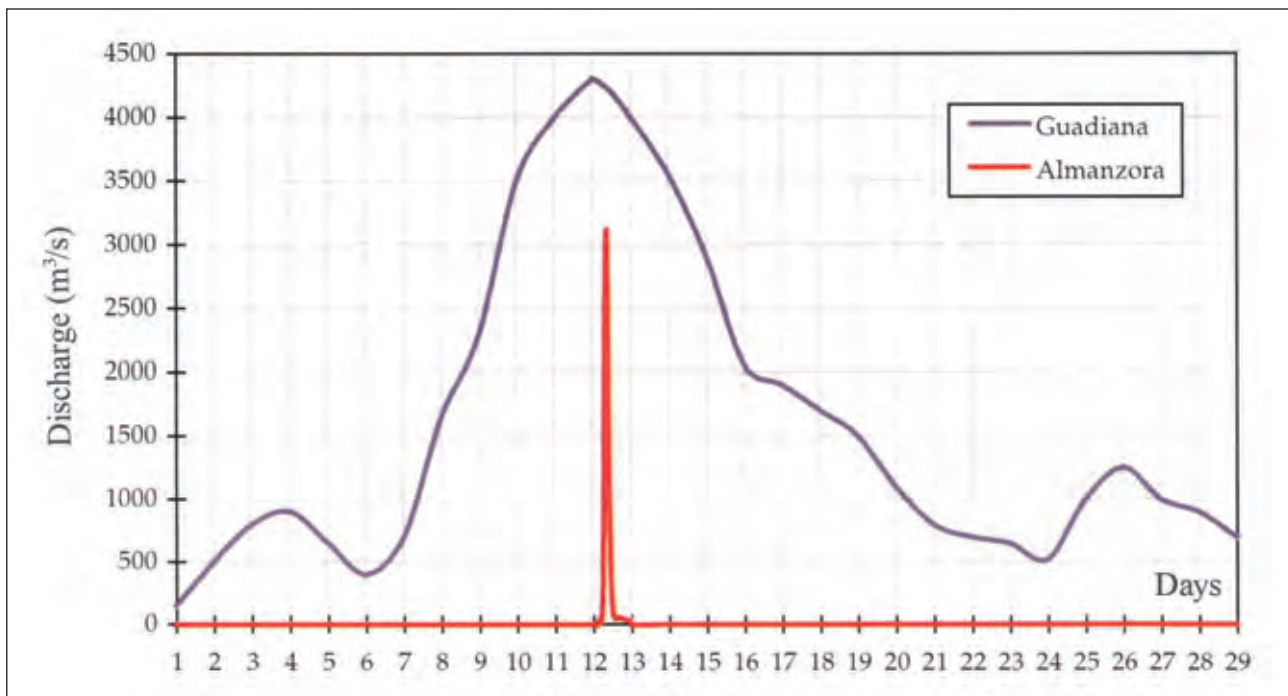
Figure 3. Basic classification for the types of floods according to their origin.

**Surface flooding** tends to stem from two origins: 1) the overflow of streamflows (rivers, streams, torrents, etc.), the waterlogging of flat or endorheic areas not connected to the river system, or the accumulation of rainfall which does not flow over the land surface (*in situ* rainfall, overfeeding of a lake); 2) or those of hydrogeological origin associated with the exsurgence or elevation of the phreatic surface to above the soil surface.

In the first case, an increase in the flow to above the channel’s capacity to carry it results in the overflow and flooding of the banks. These flow increases can occur during rising stages and/or flash floods, which differ in terms of the factors causing the flow increase (Olcina, 1994; Camarasa, 2002; Figure 4): whereas rising stages are related to widespread, sustained rainfall (frontal precipitation) or the steady melting of snowpack and glacier thawing, flash floods can occur after concentrated intensive rainfall (orographic and/or convective), ruptures of natural impoundments (lakes, lagoons and beaver dams) or artificial impoundments (obstructed bridges, dams), improper functioning or rupture of hydraulic structures (weirs<sup>25</sup>, impoundment dams, reservoirs, artificial levees), or the sudden melting of snow or ice induced by volcanic activity (Lahars and Jökulhlaups).

<sup>25</sup> Sometimes referred to as “azudes” in Spain, which derives from the Arabic word for dam.





**Figure 4.** Comparison of hydrographs of flooding of the Guadiana river (blue) and a flash flood in the Almanzora gully (red). Source: White Paper on Water<sup>26</sup>, Spanish Ministry of the Environment (2000).

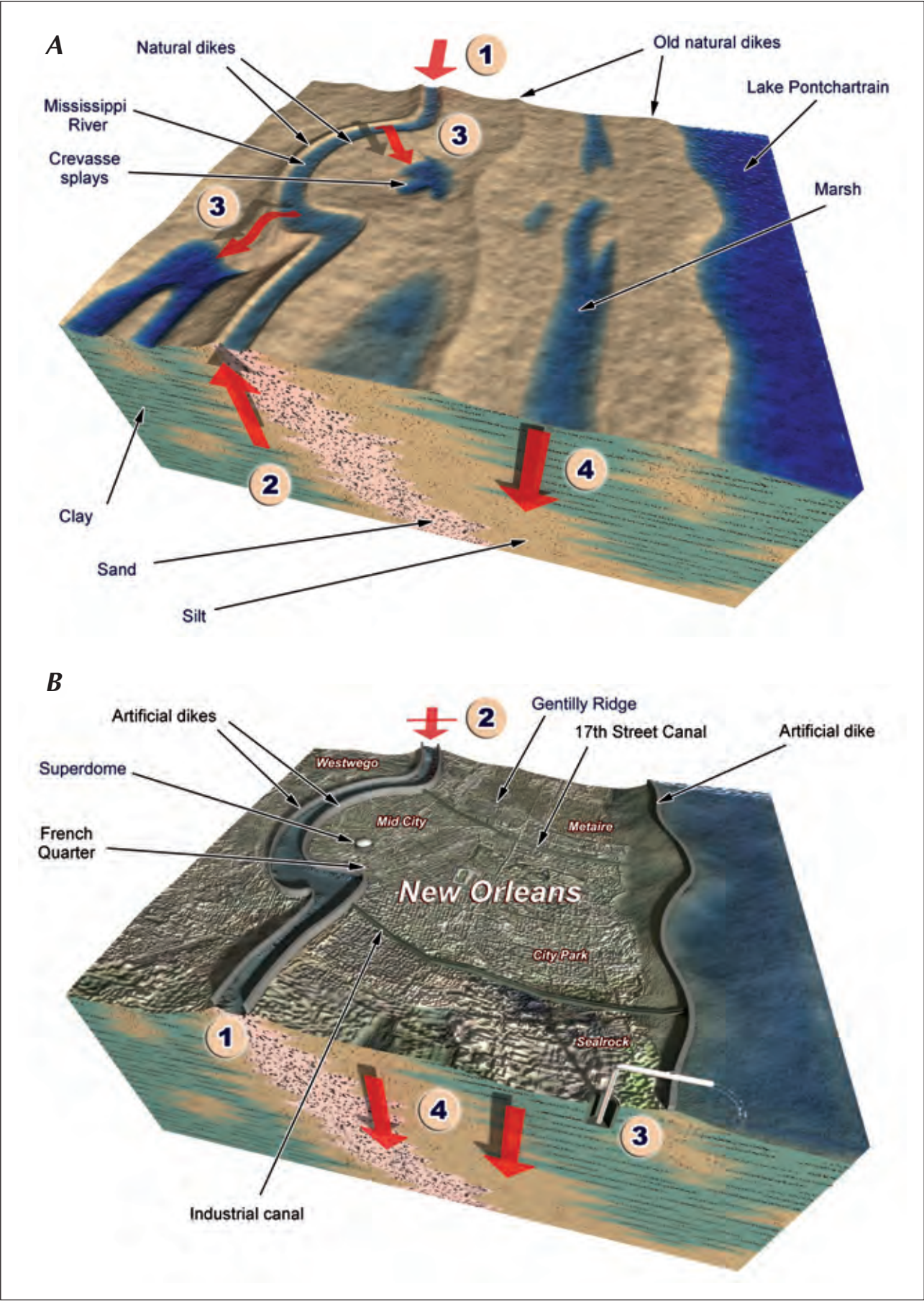
Other, less frequent, causes of surface flooding are the formation of lakes and the rise in their water levels resulting from impoundment brought about by landslides (e.g., the landslide in Olivares, Granada, in 1986 which dammed up of the Velillos River) or glacier advance, and the rise of the groundwater level over the ground surface as a consequence of aquifer discharge (Maréchal *et al.*, 2008), as occurs in karst depressions (the Zafaraya Polje in Granada; López Chicano *et al.*, 2002; Figure 6).

In addition to all of these potential direct causes, which act as triggering factors of surface flooding, there are other conditioning factors which strengthen or intensify these phenomena. They are essentially topographic parameters, such as the slope of the catchment basin and fluvial currents, or the basin's size and shape, soil type, geometry and vegetation cover. All triggering conditions (rainfall) being equal, the greatest floods occur in small mountain basins with round shapes, steep slopes, thin, impermeable soils, and scarce vegetation. Similarly, activities such as the urbanization or deforestation of large areas of basins contribute to an increase in streamflows.

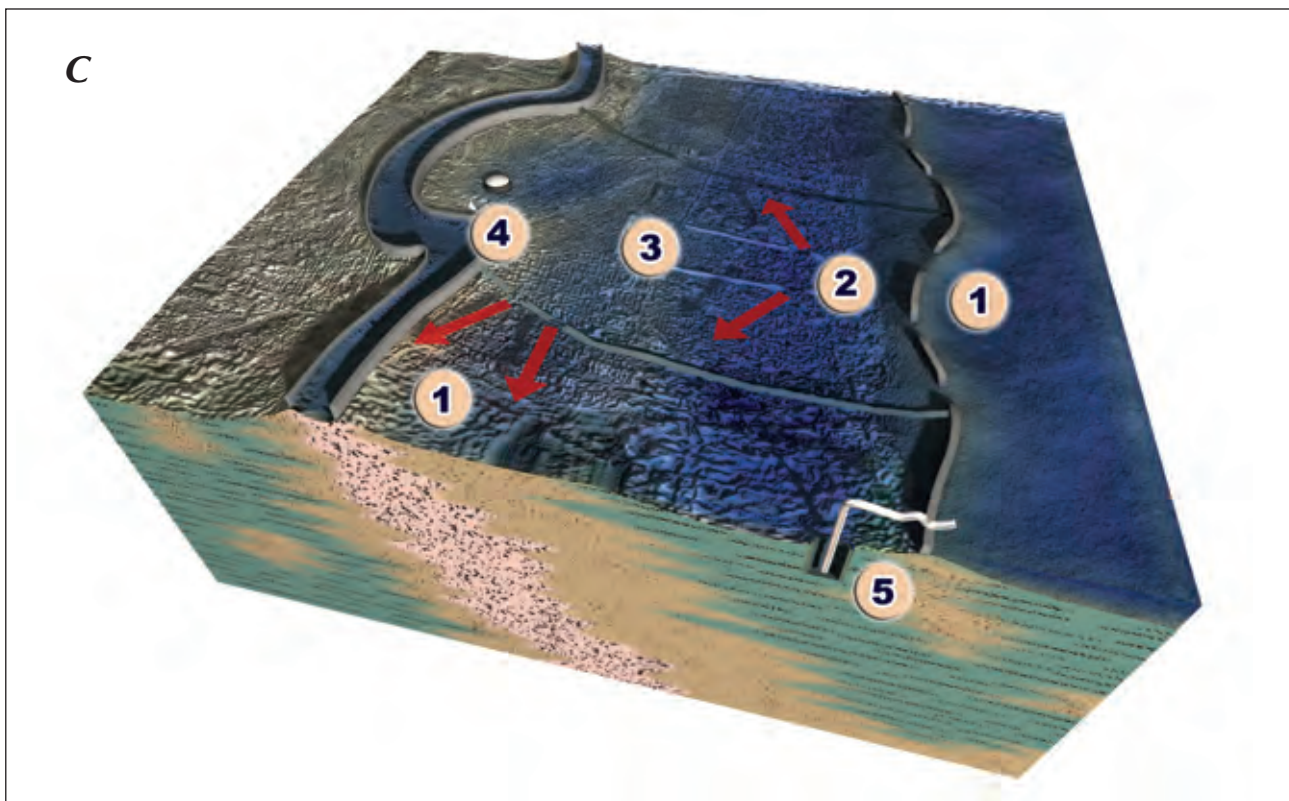
**Coastal flooding** can be caused by increases in sea or lake water levels during storms and rough weather (storm surges, gales etc.; Benavente *et al.*, 2006 and 2007), atypical cyclonic phenomena (hurricanes, typhoons, tropical storms, cyclones, tornados and waterspouts), strong tidal variations (spring and neap tides, tidal currents) and barometric variations (pressure-waves<sup>27</sup>), or as a consequence of tsunamis (owing to submarine earthquakes or displacement of large bodies of water due to landslides or volcanic eruptions). Logically, these floods usually affect coastal areas with low relief (very flat), such as deltas, bays, tidal rivers and estuaries, marshes and beaches, barrier islands, etc. A paradigmatic case of these sorts of floods is the periodical flooding of certain squares and streets in Venice, Italy, due to tidal variations. Another recent example which had severe socio-economic impacts was the flooding of New Orleans (USA) brought on by the passage of Hurricane Katrina in 2005. Occasionally, these coastal phenomena occur in combination and are facilitated or accelerated by the gradual sinking of these coastal areas, whether naturally (subsidence) or artificially (excess weight of buildings, over-use of aquifers, exploitation of mineral resources such as hydrocarbons, salt diapirs, etc.; Figure 5).

<sup>26</sup> Libro Blanco del Agua.

<sup>27</sup> Sometimes referred to as "rizaga" in Spain, which is derived from the Catalan word "rissaga".







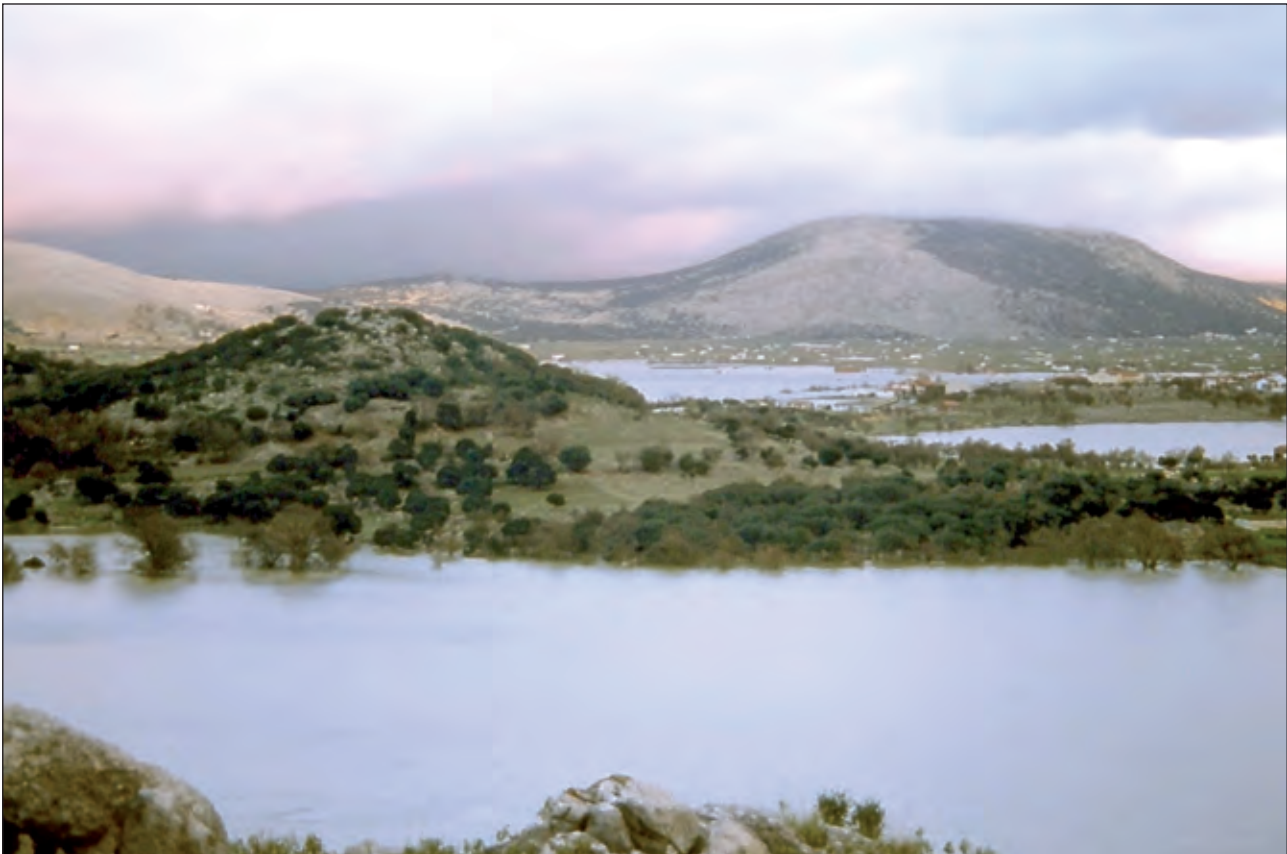
**Figure 5.** Sequence of the evolution over time of the situation in New Orleans (USA) and the flood caused by the passage of Hurricane Katrina (Díez, 2005b):

- A. Natural situation, prior to the City's establishment. The sediment load transported by the river (1) causes the bed to rise through sedimentation (2) while natural dikes overflow (3); surrounding palustrine areas are filled, compensating for sinking from natural subsidence (4).
- B. Situation of New Orleans. The construction of artificial levees (1) and a decrease in the river's bedload (2) impede overflow and sedimentation in the marsh, ending the compensation of natural subsidence; this is compounded by pumping for draining and drying the marsh (3) and the excess weight of buildings, which increases natural subsidence (4).
- C. Situation after the passage of Hurricane Katrina. The destruction of the lake's levees and the canals in several points (1) produces the flooding of great deal of the City, particularly the lowest areas of the old marsh (2), with the positions of the old levees remaining less submerged or not submerged at all (Gentilly Ridge, 3) and the old French Quarter (4), situated on the upper part of the Mississippi River's natural dike; the interruption in pumping (5) exacerbates the situation.

Finally, many floods in coastal areas have a combination or succession of land and coastal origins. For example, a river with high streamflow during a rising stage cannot empty properly into the sea or a lake due to their high water levels caused by storms or high spring tides. In these circumstances flood scenarios are also aggravated by clogged urban sewers, whose drains can become veritable exurgences. This occasionally happens in those coastal areas with the greatest tidal ranges, such as the Atlantic Coast of Galicia and Andalusia (Cobos *et al.*, 2004; Senciales González, 2000; Mintegui *et al.*, 2003; Sendra, P.J., 2002; Figure 7); or the Cantabrian Coast (Fernández and Marquínez, 2002; Marquínez *et al.*, 2003).

## Flood disasters worldwide and in Spain

It is not easy to put together detailed, profuse compilations of disasters associated with floods which have occurred in the past since we only have reliable information on the most recent disasters, in the last few decades, and since this information is based on data available in developed countries. The remainder is based on imprecise, scattered documents and accounts which are sometimes exaggerated and reliant on estimations that are not supported by statistics or census records.



**Figure 6.** Flooding of an area of the Zafarraya polje. Photo: Manuel López Chicano.



**Figure 7.** Flood in El Rocío (Doñana National Park), in the marsh at the mouth of the Guadalquivir river and Madre de las Marismas marshlands, with the effect of tides.



Nevertheless, it seems that the greatest flooding disasters on the planet have taken place in China, where the huge human population inhabiting the banks and shores of its great rivers for thousands of years has conditioned an ancestral interaction between human activities and flooding – and with documentary records which date back thousands of years. Five great floods which occurred in this country are ranked among the ten greatest natural disasters in terms of the number of lives lost (EM-DAT Website): the flooding of the Yangtze Kiang river in 1931 caused nearly 3.7 million deaths, and more than 28 million people were affected. Two others in 1959 and 1887 reached nearly 2 million deaths. It is estimated that the 1939 flood in the North of the country killed half a million people, and the one in Kaifeng, Henan province, in 1642, more than 300,000. Other countries stricken with millions of flood-related deaths are: Bangladesh, India, Japan, Pakistan, Mozambique, the Philippines and Brazil.

It is striking that the disasters which have caused the greatest economic loss in the world were not exceptionally virulent events, but ones which affected areas of considerable socio-economic development and which have occurred in recent times. In particular: the flooding of New Orleans after the passage of Hurricane Katrina in 2005, with losses estimated at more than USD 150 million (Burton and Hicks, 2005), or the 2002 floods in Central Europe (with at least EUR 25 billion in insured economic losses according to the proposal leading to the EC Directive on the assessment and management of flood risks).

In Spain, floods have caused many severe disasters. For some of them, only vague and inaccurate references are available. Among the most recent, the following are worth noting: floods along Spain's Mediterranean coast in 1982, with over EUR 1.8 million Euros in losses; the floods which affected Malaga and the Southeast in 1989, costing nearly EUR 1.2 million; those which befell the Basque Country and Cantabria in 1983, with nearly EUR 1 million in losses; or the 1957 flooding of the Turia river in Valencia, with over EUR 60 million (at that time) in losses.

With respect to human casualties, the floods in Murcia in 1651 and Catalonia-Vallès in 1962 have traditionally been cited as the events with the highest numbers of victims, in both cases close to one thousand. Then, there are the floods in (Durán, 1997): Murcia in 1879 (around 800 victims), Lorca (Murcia) in 1802 (around 700), and Catalonia in 1874 (around 600) and in 1971 (around 400). Also passing the one-hundred dead mark were the flood disasters of the low riverbank of the Júcar in 1779, the town of Consuegra (Toledo) in 1891, Murcia and Almería in 1963, and the Southeast in 1973. Among the most recent events with high numbers of deaths are the Las Nieves campground (Biescas, Huesca), with 87 deaths, Cerro de los Reyes (Badajoz) with 22, and Yebra (Guadalajara) with 10.

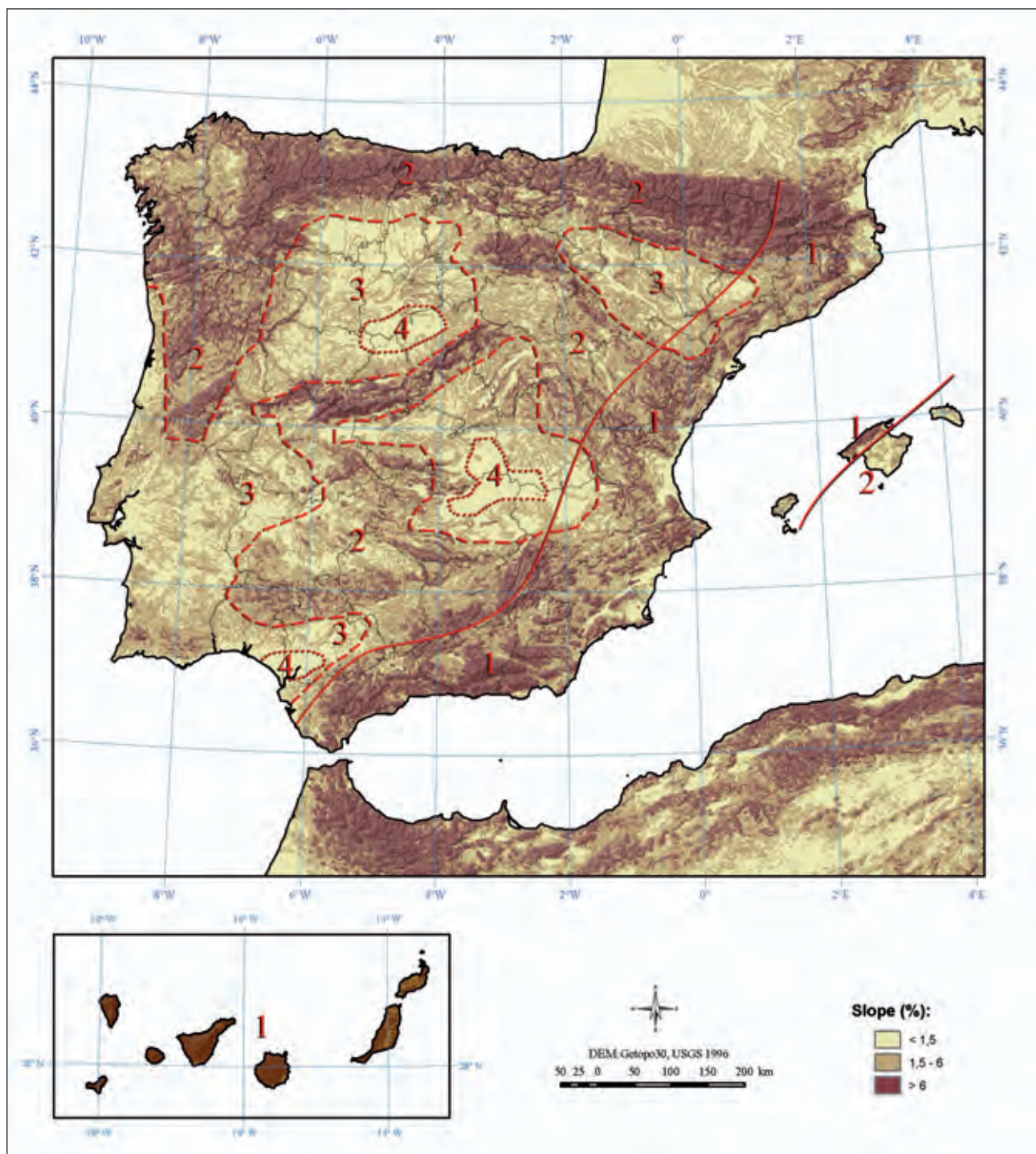
## *Flood risks in Spain*

Nearly all of the Spanish territory is subject to flood risks, albeit in varying degrees and forms (Spanish Ministry of the Environment, 2000; Camarasa, 2002). Based on historical floods, the summary surveys of the CTEI<sup>28</sup> (1985) allowed us to mark off around 1,300 trouble spots concentrated on the river basins of the North (300), the Guadalquivir (177), the Júcar (173) and the Eastern Pyrenees (172). Furthermore, over a thousand risk zones were identified, of which only 6.5% are maximum risk zones. Simplifying this diversity – but only for the sake of delimiting 'at-risk regions', there are four large areas at risk in Spain (Olcina, 1994; Figure 8):

1. Areas at of flooding associated with **flash floods in the Mediterranean watershed**; i.e., the channels of ephemeral coastal streams (gullies or ravines) or permanent coastal streams (the Llobregat, the Palancia, the Júcar, the Turia, the Segura), and their boundaries (alluvial plains, cones, and fans), which in very intense precipitation conditions in autumn (convective systems and complexes) cause flooding in population centres and agricultural lands. They affect a considerable part of the Mediterranean coast in Catalonia, the Region of Valencia, the Balearic Islands, the Region of Murcia, the coast of Andalusia and the cities of Ceuta and Melilla; but they are also common in bordering areas of Aragon and Castilla-La Mancha.

<sup>28</sup> *Comisión Técnica de Emergencias por Inundaciones* (Technical Commission for Flood Emergencies).





**Figure 8.** Main torrentiality characteristics of Spanish streams (dark brown, torrents; light brown, torrential rivers; and yellow, fluvial rivers; modified by Llorente et al., 2008b), as well as the large at-risk regions as characterised by their respective predominant flood types: 1, flash floods; 2, torrential floods; 3, flooding of big rivers; and 4, flooding of endorheic areas.

2. Areas at risk of flooding associated with **torrential floods in mountain systems**, i.e. the channels of torrents, gullies, ravines and streams, and their banks and cones, which, during intense precipitation conditions in the summer months (convective cells or thunderstorms, and orographically induced convective cells) cause flooding in population centres. They affect slopes and piedmonts of the principal mountain systems of main-

land Spain (the Cantabrian Mountains, the Pyrenees, the Iberian Range, the Central System, Montes de Toledo, Sierra Morena, and the Baetic Ranges) and the islands (Sierra de Tramuntana, Canary Islands).

3. Areas at risk of flooding associated with **rising water levels along the middle and lower reaches of the large rivers of mainland Spain**; these are the channels of rivers and their associated flood plains which, in conditions of prolonged precipitation (winter Atlantic fronts) or melting snow packs (in spring), cause the flooding of human settlements and agricultural lands. They affect the central areas of large river basins: the Duero and its tributaries from Soria to Arribes; the Tajo and its tributaries from Aranjuez; the Ebro and its tributaries from Logroño; the Guadalquivir and its tributaries from Andújar.
4. Areas at risk of flooding associated with **flat and endorheic areas in the central areas of the large river basins**; i.e., plains and marshlands which, in intense and/or prolonged precipitation conditions, accumulate rainfall *in situ*, exceeding the infiltration and drainage capacity and flooding human settlements and agricultural lands. They affect certain parts of the Duero basin (Tierra de Campos, Tierra de Pinares...), the Tajo basin (Campo Arañuelo, La Sagra), the Guadiana basin (La Mancha), Los Llanos de Albacete, etc.

On a smaller scale, there are other flood types in Spain which cause risk situations in more specific areas and on an exceptional basis, such as coastal flooding (the Atlantic and Cantabrian coasts during storms and spring tides), or floods associated with water table rises (the Zafarraya Polje and areas of La Mancha Húmeda which are prone to ponding; López Chicano *et al.*, 2002).

There is obviously a plethora of intermediate or mixed situations, as well as areas affected by two or more of the types summarized above. One of the most common is the interference with streams in rising stages and/or freshets which flood the banks at the mouth caused by concurrent adverse coastal dynamics conditions (high tides, storms).

The different hazard analyses and the corresponding maps derived from them will take into account this complexity and variety of Spain's flood events, adapting the methods and techniques of analysis and representation to the special features of the floods anticipated in each risk zone. To that end, specific recommendations will be provided for hazard areas according to the type of flood or the context in which it occurs.

## *The impact of flood events*

The first, most inherent damage caused by flooding is the actual covering by water of areas that are normally dry, and the water's **depth**, which implies the dampening of soils, the consequential loss in the load bearing capacity of land, and damage done to the structures and buildings on that land, since their foundations and structural stability may be affected. Furthermore, certain crops and vegetation may be lost after being submerged and cut off from atmospheric oxygen. What is more, service installations (electric power lines, communications networks, oil and gas pipelines, etc.) and communication routes (railways, roads, airport facilities) can remain submerged, with the resulting risk of interruption or breakdown in service. Also, the immersion of a great deal of tangible assets, such as electrical appliances, motor vehicles (Figure 9) and household furniture causes irreparable deterioration and damage, with ensuing economic losses. In this regard, there is a series of water table depth threshold values beyond which damage increases significantly, such as 0.8 meters, the average depth over which equipment on tables, worktops and shelves are submerged (the 'table effect'). In the case of toxic or dangerous installations and goods (waste dumping sites, chemical plants, thermal and nuclear power stations), damage is liable to increase because polluting agents may be diffused and dispersed in the current. Greater depths, and especially sudden depth changes (steps, pools and fords), can also present a danger to the physical integrity of humans and animals, mainly for people who are highly vulnerable due to their young age (infants and children), old age (the elderly), or different physical and mental disabilities and illnesses.

It is also important to consider the water table residence time since exposure or prolonged flooding can exacerbate the aforementioned adverse effects, such as the loss of crops (by bacterial action in anoxic environ-



**Figure 9.** Effects linked to water table depth: above, marks on a motorbike in the aftermath of flood events in Villarrubia de los Ojos (Ciudad Real) in May 2007; below, water table inundating the playground at Virgen de la Poveda chapel (Villa del Prado, Madrid) in 2001.

ments) or the breaking up of foundations, whereas rapid draining can significantly reduce damage, as it also minimizes the settling of fine materials on the bed. In coastal flooding, the covering of continental areas by seawater causes the salinization of the soils and aquifers it infiltrates.

Secondly, a flood effect liable to cause damage is stream **velocity**, which can at times knock down and sweep away goods and persons by direct or indirect impact (scouring or sediment transport). Velocities which exceed one meter per second and with a certain depth are considered enough to sweep away a person; even lower velocities are capable of floating and displacing vehicles and other equipment. Particularly dangerous are sudden changes in velocity, such as those produced in hydraulic jumps (regime changes at waterfalls and narrowings), in which the release of energy is such that belongings and persons get trapped with enormous difficulties





**Figure 10.** Effect of stream velocity on a building on the banks of the Gaznata river; a house's facade was torn off. Herradón de Pinares (Ávila), September 1<sup>st</sup>, 1999.

of being recovered or rescued. During floods, especially torrential floods, velocities can even exceed 4 or 6 m/s, rates at which heavy and voluminous objects are swept away. Even eddies, dangerous air suction phenomena triggered by the Venturi effect and extremely high pressures caused by cavitation are produced (Figure 10).

Thirdly, the stream's **force or energy** can erode the bed and banks of the channel, causing the scouring of infrastructures and slope instability, which triggers the movement of material (slumping, landslides, flows) and the consequent damage that can affect persons and properties such as infrastructures (communication routes, hydraulic works; Figure 11).

A fourth effect liable to cause damage is the **sediment load** carried along by the water, whether suspended in the fluid, as bedload (by saltation, rolling or dragging) or by flotation. Transported materials can cause harm to persons through impact, causing traumatism and abrasions of varying degrees of severity, and even death due to multiple injuries. Similar damage occurs to physical assets and buildings. These detrital materials (boulders, pebbles, gravel, sand, silt and clay) or plant remains (floating or in 'beds') produce various hydraulic effects on



**Figure 11.** Effects of the force and energy of a stream sweeping away the embankment of Villalba-Ávila railway, September 1<sup>st</sup>, 1999; the railway was inoperable for several months.

the stream, such as increase its density and viscosity (incrementing its capacity to erode and transport more materials in a feedback effect) and reduce its velocity, causing the water table to rise. In extreme cases, the lifted sediment load can transform the stream into a highly-dangerous mud or debris flow (Figure 12). Similarly, the transport of floating elements (such as plant fragments, hail or ice) can hamper the flow and passage through narrowings (bridges or sewage systems), causing them to collapse and break.

When this sediment load being transported is finally deposited in lower energy areas, it can also cause damage due to accretion, because apart from covering and burying physical assets, it can obstruct or block transport, drainage or supply infrastructures, render useless electrical appliances with filters or grilles, reduce fishery resources (shell fishing), etc.

**Other impacts** liable to cause damage, although to a lesser extent spatially and less frequently:

- Piping in banks and shores: after the flooding, the water that drenches and saturates these banks (riverbank storage) returns to the channel via subsurface flow, sweeping away fine elements which produce small underground galleries and conduits (piping conduits), the subsidence or collapse of which could cause damage (Figure 13).
- Clay or salt rock (anhydrite) expansion phenomena, when this type of material is found in flooded areas, with the resultant landform change owing to soil expansion.
- Karst reactivation phenomena, through the removal of obstructions from full conduits during the flooding, or by creating new conduits or galleries, or due to the collapse of their hanging walls.



**Figure 12.** The Romanesque Church of San Adrián de Sasabe (Huesca) was buried by a debris flow, which covered it up to the upper part of the nave.



**Figure 13.** Microcollapse of piping conduits formed in a silt-clay deposit which had been previously flooded. La Unión (Murcia).

## *Maximum probable events and extreme phenomena*

There is no validated scientific knowledge of the values of maximum probable events in the case of floods because the spatial variability of their determining and triggering factors is very high. The closest thing to maximum probable events are the calculations for estimating Probable Maximum Flood (PMF), associated with Probable Maximum Precipitation (PMP). This would be the biggest flood physically possible in a particular area of a catchment basin, assuming the occurrence of the maximum precipitation event. Nevertheless, although there are manuals for their estimation and computation (WMO<sup>29</sup>, 1986), multiple parameters and meteorological studies are required, their use as a general reference is unfeasible.

Another approach to the problem begins with the study of historical events of extreme floods (Hersch, 2004) and records of palaeofloods (Missoula) and megafloods (Snorrason *et al.*, 2002) contained in recent geological deposits (Quaternary period and, mainly, Holocene stage). By analysing their frequencies and magnitudes and using frequency distribution functions of specific extreme values, we can try to determine the maximum value which renders the distribution curve asymptotic. Furthermore, attempts have been made to correlate this upper limit curve value with the PMF value, but without great success for the time being, except for specific locations.

In view of these problems to determine maximum probable events, most experts and managers have adopted as a reference value a phenomenon of low frequency and extreme character: the flood event with a 500-year return period. The latter is applied in the Spanish Water Act<sup>30</sup> to demarcate flood-prone areas, and the Spanish Basic Directive on Planning Civil Protection<sup>31</sup> for exceptional flooding areas. It also served as technical reference for several decades in the design of certain structures (channelisation, levees) and devices for draining dams (spillways, cofferdams); nowadays, other values of lower probability are used in most developed countries.

<sup>29</sup> World Meteorological Organization.

<sup>30</sup> *Ley de Aguas*.

<sup>31</sup> *Directriz Básica española de Planificación de Protección Civil*.



These problems and doubts are compounded by the uncertainties associated with global change, in terms of the variations in the frequency and magnitude of these extreme events due to climatic fluctuations (unsteady nature of series) and the changes in land use over such extended periods of time (Benito *et al.*, 2005; Benito, 2006; see section 2.3.2).

## *Human actions which may increase risks*

Human actions which may increase risks can be grouped in three big sets, taking into account which risk factor they increase: hazard, exposure or vulnerability.

Following are some of the actions which may increase hazards by increasing discharges and their depths and velocities, modifying characteristic times to more dangerous situations, or increasing the sediment load being transported:

- Deforestation and changes in vegetation cover, diminishing interception, and therefore increasing effective rainfall.
- Surface sealing of large areas the basin, either by covering the surface with waterproof elements (buildings, asphalt), or by soil compaction (overgrazing, traffic of vehicles or heavy equipment; Figure 14).
- The opening of slopes, land clearances and exposed rocks and surfaces due to construction works and farm or forestry activities, increasing the sediment load and reducing soil infiltration capacity.
- Inappropriate design and management of interventions in the channel and floodplain, such as channelisation, artificial levees, or meander cut-offs, which transfer hazards to other areas or defer them.

## *Flood hazard analysis methods*

In Spain, as with the rest of Europe, flood hazard analysis is undertaken using a series of combined and complementary techniques and procedures which, broadly speaking, can be grouped into three methodological ap-



**Figure 14.** Surface sealing caused by compaction produced as a consequence of intense treading of livestock. La Cañada (Ávila).

proaches: historical and palaeohydrological methods, geological and geomorphological methods, and hydrological and hydraulic methods (Díez-Herrero, 2002a). There are also combined methods and those based on botanical or ecological grounds, such as dendrogeomorphological (Díez *et al.*, 2008a) and lichenometric methods, although they are still in the research phase (Figure 15).

**Historical methods** use markings and plaques on artificial elements (buildings, communication routes, public works, etc.), historical documentation (archive manuscripts and printed documents, libraries and newspaper archives) and testimonials (oral or audiovisual) to reconstitute the extent covered or the depths reached during a flood in a given historical period. A simple application of this methodology is to assume that if water has al-

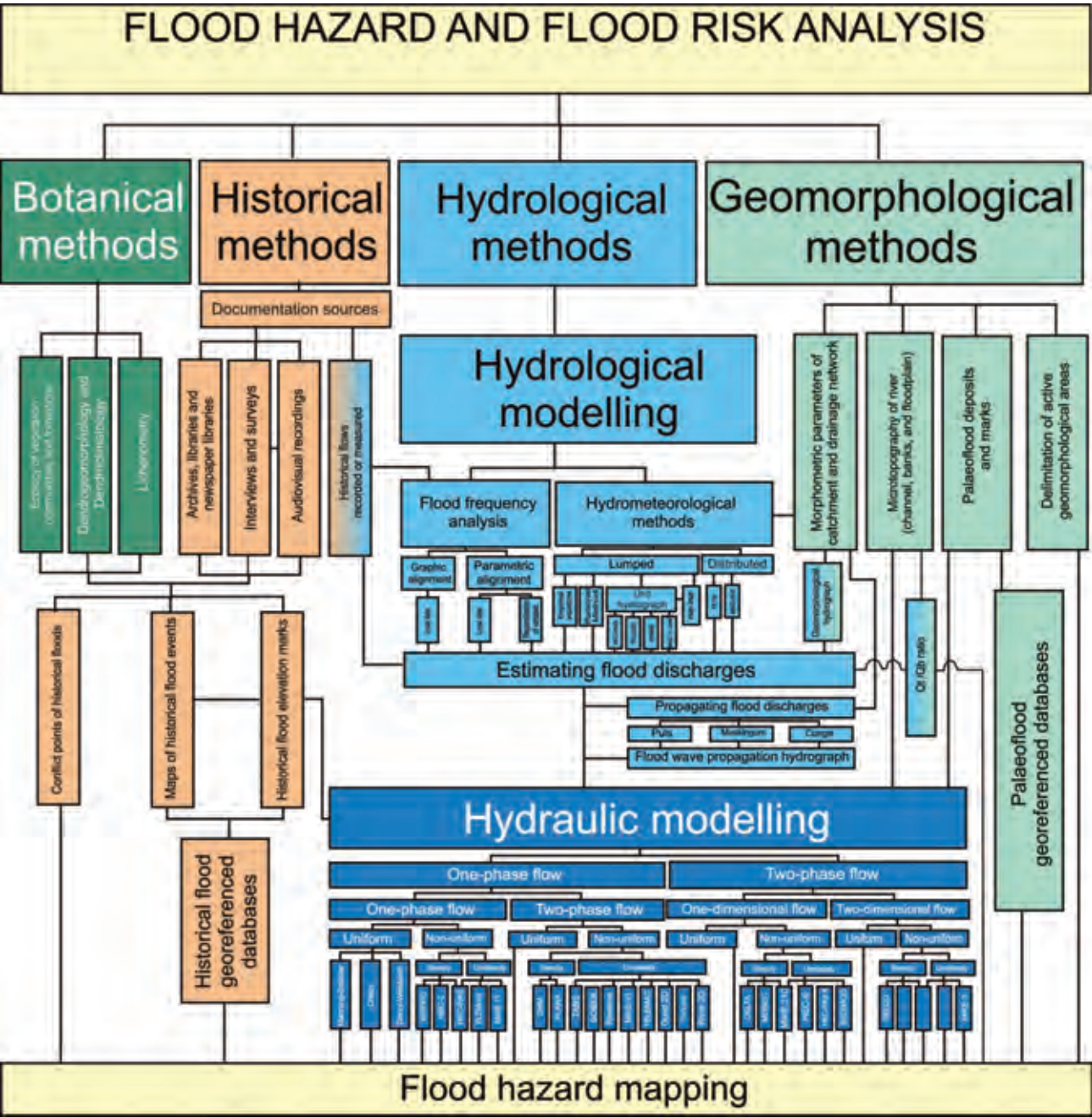


Figure 15. Chart summarising the main groups of flood hazard analysis methods and their mutual relations (modified and further developed by Díez 2002c and Díez Herrero 2008c).



ready reached certain levels in the past, it can also reach them in the not too distant future, making this area a 'historical flood' zone. Somewhat more sophisticated are the studies which convert these levels into discharges flowing through hydraulic models and assign them a certain probability so they can be introduced as complementary data in flood frequency analysis using normal recording methods; or those which assign historical flood frequencies to geomorphologic units and elements (Lastra *et al.*, 2008). More detailed information on these methods and their application can be found in Barriendos and Coeur (2004), Marquínez *et al.*, and Barnolas and Llasat (2007). For historical flood frequency analysis on a national scale (Spain), see Benito *et al.* (1996). As for data sources on historical floods, the CTEI compilation (1985) is worth noting, as well as the updates and additions to the catalogue being undertaken by the General Directorate for Civil Protection and Emergencies (Pascual and Bustamante, 2008). For information on how they are incorporated into flood frequency analysis, refer to Francés (2004a).

**Palaeohydrological methods** of gathering geological data utilise certain types of deposits or marks left by past floods (prehistoric or from times when no historical information is available), in relation to elements which can be dated through palaeontological, dendrochronological, radiometric ( $^{14}\text{C}$ , OSL, TL, etc.) or archaeological techniques. In this manner, we can also assign a probability of occurrence to discharges estimated using hydraulic modelling based on those levels and rates, incorporating them into flood frequency analysis as non systematic data (Benito, 2002; Benito *et al.*, 2004).

**Geological-geomorphological methods** use the arrangement and types of landforms and deposits generated during or after the flood event. With this method we can delimit geomorphologically active areas within the stream channel and its banks, and therefore areas prone to flood inundation within the framework of the stream's natural dynamics, their qualitative flood frequency, and even infer the order of the magnitude of certain parameters such as depth, velocity and transported sediment load. More detailed information on these methods and their application can be obtained in Ayala (1985), Baker *et al.* (1988), Díez and Pedraza (1996), Díez-Herrero (2002a), Marquínez *et al.* (2006a and b), Ortega and Garzón (2006) and Lastra *et al.* (2008). These techniques are gaining strength because they are the only ones which consider natural phenomena very difficult to model with other techniques, such as avulsion, channel migration, or sediment transport, and take into account natural developments of the fluvial system.

**Hydrological and hydraulic methods** aim, respectively, to estimate the discharges generated in a catchment or stream and compute the velocities and depths at which these discharges will flow through a certain channel reach. Hydrological methods can start with streamflow data, applying a statistical analysis of peak values, or precipitation data, through hydrometeorological rainfall-runoff conversion models based on formulas and methods such as the rational method, the unit hydrograph, the PMP-PMF, the kinematic wave, and so on. (Figure 15). Hydraulic methods are based on different hypotheses, simplifications and approximations of the flow of water in Nature (one-phase/two-phase, one-, two- or three-dimensional, uniform/non-uniform, steady/unsteady, laminar/turbulent, slow/rapid) which simplify the physical equations used to model flow (Figure 15). Solving these equations allows us to estimate different parameters (depth, velocity, energy). For more detailed information on these hydrological methods, see Ferrer (1992 and 1993), Menéndez *et al.* (1996); Díez-Herrero (2002a), Montalbán *et al.* (2003), Francés (2005) and CGRM<sup>32</sup> (2007). Initial rainfall data can be obtained at the INM<sup>33</sup> (1998), along with computer programs (see Annex A). For the curve number (CN), refer to Ferrer (2003). For hydraulic modelling, the theoretical-practical fundamentals are available in works such as Chow (1994), Martín Vide (2002) and Simarro (2006).

These broad groups of methods are not exclusive; on the contrary, all of them should be used and applied in an integrated and complementary way in flood hazard analysis whenever the required information sources are available.

In the following sections, we briefly review the methods and subtypes most widely used by the technical/scientific community for hazard analysis.

<sup>32</sup> Consejo de Gobierno de la Región de Murcia (Governing Council of the Region of Murcia).

<sup>33</sup> Instituto Nacional de Meteorología (National Institute of Meteorology).

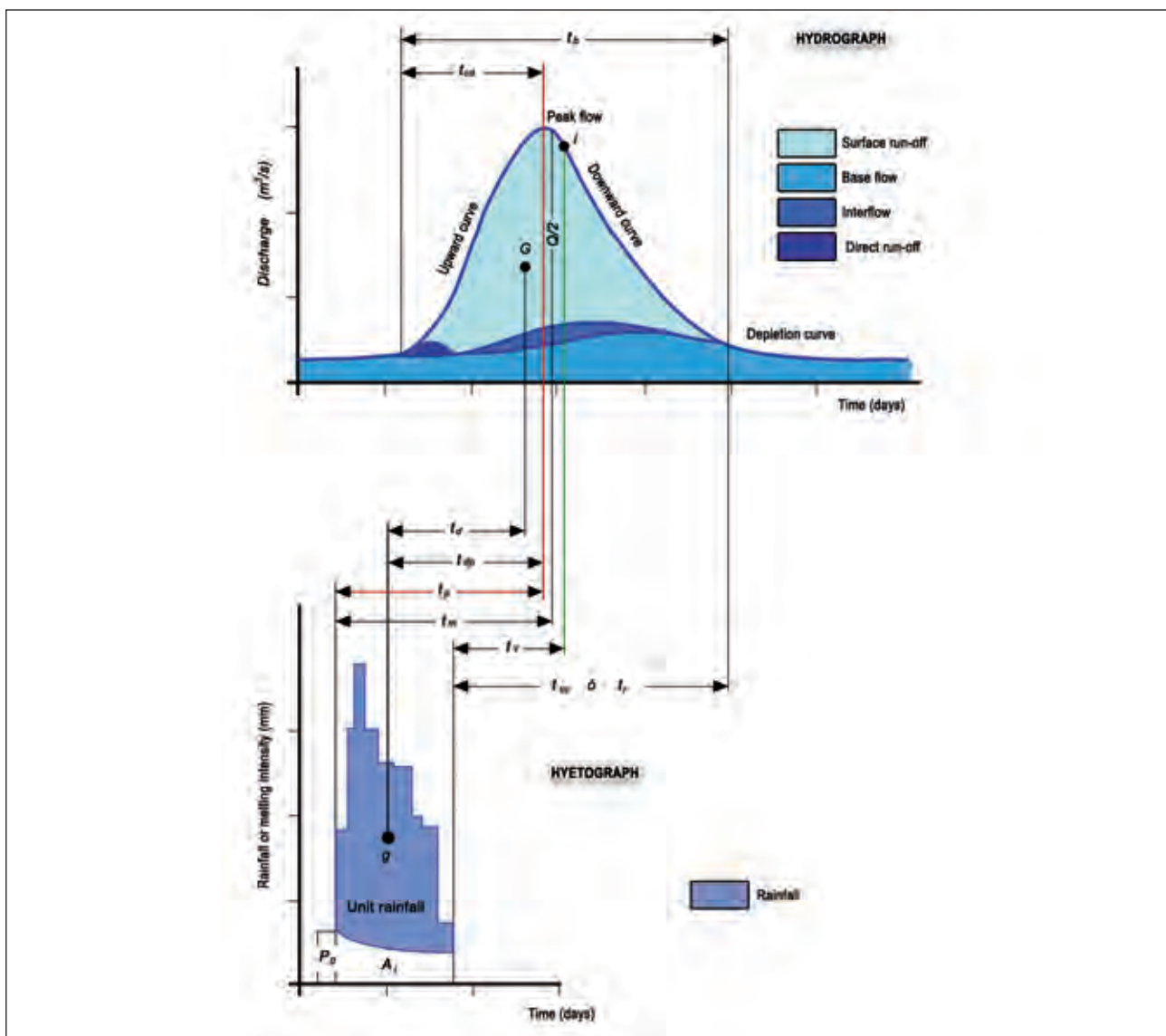


## 2.1. Hydrological-hydraulic Methods

### 2.1.1. HYDROLOGICAL METHODS

If we consider the fact that a flood is an event with abnormally high discharges recorded at a particular point or reach in the stream, then the characterisation of these abnormal discharges with respect to time, i.e. establishing the flood hydrograph corresponding to the event, will be of fundamental importance. Within this hydrograph, we can study the flood's elements (peak discharge, rising limb, falling limb, and lag time), components (surface runoff, direct runoff and subsurface runoff and base flow) and characteristic times, in relation to the corresponding hyetograph (Figure 16), and then assign an occurrence probability to it.

There are various methodologies for the hydrological study of floods, ranging from the full characterisation of the hydrograph to the determination of only one of its parameters, such as peak discharge. For the purposes of our study, we can distinguish between two general groups of methods: those aiming to analyse a past flood through streamflow data, and those aiming to estimate the streamflow of future floods or hypothetical situations



**Figure 16.** Relationship between the rainfall hyetograph and the hydrograph of the flood it generates, the components, elements and characteristic times (Based on Díez-Herrero, 2002a and Díez and Pedraza, 1996).

(design flood) based on indirect data from past floods (geological-geomorphological marks or impacts), or by analyzing precipitation and/or streamflow data recorded during other floods.

The so-called **direct methods** seek to characterise the hydrograph of an actual flood recorded at a gauging station using a limnimeter and then calibrate it with a rating curve or by means of a sequential series of instantaneous discharge measurements (areas of the sections multiplied by velocities). To achieve this, the hydrographs archived by the river basin authorities (gauging units of the basin confederations and water agencies in the Spanish autonomies) or hydrological data kept by CEDEX<sup>34</sup>, such as the HIDRO database (Quintas, 1996), with its associated tables (mainly HIDROGR) and programs.

Using the hydrograph, it is possible to work with various methodologies to carry out an exhaustive analysis of the flood's elements and components (Custodio and Llamas, 1983; Chow *et al.*, 1994): straight line, conventional depletion curve, maximum curvature, Linsley and Barnes; also obtained are the hydrograph's time characteristics or the resultants of its correlation with the hyetograph.

As regards the **indirect methods**, according to Llanos *et al.*, (1995) there are two trends in the hydrological study of floods. One is a deterministic method that advocates using the past as a determinant of present and future behaviour and approaching it by means of laws of physics and mathematical relations. The other trend is a stochastic approach, based on the random nature of the process. It proposes the application of analytical laws or functions to a set of prior observations to predict future values of the variable. The first approach, which is deterministic, uses empirical techniques and also includes historical and geological-geomorphological methodologies based on physical evidence from past floods.

**Empirical techniques** encompass, first of all, a group of empirical formulas which draw a relationship between the peak discharges which can be recorded in a stream and the area of the basin draining towards the stream, or the ratio between its area and that of a neighbouring basin with known discharges. These include the well-known formulas of Zapata, Fuller and Heras (1970b), which propose a direct proportionality between the discharges and areas of two contiguous basins, where peak discharges have been identified for one of the two basins using other techniques. On some occasions these formulas have given rise to nomograms for entire basins or certain subareas thereof. There are also more elaborate formulas and regressions based on multivariate analysis of morphometric parameters of the basins (Potenciano, 2004 and 2008). These are very widely used in the United States for initial discharge estimations (Section 2.2.1). These formulas include disputed 'black box' models, leaving out information about the basin's internal hydrological processes, which is why their use is highly limited to certain basins where they have been verified.

**Statistical or stochastic techniques** include both hydrometeorological methods and flood frequency analysis.

## HYDROMETEOROLOGICAL METHODS

As their name suggests, these methods are based on the functions for converting meteorological variables (basically rainfall and, to a lesser extent, snowmelt) into surface runoff (discharges) supported by deterministic models. Using meteorological data, the intention is to make use of the pluviometric series' higher quantity of sampling points (stations) and greater representativeness and length in comparison to the stream gauge series. There are various types of models which simulate the rainfall-runoff process (Ferrer, 1993):

- *Continuous*, which show a running balance of moisture over a prolonged period of time, including during flooding and ordinary periods (MIKE-SHE, HSPF, SIMPA).
- *Discrete*, which simulate a single event in which all that is considered is the part of rainfall which provokes surface runoff, making them particularly useful for design floods. The most common are the Rational Method, the unit hydrograph and probable maximum flood (PMF).

<sup>34</sup> Centro de Estudios y Experimentación de Obras Públicas (Centre for Public Works Studies and Experimentation).



Methods and models may also differ according to the degree of lumping or spatial distribution of the parameters and variables which comprise them, namely:

- *Lumped*, which consider a zone or area of the territory (normally a basin or sub-basin) as a single element, approaching the hydrological parameters as averaged values; one example is the Rational Method.
- *Semi-distributed*, which consider as a single unit of analysis the homogenous zones ("homogeneous hydrological response units") within the same basin or sub-basin; for example, the unit hydrograph method in the HEC-HMS application.
- *Distributed*, which consider the spatial variation of all the hydrological parameters, and work with units of analysis such as pixels, points, arcs, or polygons (vectors); one example is the TETIS application.

### *Rational Method*

This method is based on the transformation of rainfall with intensity  $I$  (which starts instantaneously and continues indefinitely) into a runoff which will continue until the time of concentration ( $t_c$ ) is reached, at which time the entire basin is contributing to the flow. At this moment of equilibrium between inflow and outflow, peak discharge ( $Q_p$ ) will be reached at the basin outlet. The volume entering the system will be the product of rainfall intensity and its area ( $IA$ ), which is then reduced by a runoff coefficient ( $C$ , between 0 and 1), which gives the proportion of water retained in the original abstractions (interception, ponding, evapotranspiration). The units of the variables are expressed using the North American system. To convert them to the International System ( $Q_p$ , m<sup>3</sup>/s;  $I$ , mm/h;  $A$ , km<sup>2</sup>), the product must be divided by 3.6, which gives the general formula:

$$Q_p = \frac{C \cdot I \cdot A}{3.6}$$

The runoff coefficient, assumed to be the mean for the basin and to be uniform over time, is calculated using standard methods (Ferrer, 1993): Horton, Holtan, SCS<sup>35</sup> (1972), or using tables which include all of the physiographic aspects that alter it. On other occasions, a calibration using a comparison with the results of flood frequency analysis (Témez, 1987) was proposed. Rainfall intensity is calculated as the average intensity for a duration equal to the time of concentration considered for different return periods, using intensity/duration curves. Various equations can be used to estimate the time of concentration (Chow *et al.*, 1994), the most common being those of the SCS (1975).

This method has been highly criticized since the time people began using it in the mid-19<sup>th</sup> century given the underlying assumption: rainfall with constant intensity over the study area in an interval  $t_c$  and runoff coefficient constant over time – an unlikely situation in a natural system. Many studies recommend that it be used only for basins with certain dimensions or in specific rainfall duration conditions. This is why it has been recommended that various modifications be made to the traditional formula so it can be adapted to other basins or time of concentration conditions. The Modified Rational Method aims to adapt it to rainfall with a duration that is greater than the time of concentration, larger basins (between 8 and 12 ha) and reconstructions of peak discharge and the hydrograph, which assumes a trapezoidal shape (Chow *et al.*, 1994).

The modification by Témez (1991), for application to basins of up to 3,000 km<sup>2</sup> and times of concentration ranging between 0.25 and 24 hours, introduces to the formula a rainfall uniformity coefficient ( $K$ ), which can be calculated as a function of the time of concentration, and the application of the area reduction factor ( $K_A$ , Témez) to the intensity estimation:

$$Q_p = \frac{C \cdot I \cdot A \cdot K}{3.6} \quad K = 1 + \frac{t_c^{1.25}}{t_c^{1.25} + 14}$$

There are various computer programs for performing these computations, some of which are adaptations of

<sup>35</sup> Soil Conservation Service.

spreadsheet applications (MS Excel), and others which are programmed for MSDOS or MS Windows: CHAC, TEMEZv2, Caudal (Annex C).

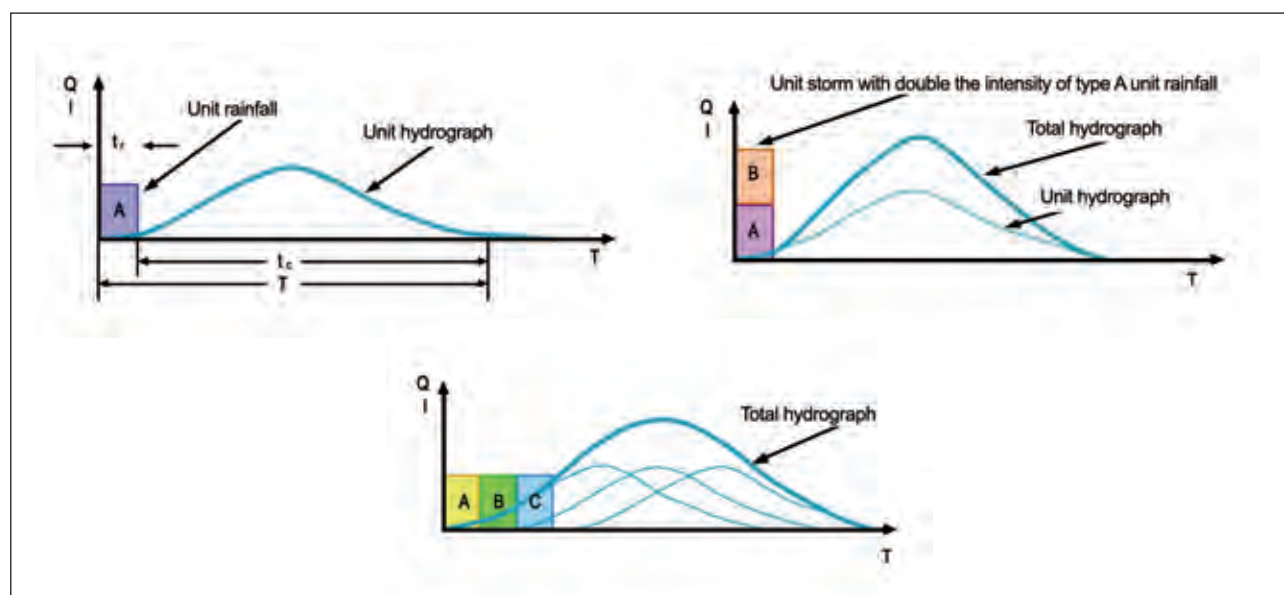
One attempt at making it comprehensive so as to be able to reconstruct not only the peak discharge, but also a flood hydrograph, is the **isochrones method**, which consists of applying lines of equal travel time to the basin and producing a planimetric representation of the areas they cover. The rational method is applied to each area, and the outlet discharge response times each area contributes to the runoff are estimated (Heras, 1970b; Potenciano, 1995).

### Unit hydrograph

For the purposes of modelling the actual hydrographs generated during natural flood events, mathematical formulas have been devised which, on the basis of the physical phenomenon they deal with, allow us to obtain synthetic hydrographs. They usually only aim to calculate the surface component of the hydrograph based on the corresponding hyetograph, disregarding the magnitude of the base flow during the flood.

The most frequently used method is based on the unit hydrograph concept (Sherman, 1932), i.e. the surface runoff caused by 1 mm of net rainfall uniformly distributed over the basin and with constant distribution along a given time interval ( $D$ ). It consists of obtaining a standard hydrograph for each basin which has this basic hydrograph generated by a short storm (lasting  $1/3$  to  $1/5$  of  $t_c$ ), and adapting it to any precipitation event by breaking it down into intervals of duration  $D$ . For this to be possible, the following assumptions are made: constant time base, storms of equal duration produce hydrographs with an identical time base; affinity or proportionality between rainfall intensities and the hydrographs' discharges; additivity or superposition, several basic hydrographs are equal to their sum (Figure 17).

To obtain the unit hydrograph directly from the hyetograph and hydrograph records of several storm events, one must simply divide the discharges of the surface by the amount (mm) of net rainfall for a duration interval  $D$ . Typically, real data are not available, which is why there is an established formula for calculating the different parameters required in a synthetic hydrograph, the most customary being:



**Figure 17.** Representation of the three assumptions that the unit hydrograph method must satisfy (based on Ferrer, 1993): time base constancy, affinity or proportionality, and additivity or superposition.



- SCS dimensionless unit hydrograph (1972), based on a dimensionless hydrograph obtained by analysing small, rural basins. The only parameter required is the lag-to-peak time, which is used to calculate time to peak and peak discharge.
- The Clark instantaneous unit hydrograph (IUH; Clark, 1945) is the result of evenly distributing a unit of rainfall across a basin for an infinitely small time duration. It involves evaluating sums, but with constant variables, that is, an integral defined between 0 and  $t$ . Its use is based on the hypothesis that the basin's IUH is the result of translating excess rainfall and routing it for storage in the basin (by means of a hypothetical linear dam).
- Synthetic unit hydrographs based on basin characteristics: Snyder (1938) and Gray (1961).
- The Témez triangular unit hydrograph (1987), similar to the SCS hydrograph, but with the hydrograph being derived from time of concentration, from which the lag-to-peak time, time base and peak discharge are obtained.

All of these methodologies and calculation procedures are built into computer programs which, since the late 60's, have made it easier to obtain synthetic hydrographs from a hyetograph, requiring only a limited amount of additional data related to the basin configuration to calculate characteristic times. The most standard one, without a doubt, is the HEC-1 program (HEC, 1981), which uses the Clark unit hydrograph methodology or kinematic wave methods. Following several revisions in 1970, 1973 and 1981, the first PC version was developed in 1984 and updated in 1988 with a system of menus. In the past decade, an improved version was developed for the MS Windows environment called HEC-HMS (Annex C). The processes modelled are: rainfall, interception and infiltration, runoff, and flood wave propagation and routing. This permits the calculation of hydrographs at different points of the basin.

Other noteworthy computer programs for the hydrometeorological modelling of flood events are (Annex C): TR-20 and TR-55 (US Department of Agriculture; SCS, 1973), based on the methods of the SCS; SWMM (RUNOFF) of the US Environmental Protection Agency; MIKE 11 UHM (DHI); and DRM3 Distributed Routing Rainfall-Runoff Model; Alley and Smith, 1982), developed by the US Geological Survey (USGS).

#### *Probable Maximum Flood (PMF)*

This involves calculating the estimated extreme values (EV) of extreme meteorological events, primarily probable maximum precipitation (PMP) and the associated probable maximum storms (PMS), and which are fitted to the Probable Maximum Flood (PMF).

The PMP is the greatest amount of rainfall (mm) that is physically possible in an area for a duration and period of a given year. PMP characterization is based on meteorological analysis according to three groups of methods (Chow *et al.*, 1994):

- a) Application of the storm models of convective-type meteorological events when there is no existing information, or in regions of rugged topography (WMO, 1986).
- b) Maximisation of actual storms, adjusting observed precipitation upwards using the ratio between the actual moisture inflow and the estimated PMP. For this purpose, storms from other areas of the basin may be transposed if there are no prior records in this zone.
- c) Generalised PMP maps, which record the estimations made in some countries, such as the United States, where data exist since several decades (Shreiner and Riedel, 1978). In other European countries, this approach is compulsory only for high-risk installations, such as nuclear power plants or large dams.

PMS is the temporal distribution the PMP's precipitation, expressed as maximum quantities (mm) for given durations. In short, it aims to reconstruct the shape of the maximum probable storm's hyetograph, in which asymmetrical shapes with frequently growing intensities are adopted. These are conservative models which lead to greater precipitation towards the end of the storm.

PMF is the hydrograph of the flood produced by a PMP with its corresponding PMS, with the rainfall-runoff transposition being computed in a normal fashion using the unit hydrograph method, often with the HEC-1 or HEC-HMS application.

### *Distributed hydrological modelling: the TETIS model*

Distributed models, contrary to lumped models, do not consider the basin as a single element; rather, they work by discretizing it into smaller units (discrete elements) using grid cells (rectangular, triangular, quadrangular) whose basic calculation unit is the pixel. In this way, all of the parameters have spatial variability up to each basic unit at a maximum so that there is interaction between all of the parameters at the most basic level in the computation processes (re-infiltration in a slope or channel, saturation by interflow, water table gradient, etc.).

The processes involved in runoff generation are: interception, detention storage, infiltration, evaporation, snowmelt, percolation, groundwater recharge, surface runoff, surface flow and base flow. Representing these processes in physical models results in a series of differential equations, the solution of which is attacked using numerical methods, whereas by discretizing in time and space, the fundamental equations are linearised with their respective equations of state. All of this leads to simplifications and scale errors, which is why the basin must be discretized to an adequate level of detail, and a fine-tuned calibration should be carried out.

The TETIS model was developed by the Institute of Hydraulic and Environmental Engineering<sup>36</sup> (Polytechnic University of Valencia; Francés, 2004b; Montoya *et al.*, 2006; Vélez and Francés, 2006) and is a conceptual distributed model available free of charge at <http://lluvia.dihma.upv.es/>.

The variables interpolated in the TETIS model are: rainfall (using a maximum of 6 rain gauges), the water equivalent (using snow gauge stations and a contour-line matrix map of snow cover), temperature (based on altitude above sea level by means of a gradient usually equal to  $-6.5^{\circ}\text{C}/1,000\text{ m}$ ), and potential evapotranspiration (using the inverse distance method).

This model calculates runoff using the kinematic wave approach (simplification of the Saint Venant's principle), taking into account geomorphological characteristics of the catchment to route the flow along the channel (geomorphological kinematic wave). It can be represented as five vertically-linked tanks (Figure 18) by means of simple conceptual relationships. In the first tank (T: Static Storage), exceedance is calculated using rainfall and evapotranspiration data. The second tank (T2: Surface Storage) collects the exceedance and extracts the direct runoff values associated with the soil's saturated hydraulic conductivity. The next tank (T3: Gravitational Storage), collects infiltration water which does not form runoff and which can be transported vertically through the subsoil by percolation. Part of it does not percolate and generates subsurface flow. The water transported through the subsoil is stored in the Aquifer (T4), forming underground losses. The remainder will become the base flow which will form the discharge, together with the direct runoff and interflow, in the channel (T5).

In addition to this vertical connection, the model cells are related horizontally in the "flow direction" (determined by maximum slope), as shown in Figure 19.

The data required in order to work with the model are, on the one hand, hydrological (rainfall time series, evapotranspiration and gauging stations) and, on the other, cartographic (DTM and derivatives such as flow direction, slopes, etc. edaphologic maps, vegetation cover maps, geological maps, hydrogeological maps, sedimentological maps, etc.). A geomorphological study of the zone must be conducted to obtain geomorphological parameters and relationships used for routing the flow through the channel using the Geomorphological Kinematic Wave.

TETIS includes a few correction factors which must be determined via automatic calibration and which glob-

<sup>36</sup> Instituto de Ingeniería del Agua y Medio Ambiente.



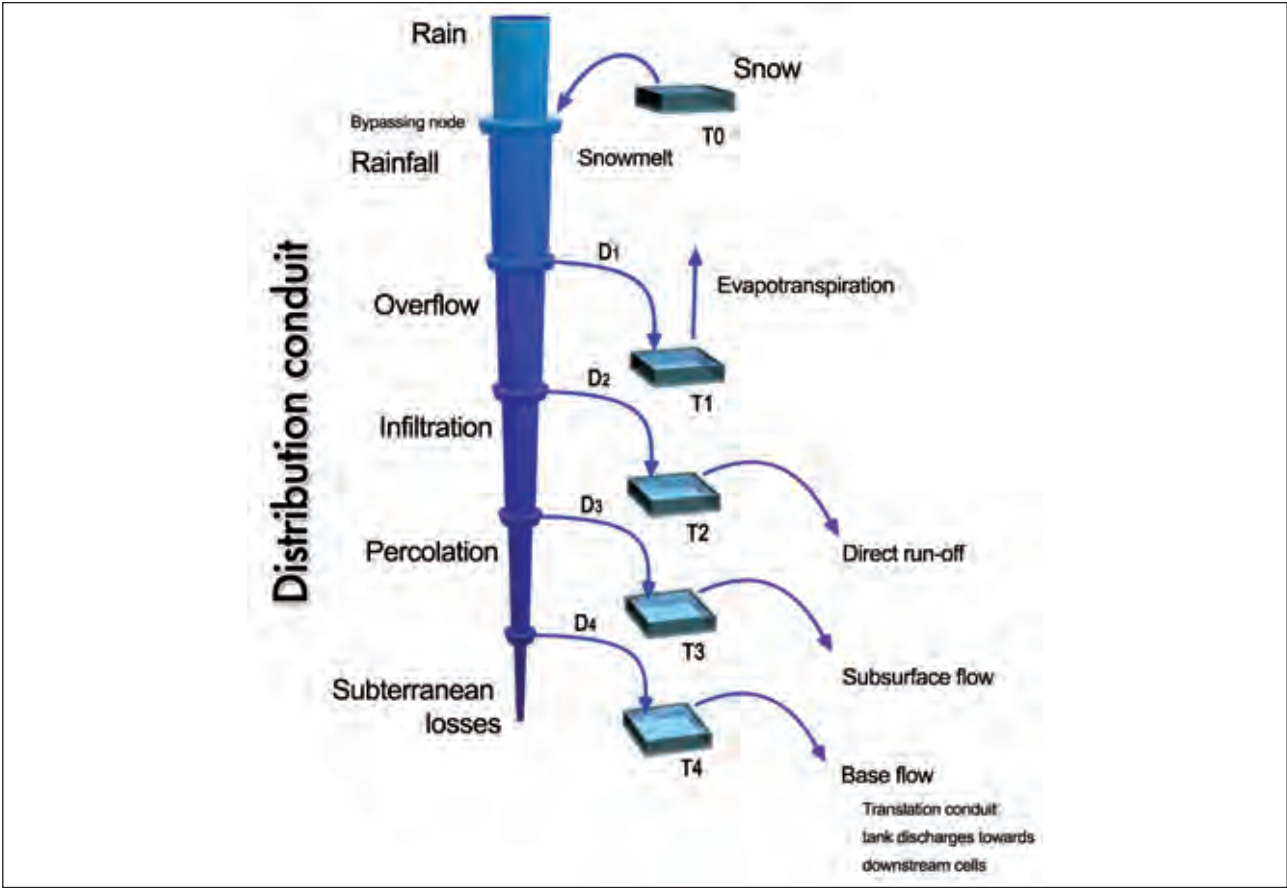


Figure 18. Conceptual model of the vertical movement of water for each cell (based on Francés et al., 2002).

ally correct the different maps and processes represented. The calibration is done through estimation by comparing the observed and simulated for a state variable in the model. This calibration is usually unstable due to the high number of parameters involved. The solution to this instability is to use a structure separated from the effective parameter. This way, the number of variables to be calibrated related to the cell parameters is reduced to nine, irrespective of the number of cells. The most common calibration methods may be manual (trial and error), automatic (SCE-VA), and multi-criteria.

### FLOOD FREQUENCY ANALYSIS

The records produced by streamflow measurement devices have certain properties which make them indistinguishable in practice from a stochastic process governed by the laws of chance. This explains why stochastic

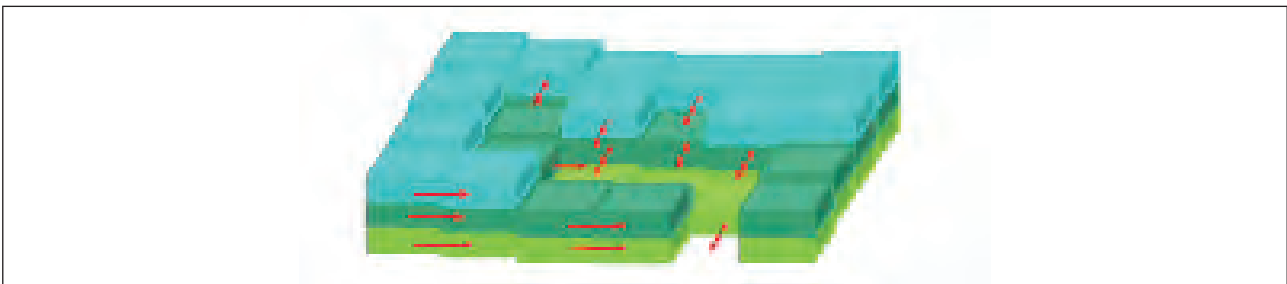


Figure 19. Representation of the behaviour of the horizontal flow in the TETIS model (taken from Vélez, 2001).



techniques are utilized as tools in the modelling of the streamflow estimation process, both in time and space (García-Bartual, 1996).

Therefore, once the annual maximum mean daily discharge series have been obtained and completed for each gauging station, they are subjected to flood frequency analysis with the aim of estimating frequency distribution. The data from these series are considered independent and evenly distributed and, consequently, the peak discharges act as a random variable ( $Q_{\max}$ ). The available data series would be samples of distributed populations fitted to a theoretical function.

Supposing that a peak discharge episode is extreme when it surpasses a threshold  $Q_{\max-u}$ , the return period will be the time in years (as these are annual series) between events which satisfy the condition  $Q \geq Q_{\max-u}$ . The return period ( $T$ ) of a discharge  $Q \geq Q_{\max-u}$  (in general, an event whose magnitude is greater than or equal to a given value) is the average value of the return periods for a sufficiently numerous series of data, that is, the expected value of  $\tau$ , or  $T=E(\tau)$ .

Therefore, the probability of a discharge greater than or equal to a threshold  $Q_{\max-u}$ ,  $p=P(Q \geq Q_{\max-u})$  is the inverse of the return period, i.e.  $p=1/T$ . The idea of measuring the importance of a discharge by its frequency came from Fuller, who, in 1915, introduced the concept of return period as an inverse of the probability of surpassing a given discharge. For time series that are long enough, the standard practice is to estimate probability in terms of the accumulated empirical frequency, using expressions like:

$P(Q < Q_i) \cong F_i = i / N$	California
$P(Q < Q_i) \cong F_i = (i-1) / N$	California, modified
$P(Q < Q_i) \cong F_i = i / (N+1)$	Weibull
$P(Q < Q_i) \cong F_i = (i-0.44) / (N+0.12)$	Gringorten
$P(Q < Q_i) \cong F_i = (i-0.5) / N$	Hazen
$P(Q < Q_i) \cong F_i = (2i-1) / 2N$	Gumbel
$P(Q < Q_i) \cong F_i = (i-0.3) / (N+0.4)$	Chegodayev

where  $Q_i$  is the  $i^{\text{th}}$  element of the series of  $N$  data arranged in ascending order;  $i$  is the ordinal position of this element.

Among the most commonly used formulas are those of Weibull (adopted by the USWRC<sup>37</sup>, 1981), Chegodayev (Russia and Eastern Europe) and Gringorten. The work of Cunnane (1978) indicates that the former produces more biased results (low return periods for maximum values). This is preferable to the Gringorten formula if the underlying population is of the Gumbel type (or exponential), or the Hazen formula for more skewed populations.

This study can be conducted with models for predicting floods at a single location (univariate), multiple locations (multivariate), or regional floods, or historical and palaeoflood information. The first approaches use non-parametric techniques, basically through visually checking fittings to distribution function graphs, or parametric techniques, which attempt to fit data to a statistical model (distribution function + parameter estimation method + model for using local and regional data).

### *Flood frequency analysis using univariate models*

- Non-parametric methods: graphical resolution  
In its simplest mode, this consists of graphically representing the values of the probabilities assigned to each streamflow (using empirical formulas) as ordinates, versus these values (abscissa), attempting to manually fit the points to a function. This facilitates the entry of historical and regional data but has the drawback of subjectivity in terms of how the graph is plotted, particularly as regards extrapolations.

<sup>37</sup> US Water Resource Council.



Since probability distributions habitually show exponential patterns, semilogarithmic scales are often used for representation (also known as Gumbel probability paper), where the values are adjusted approximately to a regression line.

- Parametric methods: statistical models

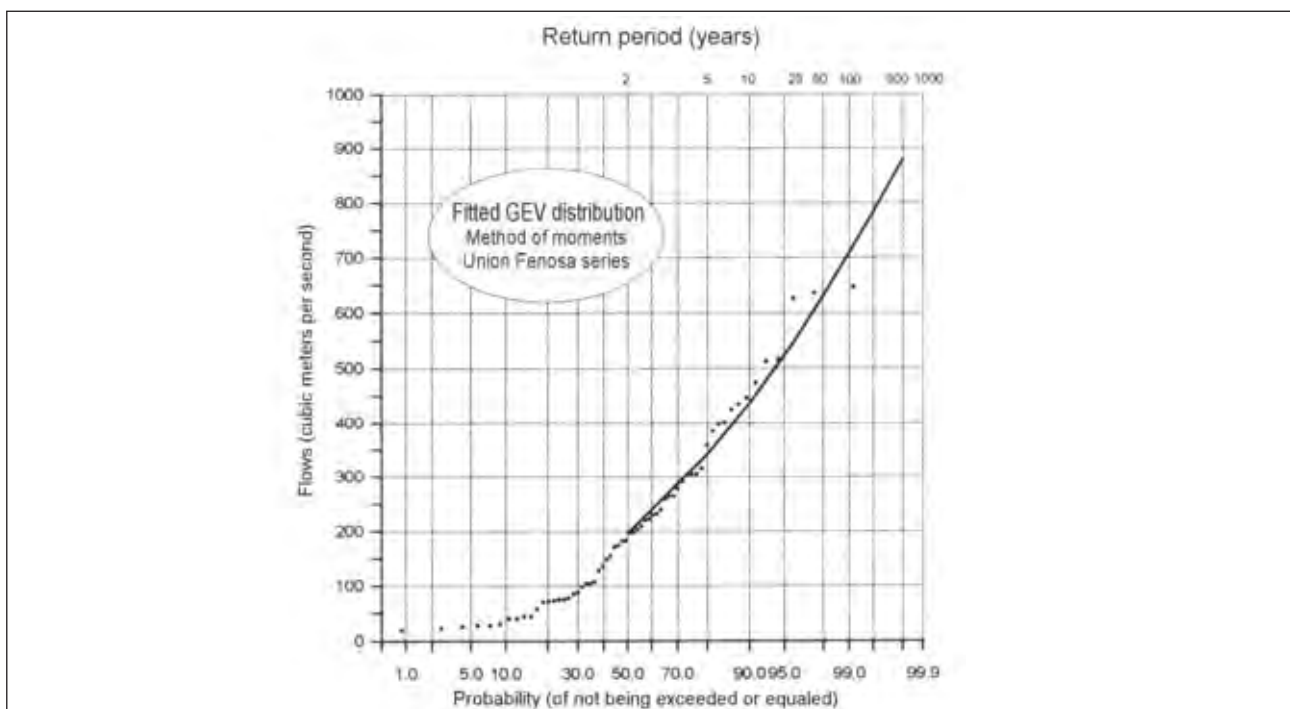
Defining a statistical model using parametric methods involves: choosing the distribution type, method for fitting parameters and quantiles, and the procedure for using local and regional data (Cunnane, 1987).

In the 1930s, Hazen (1930) started systematically using statistical distribution functions to fit flood frequency data. Currently, the distribution functions most commonly used internationally are (WMO, 1989; Ferrer, 1992):

- Extreme value distributions: generalized extreme value (GEV) distributions, including, as specific cases, Gumbel (EVI), Frechet (EVII) and Weibull (EVIII), and two-component extreme value (TCEV) distributions.
- Distributions based on the Gamma function of 2 or 3 parameters in real or logarithmic space: Pearson type III (PIII), Log-Pearson type III (LPIII) and their specific cases of two-parameter lognormal and generalized Pareto distribution (GPD).

From among the methods of estimating quantiles based on the annual maximum series, three are most widely used (Ferrer, 1992):

- Method of moments (MOM) in real or logarithmic space (LMOM). It does not use all of the sample data exhaustively. It is good for its lower sensibility to incorrect distribution model choices.
- Maximum Likelihood (ML). This is often the most efficient approach (less variance in the estimated parameters), but it is very sensitive to the distribution model choice.
- Probability weighted moments (PWM). Gives more weight to the higher values in the series, having the effect of producing more conservative values.



**Figure 20.** Fitting of a GEV frequency distribution using a MOM parameter estimation method for the annual maximum mean daily discharge series of El Burgillo reservoir (Tajo basin, Ávila). Data provided by Unión FENOSA (Díez and Pedraza, 1997b).

Of the many possible combinations, three are most widely cited in the specialized literature:

- GEV + PWM
- LPIII + LMOM
- TCEV + ML

The computer programs CHAC, LEYES and TESAM (CEH<sup>38</sup>, 1991) contain the most widely used combinations of distribution types and adjustment methods in the field, presupposing the use of local data only. The application HECWRC (USACE<sup>39</sup>, 1982a) conducts the analysis using the LPIII + LMOM combination, adopted by United States authorities (USWRC, 1981). Other noteworthy computer programs for flood frequency analysis: HEC FFA (USACE), PEAKFQ (USGS), Micro-FRS (British Flood Studies Software; NERC<sup>40</sup>, 1975) and CFA (Consolidated Frequency Analysis Package in Canada), developed by Environment Canada (Annex C). The GEV function is recommended by the NERC (1975) for adjusting the distribution of annual floods in The United Kingdom. Furthermore, when combined with MOM and PWM it is considered optimal for its low variance and non-severe bias (Figure 20). For average-size samples (N=50), variances are comparable to those of ML estimators, and for smaller samples they are substantially better.

The validity or goodness of fit can be verified by means of a simple Kolmogorov-Smirnov test, or the  $\chi^2$  test on relative or cumulative frequency functions. However, one must be prudent here: Kolmogorov-Smirnov goodness of fit tests have the problem of not being sensitive to the model's tail behaviour (behaviour of floods of high return period). If one of the tests does not reject the validity of a model, this cannot be interpreted as having confirmed it (Salas, 1995).

- Distinction of flows corresponding to exceptional floods in univariate models  
Considering a small number of flood events from the historical period as exceptional floods opens a new path of analysis as it allows us to assign them different weights from the rest of the data when assigning sample frequencies, thereby improving the estimation of high-return-period quantiles.  
The most well-known data series weighting methodology is the one recommended by the US Water Resource Council (USWRC, 1981). It consists of assigning a weight of one to the major floods, and a weight of  $(N+M-Z)/N$  to the remaining ordinary records, where N is the amount of ordinary data, M the amount of historical data, and Z the amount of exceptional data. An LPIII function with an LMOM estimator can be fit to the resulting (N+M) series using the ANECAV spreadsheet (CEH, 1992) completed with the formulas needed to calculate the skew coefficient and thereby obtain the frequency factor of the function ( $K_T$ ).  
To ingrate palaeohydrology data into flood frequency analysis, a maximum likelihood algorithm has been developed (Stedinger and Cohn, 1986). This algorithm describes the data in the form of concrete values, flow ranges or minimum thresholds which are not exceeded. To incorporate historical information into the systematic series, the non-systematic information is typically censored using censor levels (reference threshold, binomially-censored, or censored) or maximum known floods (Francés *et al.*, 1991).

### *Flood frequency analysis using regional predictive models*

With the aim of clearing doubt concerning the representativeness of a single sample, which produces a high variance in the flood frequency analysis parameter and quantile estimates, methodologies have been developed which assume the existence of a homogenous region with respect to certain statistical characteristics (Ferrer, 1996).

The predictive regional models are based on the idea that the characteristics of each gauged location are considered a dependent variable, and the remaining climatic or physiographic properties of the region's group of gauging stations are considered independent variables.

A classic regionalisation model is the flood-index approach, a particular case of the variable index, which con-

<sup>38</sup> Centro de Estudios Hidrográficos (Centre for Hydrographic Studies).

<sup>39</sup> US Army Corps of Engineers.

<sup>40</sup> Natural Environment Research Council.



siders statistics  $C_s$  and  $C_v$  constant in the region and assumes that the variable resulting from the quotient of the average of each series follows the same frequency distribution in the entire region (Medeiro and Jiménez, 2007). Subsequent developments and innovations use other methods of standardising the series: statistically weighted moments, logarithmic mean, or parameters of the TCEV model.

To obtain regional quantiles from the local ones, various methodological variants can be used:

- 1) Simple regional mean of the local quantiles (Dalrymple, 1960).
- 2) Weighted regional mean of the local quantiles, in accordance with the size of the series.
- 3) Simple regional mean of local quantiles, distinguishing between two or more physiographic regions of application (Medeiro and Jiménez, 2007).
- 4) Regional quantiles considering the standardised data from all stations as a single set (NERC, 1975).

Adding two other procedures (Dalrymple, 1960; NERC, 1975) to the traditional methods is justified in that the quantile estimation models based on regional data use ordinary least square regressions in estimating parameters. However, the assumption of equality between the independent variables is uncertain in flood records due to differences in the records' time periods and measurement conditions. Hence the need to introduce a simple weighting factor based on record time period.

The hypotheses put forward by Dalrymple (1960) were subsequently highly disputed as regards the assumed independence of  $C_v$  in relation to the size of the basin. However, other more recent studies applying this method (Frend, 1989) do not detect this problem. In fact, the index-flood method is the most widely used regional model on a national level in countries such as The United Kingdom (NERC, 1975).

## 2.1.2. HYDRAULIC METHODS

### ONE-DIMENSIONAL FLOW

Fluvial processes are the result of the energy of a mass of water being displaced by gravity through open channels and adapting itself to constraints imposed by its viscosity, friction with the river bed and the load of material transported. Since water is a Newtonian fluid, with relatively small changes in shear stress ( $\tau$ , or force per unit area), its kinematic viscosity hardly varies. Therefore, except in streams with fine materials (such as mud), which may have pseudoplastic or viscoelastic behaviour, deformation in streams is proportional to shear stress, and the dynamic viscosity depends on pressure and temperature.

The flow of water in a stream can be simplified as being one-dimensional, that is, the depth and velocity vary only in the longitudinal direction of the channel, whose axis is assumed to be roughly a straight line, and that the velocity is constant at any given point in a cross section. In this supposition, water movement in the so-called 'fluvial phase', that is, concentrated on irregular prismatic collectors, is governed by the Saint-Venant principle: continuity and conservation of momentum. These formulate, respectively, the inflow-outflow ratio in a closed area, at the rhythm at which density varies, and the equality between the momentum variation and resultant of the external forces acting on the fluid:

Continuity equation,

$$A \cdot \frac{\delta v}{\delta x} + B \cdot v \cdot \frac{\delta y}{\delta x} + B \cdot \frac{\delta y}{\delta t} = 0$$

Equation for conservation of momentum,

$$\frac{\delta v}{\delta t} + v \frac{\delta v}{\delta x} + g \frac{\delta y}{\delta x} + g \frac{\delta z}{\delta x} + g \cdot S_f = 0$$

Where  $A$  is cross-sectional area of flow,  $v$  is mean velocity,  $x$  is the position abscissa (location in the conduit of the section considered),  $B$  is water surface width for depth  $y$ ,  $y$  is water depth,  $t$  is time,  $g$  is gravitational acceleration,  $z$  is the elevation of the channel bottom,  $S_f$  energy grade line slope, which is a function of velocity, roughness and hydraulic radius.

The types of flows in the conduit can be classified based on kinematic or structural considerations. Kinematic classification takes into account the velocity vector's stability-variability in time and space according to the continuity equation:

- a) With respect to space (does not change in time)
  - Uniform flow, velocity does not vary in space,  $\delta v / \delta x = 0$
  - Varied flow, velocity varies in space,  $\delta v / \delta x \neq 0$
- b) With respect to time (does not change in space)
  - Steady flow, velocity does not vary in time,  $\delta v / \delta t = 0$
  - Unsteady flow, velocity changes in time,  $\delta v / \delta t \neq 0$

The velocity of water in a conduit varies in time ( $t$ ) as it moves through the conduit ( $x$ ); the same is true at different points of its cross section. The main differences are due to energy losses due to friction with the channel walls or bottom and, to a lesser extent, between the free surface and the air. The different possible combinations of flows are modelled using different tools, from physical models for artificial channels to mathematical models.

Structural classification considers the relative importance between the forces of inertia, viscosity and gravity, according to the conservation of momentum. The Reynolds number ( $R_e$ ) quantifies the effect of the first two according to several characteristic values:

$$R_e = \frac{\rho \cdot v \cdot D}{\mu} = \frac{v \cdot L}{\mu_c}$$

Laminar flow	$R_e < 20,000$
Transitional flow	$20,000 < R_e < 30,000$
Turbulent flow	$R_e > 30,000$

Where  $\rho$  is water density,  $v$  is velocity,  $D$  is conduit diameter,  $\mu$  is dynamic viscosity,  $L$  is characteristic length (in this case, for hydraulic structures), and  $\mu_c$  is kinematic viscosity ( $10^{-6} \text{ m}^2/\text{s}$  at  $20^\circ\text{C}$ ).

The effect of the ratio of inertial forces to gravitational forces determines various flow types: tranquil and rapid, depending on the perturbations which may be transferred in the upstream direction or only downstream. The Froude number ( $F_e$ ) is used to differentiate them by relating flow velocity and gravity wave celerity:

$$F_e = \frac{v}{\sqrt{g \cdot L}}$$

Tranquil or slow flow (subcritical)	$F_e < 1$
Critical flow (minimum energy)	$F_e = 1$
Rapid flow (supercritical)	$F_e > 1$

Where  $v$  is velocity,  $g$  is gravitational acceleration, and  $L$  is characteristic length.

In Nature, streamflow is unsteady, varied, turbulent and tranquil (at times close to critical). A rapid flow is less frequent, as high velocities involve higher percentages of erosion and sediment transport. This implies an increase in roughness and depth and a reduction in slopes and velocities, which tends to bring the flow back to tranquil.



### *Steady uniform flow: Manning's equation*

Uniform flow takes place when the channel bed slope ( $S_0$ ) is equal to the energy grade line slope ( $S_f$ ), and all of the other terms of the conservation of momentum equation are considered negligible. In general, it is also understood that the flow is steady, which means that the energy gradient line, water surface, and channel bottom are parallel lines. Considering this methodological simplification, there are various empirical formulas which allow one to obtain flow-depth ratios in a one-to-one manner, based on parameters as simple as bed roughness.

The most well-known and widely used is the Manning's equation, or, more accurately, the Strickler-Manning equation, which relates velocity to channel morphometry parameters and with a roughness coefficient which is tabulated for different bed materials:

$$v = \frac{R^{2/3} \cdot S^{1/2}}{n}$$

where  $v$  is the average streamflow velocity,  $R$  is the hydraulic radius ( $A/P$ ),  $S$  is the energy grade line slope (coincident with the bed), and  $n$  is the roughness coefficient.

The dimensionless number  $n$ , which is essential in discharge computations ( $Q = V \cdot A$ ), or depths derived from discharges, is tabulated for different fluvial bed types, depending on their roughness and the presence of obstacles to flow (see Annex A). Recently, alternatives to this dimensionless number have been proposed, incorporating detailed microtopographic analyses in order to estimate roughness (Casas Planes, 2007). In natural channels,  $n$  has an approximate value of 0.030, whereas in irregular channels it may double. There are graphical examples of streams where this has been calibrated. Other rational or empirical equations used in computing discharge and depth in uniform flow regimes are:

- the Chézy equation,

$$v = c \cdot \sqrt{R \cdot S}$$

- the Darcy-Weisbach equation,

$$ff = \frac{8 \cdot g \cdot R \cdot S}{v^2}$$

Where  $v$  is mean flow velocity,  $c$  and  $ff$  are the respective roughness coefficients,  $R$  is hydraulic radius ( $A/P$ ),  $S$  is the energy grade line slope, and  $g$  is gravitational acceleration.

### *Steady gradually varied flow regime*

If we maintain the methodological hypothesis of a steady flow but with a gradual variation of velocity in space, and therefore a gradual variation in depth as the discharge does not change, the flow regime is referred to as a gradually varied flow in which the pressure distribution is hydrostatic. The profiles can be analysed from consideration of supercritical and subcritical flow regimes.

To estimate velocities and flow depths, the most frequently-used method is the Standard Step Method, which solves the gradually varied flow energy equation by comparing energy in two consecutive sections (Figure 21) using an iterative process of successive approximations.





**Figure 21.** Bathymetry probe survey on the Tajo river channel, the results of which are used in hydraulic models.

There are computer programs designed to perform these computations (Annex C), such as HEC-2 (Water Surface Profiles), developed by B.S. Eichert at the *Hydrology Engineering Center (USACE, 1982b)*, which also offers a range of optional features, such as the simultaneous calculation of multiple profiles, tributary streams, bifurcations, etc. An updated, more sophisticated version of this program, available for the Windows environment, is HEC-RAS (*River Analysis System; USACE*), which can analyse a full network of channels, a dendritic system, or a single river reach. It is capable of modelling subcritical, supercritical and mixed flow regime water surface profiles (Figure 22). Other such computer programs are: WSPRO (USGS and *Federal Highway Administration; Shearman, 1988*); WSPRO and FLDWY (*US Department of Agriculture*); E431/J635 (*US Geological Survey*); QUICK-2 (*FEMA*); HY8 (*Federal Highway Administration*) and CAUCES (*Centre for Hydrographic studies, CEDEX, Spain*).

When the flow goes from tranquil to rapid, or vice versa, the depth must pass through critical values ( $y_c$ ). In the first case, these points are known as control sections; in the second, a hydraulic jump characteristic is produced. In such situations flow can be estimated using a formula derived from the Froude equation in conditions of minimum specific energy (Daugherty *et al.*, 1989) since the bed's roughness coefficient is constant:

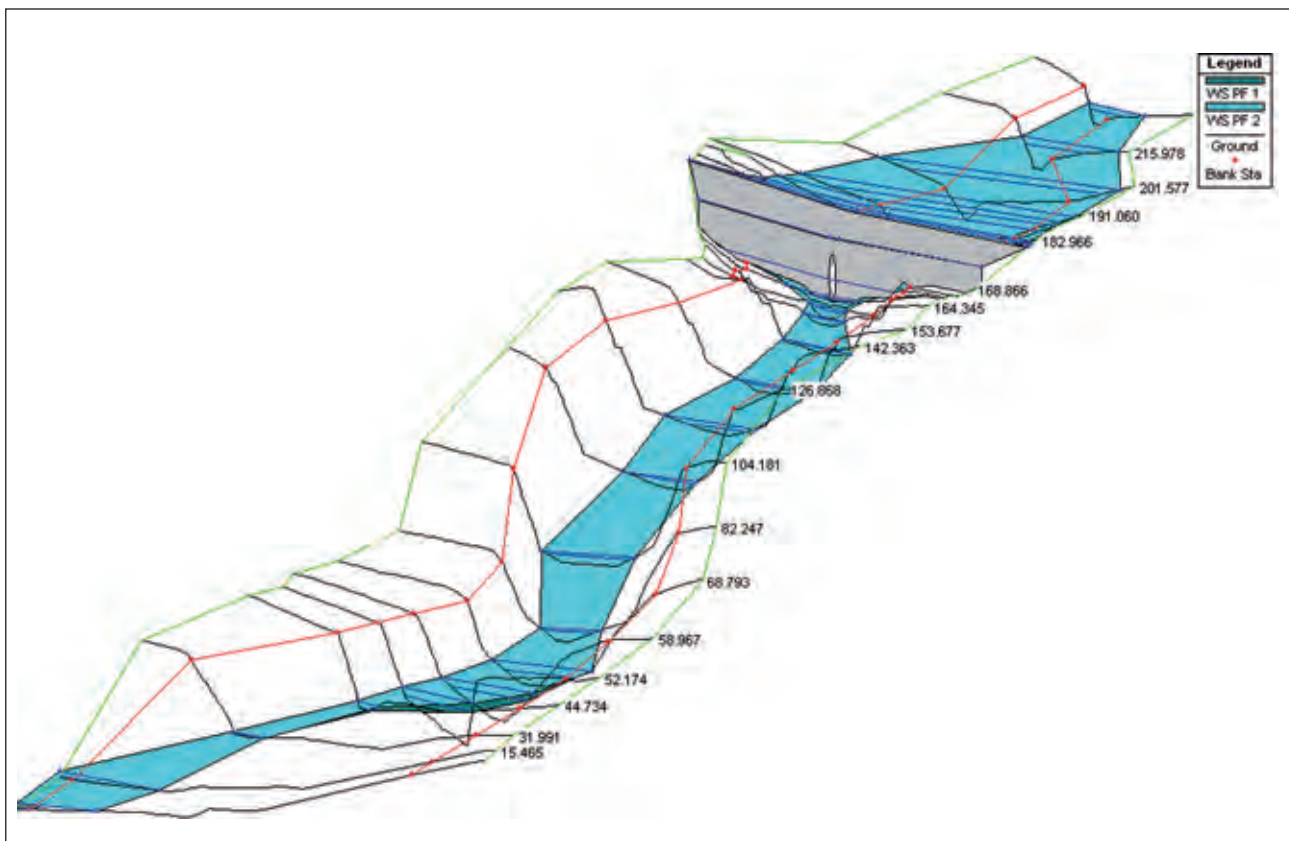
$$Q = \sqrt{\frac{A^3 \cdot g}{B}}$$

Where A is the cross-sectional area, B is the water surface width, and g is gravitational acceleration.

This technique has been used, among others, by Benito *et al.* (1998), to estimate discharge at different flood-control dams in the Arás gully (Biescas) for the flood of August 1996.

#### *Unsteady flow regime*

For estimating depths when modelling unsteady flows, that is, flows in which velocity varies with time, various programs (Annex C) can be used which solve Saint Venant equations by employing the “method of characteristics”:



**Figure 22.** Typical graph of results from the HEC-RAS program.

- FLDWAY and its predecessors DWOPER (NETWORK) and DAMBRK are based on the one-dimensional equations of St. Venant. They were developed by the *US National Weather Service* (Fread and Lewis, 1988).
- SWMM (US Environmental Protection Agency and Oregon State University) and MIKE 11 HD (Danish Hydraulic Institute, Denmark) are models developed to analyse quality and resources problems, respectively, although they contain modules capable of analyzing unsteady flow (EXTRAN).
- ISIS (HR Wallingford, United Kingdom).
- FEQ 8.92 and FEQUTL 4.68 (US Geological Survey).
- UNET (US Army Corps of Engineers).

## TWO-DIMENSIONAL FLOW

During a flood event, water flow is often not restricted to the unidirectional centreline of a main channel; rather, it spills over and occupies the banks and flood plain. Under these conditions, simplifying the flow to one dimension is insufficient for modelling the secondary flows perpendicular to the channel's main flow direction (Figure 23). There are other situations which are also more suited to two-dimensional modelling, such as confluences of rivers, flows around structures, compound channels, pronounced curvatures, and urban settings. In some cases in which there are areas whose flow may be simplified to 1D and other areas for which this is insufficient and that are more suited to 2D simplification, linking the two models makes it possible to implement solutions capable of obtaining the best performance of each of the simplifications (Figure 24). An example is the study of flows in urban settings in which sewer systems and gutters are taken into account. Another example is when elements whose size is less than that of the cell are incorporated into the model, as is the case for irrigation ditches, small channels, etc.

If river flows are in fact 3D (Figure 25), a 2D simplification is acceptable if the variations in the horizontal and



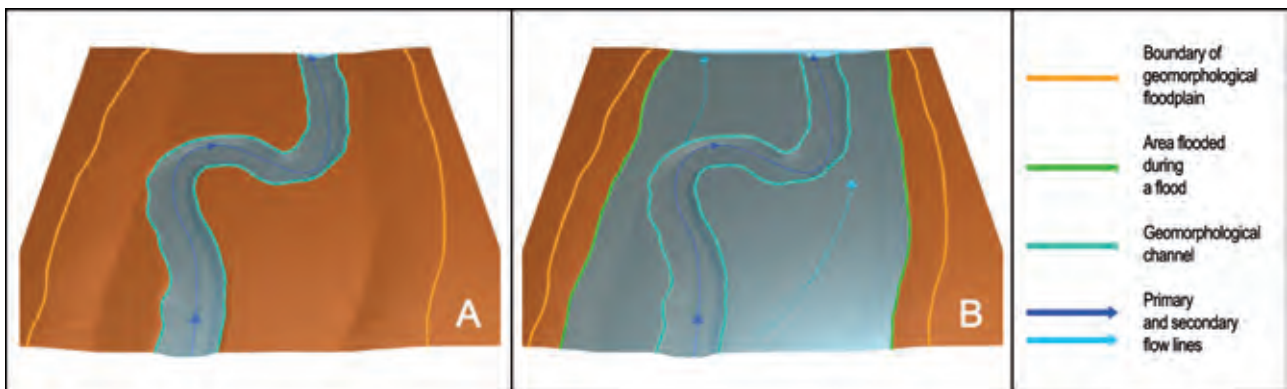


Figure 23. Primary and secondary flow directions in low-water and ordinary maximum flood conditions (A) and in overbank conditions (B).

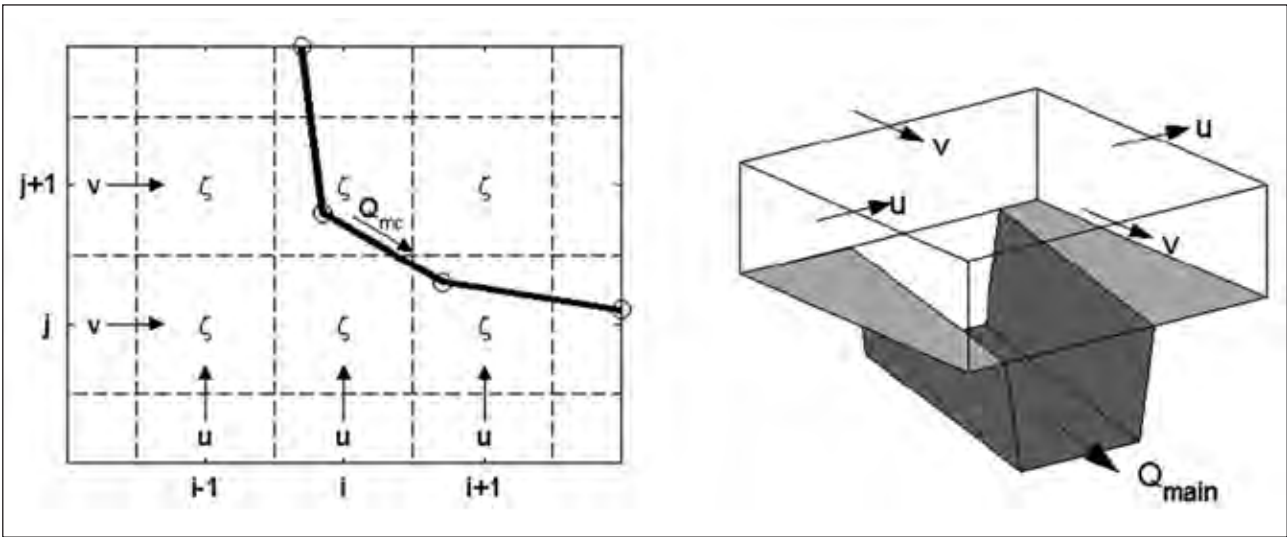


Figure 24. Diagram of a combined 1D-2D model. The water surface elevation is indicated in each  $ij$  cell with the  $\zeta$  symbol. The  $u$  and  $v$  components are the velocities at the boundary of each cell. The line is plotted by the 1D model is in bold, with the circles indicating its calculation points. In cells containing circles,  $\zeta$  values are shared between the 1D and 2D model (Frank et al. 2001).

vertical components are small and if the vertical pressure distribution is hydrostatic. In this case, vertically-integrated shallow water equations (SWE) can be used. They are:

Continuity:

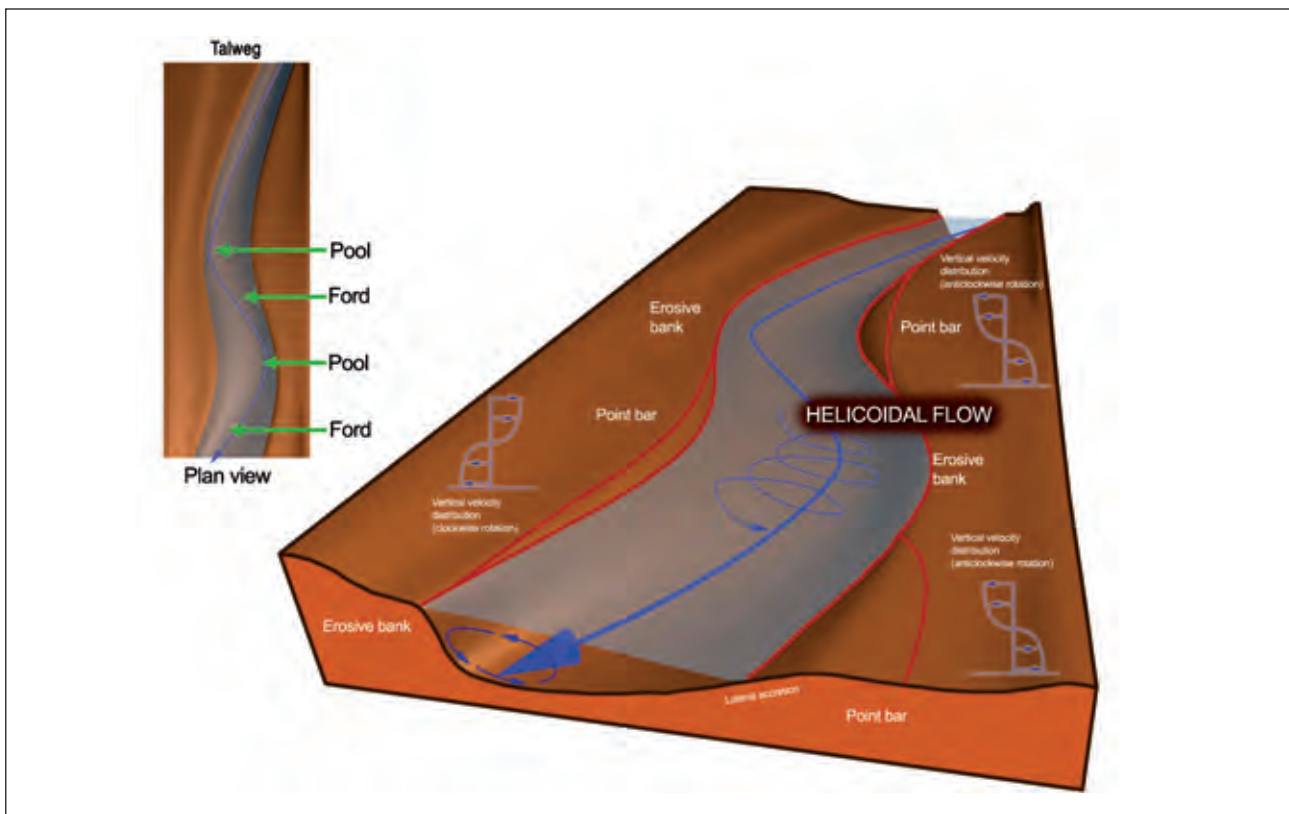
$$\frac{\partial h}{\partial t} + \frac{\partial(uh)}{\partial x} + \frac{\partial(vh)}{\partial y} = 0$$

Dynamics:

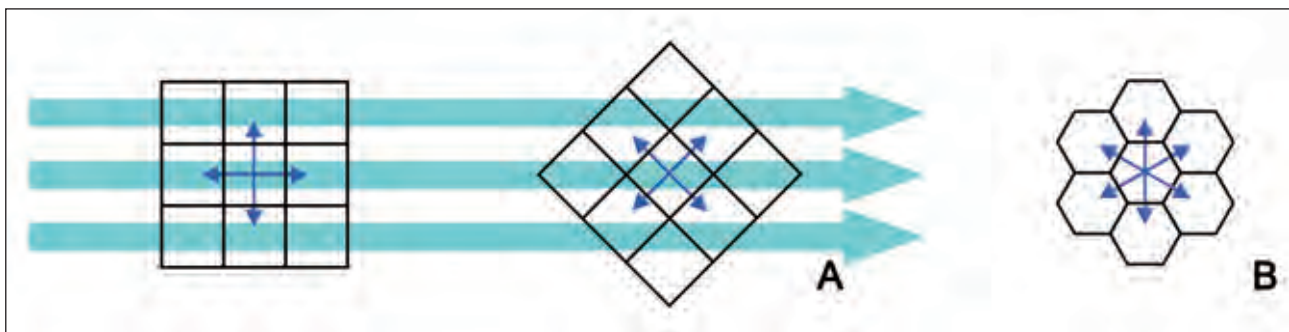
$$\begin{aligned} \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + g \frac{\partial h}{\partial x} &= R_x \\ \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + g \frac{\partial h}{\partial y} &= R_y \end{aligned}$$

Where  $u$  and  $v$  are the horizontal components of velocity,  $x$  and  $y$  are their respective directions,  $h$  is depth,  $g$  is gravity, and  $R$  is the bed roughness factor in the corresponding direction.





**Figure 25.** Three-dimensional flow (3D) in straight and meandering reaches. Based on a synthesis of different bibliographical sources coupled with further elaboration.



**Figure 26.** Exact solution in the event the grid elements are aligned with the flow direction, and maximum error if they are at a  $45^\circ$  angle in relation to the flow direction (A), followed by a hexagonal grid (B) (Jordan, 2003).

Shallow water equations are nonlinear and the system of equations is hyperbolic, which may result in discontinuities appearing in the solution (hydraulic jumps or wave fronts). For this reason, numerical approximation methods are used which apply schemes of finite differences, finite elements or finite volumes, the first of which is most common.

Although two-dimensional models are normally oriented towards computations with regular grids (with two computing directions,  $x$  and  $y$ ), there are other grid models which allow one to significantly reduce calculation error for flows which are oblique to the basic element, or pixel (Figure 26). Other solutions are models using multiple grids or curvilinear grids (Figure 27); for morphodynamic analysis of rivers, flexible meshes or grids which are variable in time are used.

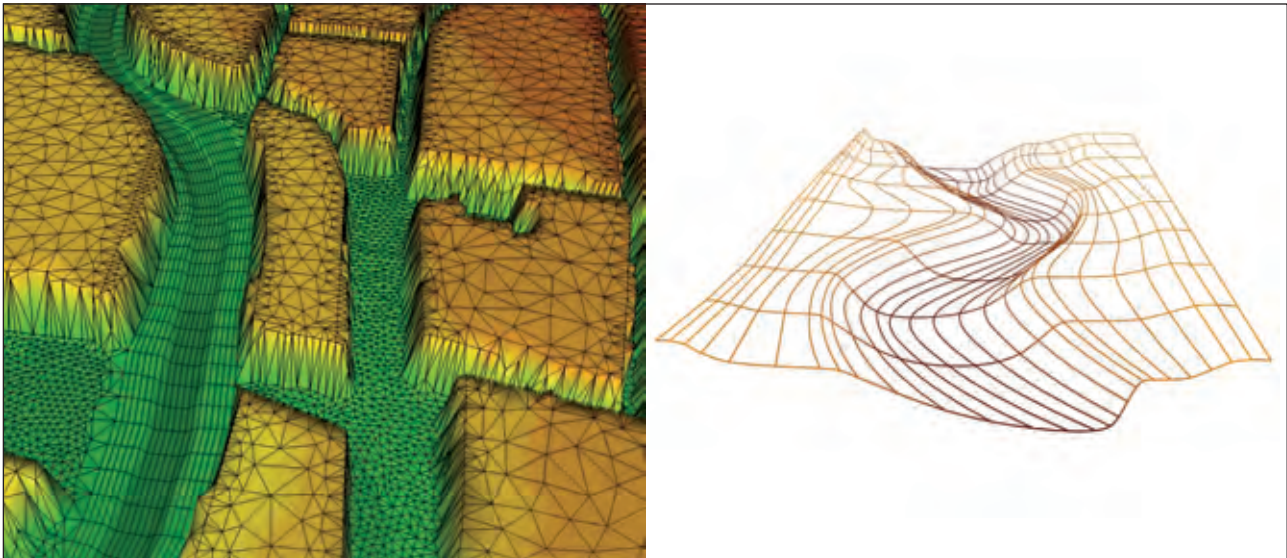


Figure 27. Example of a multiple grid, with quadrangular and triangular grid (Linés et al., 2008), along with a curvilinear grid.

There are many applications on the market which are capable of two-dimensional hydrodynamic modelling for free-surface flows, and some of them are particularly geared towards use in modelling floodplains (Garrote de Marcos *et al.*, 2007) or alluvial fans (Jordan, 2003). Among them, Garrote de Marcos distinguishes the following, owing to their accessibility and technical and sales support: Sobek, Mike21, Quad2D, TUFLOW, RMA2, FESWMS and River2D. In addition to some of the abovementioned models, the Federal Emergency Manage-

Table 1. Main differences between most common 2D models.

Software	Grid type <sup>(1)</sup>	Numerical method <sup>(2)</sup>	1D+2D link
Sobek	S, M, F	D	Yes
MikeFlood	S, Q, T, F, M	D	Yes
Quad2D	S, T	V	No
TUFLOW	Q, T	E	Yes
RMA2	T, Q, R	E	Yes
FESWMS	T, Q	E	No
River2D	T	E	No
DHM21	S	D	No
FLO-2D	S	V	No
(1) S: Squared T: Triangular Q: Quadrangular R: Curvilinear F: Flexible		(2) D: Finite difference E: Finite Element V: Finite Volume	



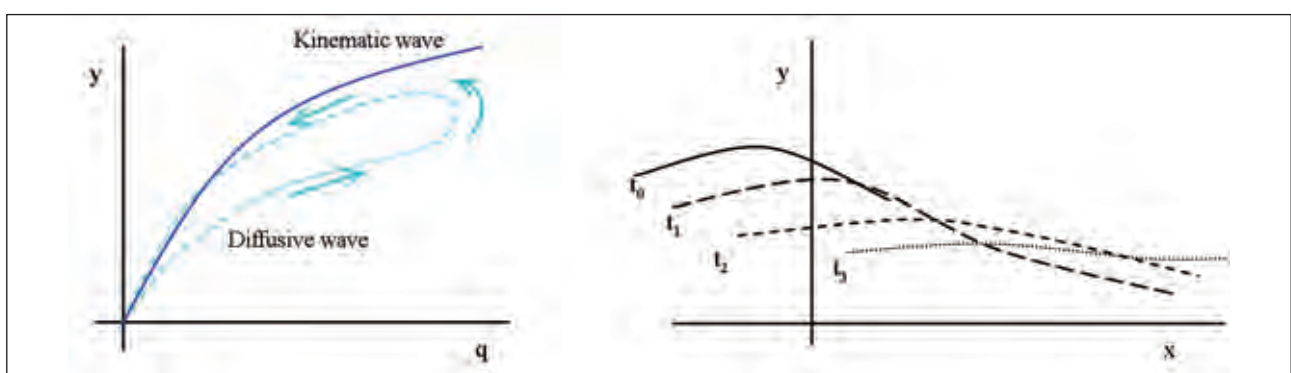
ment Agency (FEMA) includes on its “white list” some 2D hydraulic models it endorses for carrying out its flood risk mapping: TABS (which, in reality, is a package comprised of RMA2, RMA4, RMA10, SED2D, and GFGEN), MIKE FLOOD (combination of Mike21 and Mike11) and FLO-2D. For some particular cases, FEMA admits other models, such as the S2DMM and the DHM21. Among these different models, the underlying differences are the grid type, the numerical approximation method and model, their abilities to connect to other models, the ease with which they interface with GIS (Geographic Information System) or other tools, user friendliness, computation speed, contour conditions, the quantity and quality of presentation of results, etc. (Table 1). A compilation of these and other differences can be found in Garrote de Marcos *et al.* (2007).

**Sobek**, developed by Delft Hydraulic (Netherlands), is probably one of the most widespread tools for analysing surface water hydraulic systems. Like many of the tools in the industry, Sobek is actually comprised of over twenty modules for attacking different water-related problems. To put it otherwise, it provides a range of usage simplifications for different analysis problems, whether related to the hydrodynamics of rivers and estuaries (1D, 2D, and 1D+2D), urban channel and drainage systems, water quality, river morphodynamics, salt intrusion, sediment transport, etc.

Developed by DHI Water & Environment (Denmark), **MIKE FLOOD** has been since 2008 an integrated 1D-2D flood modelling tool, although, as is the case with Sobek, the “Mike” product range features a wide range of tools (over a dozen) designed to address problems related to distributed hydrology, urban drainage system hydraulics, river morphodynamics, sediment transport, real-time analysis and forecasting, water quality, etc.

Developed by the University of Zaragoza and marketed by INCLAM (Spain), **Guad2D** is a 2D hydraulic analysis tool with a few modules all of which are designed for building models and presenting dynamic results. It is noteworthy for its highly superior computation efficiency in comparison to other tools (Garrote de Marcos, 2007; Linés, 2008), although it lacks a 1D connection.

All of the abovementioned models aim to fully solve SWE equations in two dimensions, although there are other simplifications (disregarding the least relevant factors) which may in some cases be useful in terms of computational economy. These simplifications, which are becoming increasingly obsolete, are the kinematic wave model and the diffusive wave model (DHM21 supports both simplifications). In the kinematic wave model the energy slope is equal to the channel bottom slope, whereas in the diffusive wave model the energy slope is equal to the water surface slope. Martín Vide (2006) explains in an intuitive manner the effect of these two simplifications in terms of depth variation in time and space. Namely, while the kinematic wave produces a pure translation effect there is only one depth value for a given discharge, the diffusive wave produces an attenuation effect during translation, and there may be different flow depth values for equal discharge values (Figure 28). Martín Vide (2006) points out that the kinematic wave model can be useful for steep slopes (up to 0.2%) as long as no cases of torrential dynamics arise (according to Meunier 1991, it would be for slopes greater than



**Figure 28.** Simplifications of kinematic wave and diffusive wave (left) and the passing of a diffusive wave (right) (Martín Vide, 2006).



6%, or, according to Salaheldin *et al.*, 2000, they would be situations in which wave fronts are produced that cause non-hydrostatic pressure distribution), whereas the diffusive wave is better suited to rivers with slow rising periods.

There is a plethora of other lesser known two-dimensional modelling programs and semi-two-dimensional programmes (TELEMAC, LISFLOOD-FP, TASE/SWAN Plus, DELFT2D, Flowroute, CE-QUAL-W2, ADCIRC, CH2D, CCHE2D, etc.) which are sometimes designed to meet the needs of specific cases, such as the well-known example of the PLANA model in Spain (Fundación Agustín Bethencourt, 1989). The latter model (semi-two-dimensional) does not fully solve Saint Venant equations but rather considers the equation of continuity between the grid cells in which the floodplain is discretized based on obstacles and barriers (which assume multiple contour conditions) and studies the hydraulic connections between them. Its integration into the GRASS GIS gave rise to the GISPLANA model, which was applied to the study of the Júcar floodplain (Estrela and Quintas, 1996). A similar cell grid scheme was applied by Riccardi (1997) to compute flow depth and velocity in a two-dimensional flow for application to the Rosario region in Argentina.

There are various comparative studies on the different two-dimensional models, as well as studies which offer in-depth examination of questions which are merely practical or analytical and technical among the different models, or which analyze the effects of the variations in different parameters. A few examples of these studies are: Garrote de Marcos *et al.* (2007); Linés (2008); Linés *et al.* (2008); Sale and Giosa (2008); Brufau and García Navarro (2007); Tenakoon, KBM (2004).

### 3D MODELS

Complete 3D modelling of turbulent flows is based on Reynolds-averaged Navier–Stokes (RANS) equations, which are not currently practical in fluvial dynamics due to their high computation cost (Fernández Bono, 2007), although they do apply to occasional situations such as the effects of bridge pylons other obstacles, or many other situations unrelated to natural dynamics (industrial and aeronautical engineering). RANS can be expressed as follows for an incompressible Newtonian fluid:

$$\rho \frac{\partial \bar{u}_i}{\partial t} + \frac{\partial \bar{u}_j \bar{u}_i}{\partial x_j} = \bar{p} \bar{f}_i + \frac{\partial}{\partial x_j} \left[ -\bar{p} \delta_{ij} + \mu \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) - \rho \overline{u'_i u'_j} \right]$$

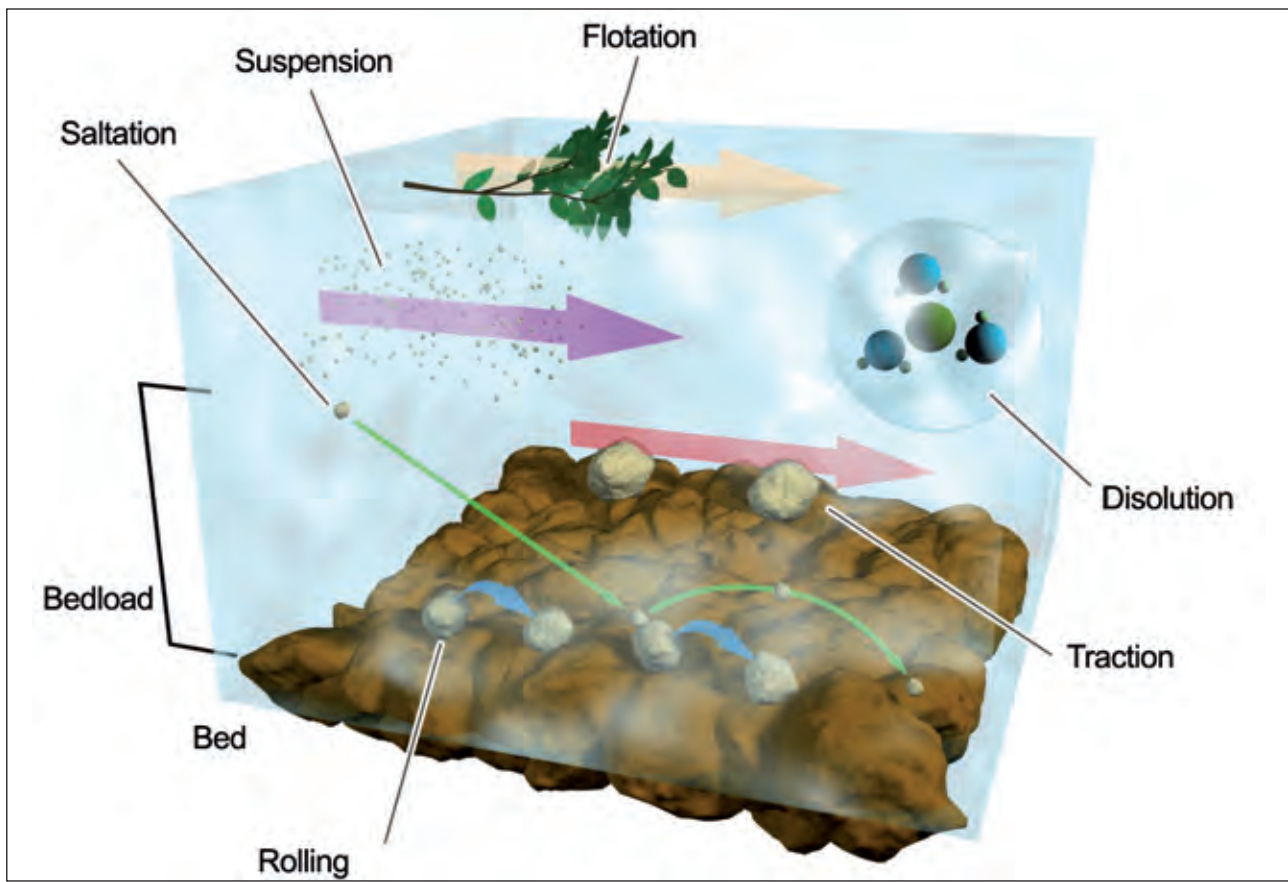
Where  $\rho$  is fluid density,  $p$  is pressure,  $u$  is components of velocity,  $t$  is time,  $\mu$  is dynamic viscosity, and  $\delta_{ij}$  is the Kronecker delta. Some of the programs which perform 3D modelling are: MIKE 3, DELFT3D, TELEMAC 3D, FLOW 3D, AULOS, FLOTRAN, CFX, PHOENIX, CORMIX, H3D, CCHE3D.

### TWO-PHASE FLOW AND SEDIMENT TRANSPORT

As has been mentioned earlier, fluvial dynamics is complex, and mathematical analysis methods can only approach it through simplifications which, as computing technology advances, are constantly being solved or implemented. Although we mentioned that the first simplification involved averaging velocities along the channel (1D models) or disregarding vertical variations (2D models), there are tools which are capable of solving SWEs in 3D – albeit at a computational cost which continues to be exorbitant. Flow in rivers is certainly 3D in terms of the variations in average velocity vectors; however, now that we have reached this stage, the influence of the sediment load on flow behaviour may be even more relevant. The solids carried along by a stream may travel in different ways (Figure 29), and of particular interest in flood hazard analyses are: solids in flotation (floating or in beds), owing to their potential to obstruct or dam up the streamflow; suspended solids, which in high concentrations can alter fluid properties (density, viscosity, deformation-force ratios), bedload and bed movement, since it alters the surface over which the stream flows and generates dynamic turbulence and obstacles.





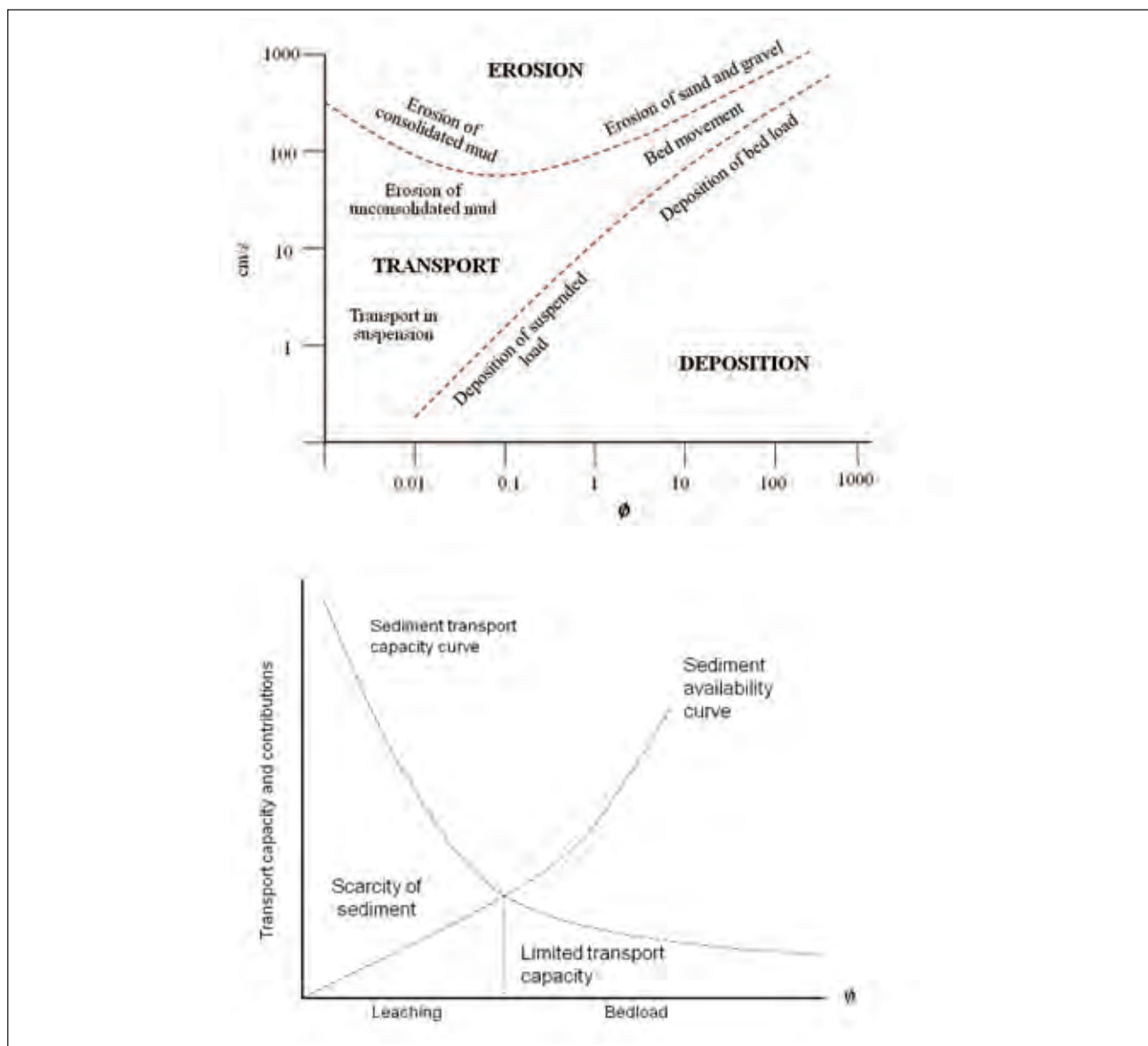


**Figure 29.** Fundamental types of sediment transport in rivers.

The mathematical approximations to the problem of bedload or sediment transport (referred to as ‘two-phase approximations’ when they consider the sediment movement phase separately from the water movement phase and ‘one-phase’ when the sediment concentration is such that transport en masse is produced; Mintegui *et al.*, 2006) are centred on two basic concepts. The first is the relationship between a stream’s energy and the sediment granulometry. The second is the quantity of material available (Figure 30). The water-sediment interrelation has only been taken into account on rare occasions until now. When it is taken into account, it is as an increase in roughness parameters or a variation in turbulence parameters using non-Newtonian fluids models (Figure 31) or mobile bed and boundary models (fluvial morphodynamics models), in which hydraulic computations are conducted in ‘clean water’ with bathymetry readings which vary over time (flexible grids), the alteration of which depends on previously calculated flow conditions.

Many problems arise when sediment transport models are used, which is why they are considered imperfect or invalid to this day (Fernández Bono, 2007), or at best useful for obtaining qualitative guidance, mainly because the different equations, when put to use, have proven to lack universal validity, coupled with the fact that we have not been able to establish which is the most appropriate for different ranges of situations (*op. cit.*). Agreement has not even been reached regarding the equations which describe the instant in which sediment transport is initiated (Armanini, 1999).

A few of the computation tools discussed earlier (both 1D and 2D and their respective connections) include different options for estimating sediment transport (for example: Sobek, Mike, HEC-RAS) and which are usually structured as advection-dispersion models (used mostly for water quality, but which can also be used for dissolved elements such as very fine suspended materials), cohesive sediment transport models, non-cohesive



**Figure 30.** Above is the Hjulström diagram (for a depth of 1 m; Hjulström, 1935); below, the relationship between transport capacity and availability of material (Julien, 1995).

sediment transport models and bedload transport models. Furthermore, they usually allow one to choose from several of the many equations used to date, notably:

- Meyer-Peter *et al.* (1934): bedload transport.
- Lane and Kalinske (1939): suspended sediment.
- Meyer-Peter and Muller (1948): bedload.
- Einstein and Brown (1950): bedload.
- Bagnol (1956): bedload.
- Sato, Kikkawa and Ashida (1957): bedload.
- Schoklitsh (1962): bedload.
- Engelund and Hansen (1967): total sediment load.
- Graf and Acaroglu (1968): bedload.
- Pica (1972): bedload.
- Ashida and Michiue (1972): bedload and suspended sediment.

- Ackers and White (1973): total sediment load.
- Yang (1973): total sediment load of sand and gravel.
- Engelund and Fredsøe (1976): bedload and suspended sediment.
- Mizuyama (1977): bedload.
- Parker (1979): bedload.
- Parker *et al.* (1982): bedload.
- Smart and Jaeggi (1983): total sediment load.
- Van Rijn (1984): bedload and suspended sediment.
- Rickenmann (1991): bedload.
- Aguirre-Pe *et al.* (2000): bedload.

**Table 2.** Some of the tools which calculate sediment transport and river morphodynamics (mobile bed).

1D Models	2D Models	3D Models
MOBED	SOBEK	H3D
MOSEC	GSTARS	TELEMAC3D
DELTA	BRI-STARS	FLOW3D
FLUVIAL12	MIKE21 and MIKE21C	Delft3D
IALLUVIAL	SMS (SED2D)	
HEC-6	CCHE2D	
HEC-RAS	SSIIMM	
MIKE11	TELEMAC 2D	
SEDIMOD	FLO 2D	
	DELFT3D	

A compilation and classification of the equations for estimating sediment discharge (or bedload discharge) can be found in Mintegui *et al.* (2006).

Typically, to estimate bed morphology changes, the Exner sediment continuity equation (1925) is taken into account; it is a function dependent on the quantity of sediment transported and evaluated with one of the previous formulas. The Exner equation can be expressed as follows:

$$\frac{\partial S}{\partial x} + (1-\epsilon)w \cdot \frac{\partial z}{\partial t} = 0$$

Where: S is the sediment discharge, x is the longitudinal coordinate,  $\epsilon$  is porosity, z is bed height, t is time, and w is channel width.

A comparison of the tools for assessing sediment transport (mobile bed, dissolved or suspended transport, and bedload) can be found in Table 2, and a compilation of some of them can be found in Fernández Bono (2007).

In the torrential dynamics, it is not uncommon to encounter flows of mud and detritus, sometimes called hyperconcentrated flows because of the volumetric ratio between the liquid phase and the solid phase, in which the solid phase is prevalent (Figure 31), or its concentration is such that flow behaviour cannot be considered



**Figure 31.** Torrential headwaters of the Fana de Genestaza (Asturias), where frequent phenomena of debris flow and debris floods are generated and transferred and in which sediment load plays a fundamental role. Photo: Alejandro Gaona.

Newtonian, but rather one closer related to a Bingham plastic. Following is the general formula of the rheological equation (Bateman and Medina, 2007):

$$\tau = \tau_0 + \mu_m \frac{dV}{dz} + \zeta \left( \frac{dV}{dz} \right)^2$$

Where:  $\tau$  is shear stress,  $\tau_0$  shear stress threshold,  $\mu_m$  is viscosity, and  $\zeta$  is a turbulence parameter.

## 2.2. Geological-geomorphological Methods

The methods, techniques, and sources of information originating in geology, or knowledge derived from the earth sciences, can be applied to flood hazard mapping and analysis in seven broad areas or fields:

- The configuration of relief forms (geomorphological analysis) as a conditioning factor of flash floods and fluvial inundations when morphographic, morphodynamic and morphological-evolutionary factors are considered.
- The mapped layout of fluvial forms and deposits (geomorphological mapping) as a basis for flood hazard mapping.
- Geological and geomorphological composition as the basis for identifying transported and/or transportable sediment load in a stream during a flood.
- The lithologic composition of the substrate and surface formations as a point of reference for estimating initial abstractions in the rainfall-runoff transformation process in runoff genesis during flood events.
- The hydrogeological functioning of groundwater as a flood trigger by a rise in the water table.
- The analysis and mapping of other geological phenomena associated with flooding (landslides, piping, karstification, erosion, deposition).
- The palaeohydrological study of palaeofloods from geological-sedimentological records (see Section 2.3.2).

Having said the above, one must not forget the importance of geological and geomorphological knowledge in the study and analysis of the hazard of other flood types, such as those associated with coastal dynamics (Cobos *et al.*, 2004; Benavente *et al.*, 2006 and 2007), or those which occur in aclinal and/or endorheic areas with no connection to the drainage network.

### 2.2.1. GEOMORPHOLOGICAL CONDITIONING FACTORS FOR FLUVIAL FLOODS

Geomorphology is a scientific discipline concerned with the spatial-temporal description, analysis, and interpretation of relief forms and the recent deposits associated therewith (surface formations). Halfway between surface geology (external geodynamics) and physical geography, it draws upon methods and techniques from other branches of science (physics, chemistry, volcanology, structural geology, climatology) and humanities (history, archaeology).

Fluvial geomorphology, the study of the forms and deposits of rivers, streams, and torrents, plays an important role in the study of the genesis and propagation of fluvial floods, as well as the effects of the inundation of the banks of streams where these events occur. This influence manifests itself in a three-faceted manner: surface configuration: in terms of the forms of the earth's surface; dynamics: referring to the actions which develop fluvial processes and the resulting products (forms and deposits); and evolution, in reference to the trends and pace of relief changes which affect flood-prone areas.

Thus, the geomorphological conditioning factors of fluvial floods may be discussed from three perspectives: morphographic, morphodynamic, and morphological-evolutionary. These conditioning factors also may be discussed at different spatial-temporal levels, which cover everything from the geomorphological dependency of characteristic times on the hyetograph-hydrograph relationship (time of concentration), to the role of the micro-morphology of the channel and banks in each flood event's characteristic hydraulic flow model.

#### FLUVIAL MORPHOLOGY

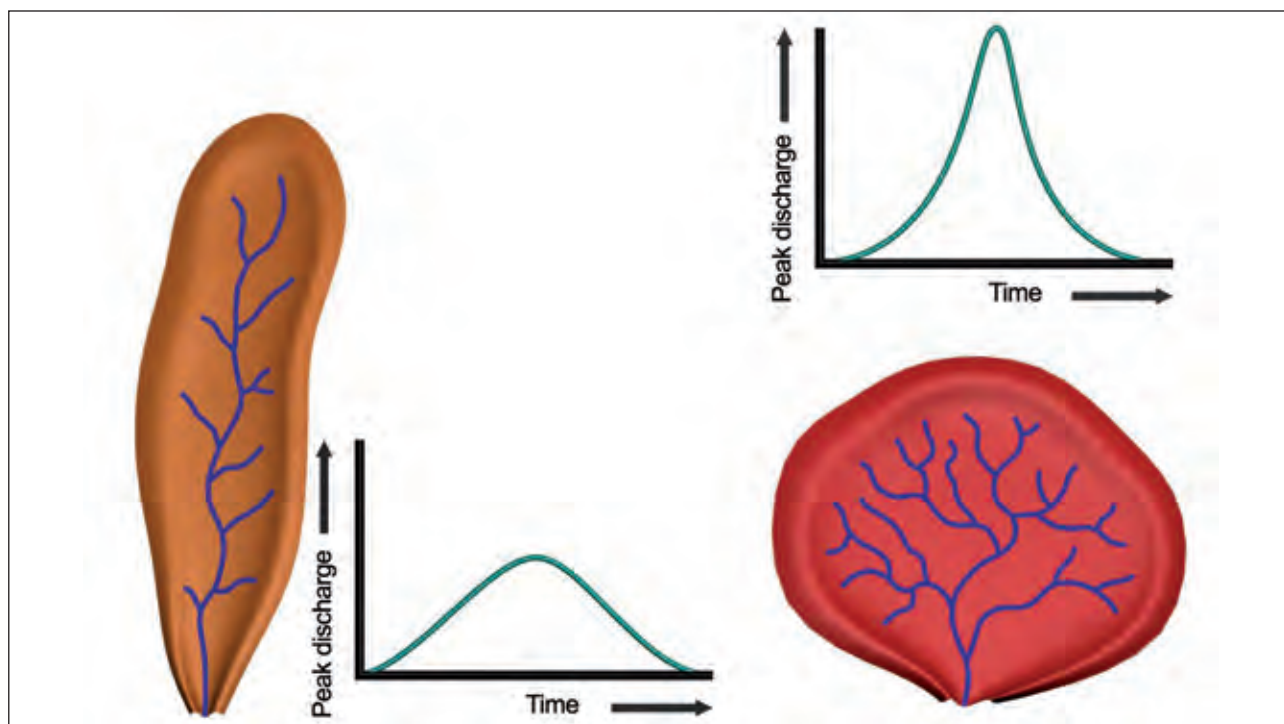
The role of fluvial morphology in floods manifests itself in three different spatial areas: areal or catchment basin, at the regional to local scale; linear or hydrographic network, also at the regional to local scale; and specific or stream reaches, at the comarca to local scale. These areas are interconnected with many other levels of influence, such the interference of basin morphology in flood genesis, the effect of stream morphology on fluvial hydraulics, and the influence of drainage network morphology on propagation. An excellent compilation of the correlations between morphometric parameters and flood discharges, usually based on local or regional studies in the USA, can be found in the bibliography of Patton (1988). This chapter will emphasize more global relationships with practical applications in the estimation of such discharges and their characteristic times.

##### *Catchment areas*

The relief layout in catchment areas determines the genesis and type of floods in two ways, attributable to the dual physiographic and morphometric facets of fluvial morphology:

- a) The relief, due to its altitude or layout (slope or orientation), can induce meteorological situations which favour intense and/or abundant rainfall. Such is the case with basins bordered by mountain ranges that act as barriers to atmospheric circulation, which causes orographic precipitation, from convective precipitation due to the warming and rising of moist air masses in valleys and low-lying areas of the basin, or to the sudden melting of snow or glacial accumulations from the peripheral peaks. The layout of the catchment area itself, elongated in the direction and orientation of the progression of atmospheric disturbances (fronts), can aggravate the situation by maximizing precipitation.
- b) The general geomorphological layout of the catchment area (slope, elongation, circularity, compactness) has an extreme influence on abstractions [initial losses] (especially infiltration and surface retention) and therefore influences the hydrograph (relationship between its elements and components) and the magnitude of the characteristic times in the hyetograph-hydrograph relationships (base times, times of concentration). In this manner, and under the same conditions for other factors (area, substrate impermeability, plant cover), catchment areas which have scant slope, are elongated, irregular and less compact will have more abstraction and will generate more homogenous hydrographs (flatter) with larger base times (Figure 32).





**Figure 32.** Qualitative relationship between drainage basin shape and hydrological response. Adapted from Strahler (1964).

In this respect, some basic measures have been defined which can be obtained from the direct observation of the basin map; they are useful for morphometric characterization:

- Area (A), total surface of the basin.
- Perimeter (P), length of the boundary of the catchment area (divide).
- Average height ( $h_m$ ), average height of the catchment points above sea level.
- Length of the catchment area (L), in different directions.
- Relief or amplitude of the relief of the catchment area (R), the height difference between the lowest and highest points.
- Order or magnitude of the catchment area (M or  $\omega$ ), number of catchment areas of a given order (N), and area of the catchments of a given order (A).

Additionally, different morphometric indices have been developed (Gardiner, 1974) that are useful for describing quantitatively the morphological factors of basins which influence the type of floods that are generated in them (Table 3).

Since the middle of last century, we have been well aware of the exponential relationship between the area of the basin and the probable peak discharge for a given return period:  $Q_p = aA^b$  (Patton and Baker, 1976). Parameter  $b$  of this equation changes depending on the region under study, with characteristic values between 0.5 and 0.8, and increasing with the return period under study (Thomas and Benson, 1970). However, these broad approximations shed little light on the physical processes of runoff generation (Patton, 1988). Some simple flood discharge estimation methods, such as the popular empirical equations of Zapata and Heras, also base their formulation on the relationship between basic morphometric measurements (areas) of adjacent catchment areas. There are also studies which relate the magnitudes of the palaeoflood discharges to the morphometric characteristics of the basins (Martínez Goytre, 1993). Other, more elaborate hydrometeorological methods of the rational type place particular emphasis on the basin's area (A) in its basic formulation ( $Q_p = CIA/3.6$ ) and in the estimation of reduction factors by area (NERC, 1975, NWS, 1961;  $K_A$ , Témez, 1991) for the calculation of rainfall intensity. Even the most sophisticated methods, such as the unit hydrograph, cannot forgo this important morphometric parameter and must include it as input in the model.

**Table 3.** Principle types of morphometric indices and constructions for the characterization of the shape, size and height of the catchment basin and which are useful in flood hydrology. Modified and further developed based on Gardiner (1974).

	INDICES	STRUCTURES
FORM	<ul style="list-style-type: none"> <li>- Circularity (<math>A/P^2</math> ó <math>4\pi \cdot A/ P^2</math>)</li> <li>- Compactness (<math>P/ 2\pi \cdot R</math>)</li> <li>- Form factor (<math>A/L^2</math>)</li> <li>- Gravelius index (<math>P/A^{0.5}</math>)</li> <li>- Elongation ratio (<math>A^{0.5}/L</math>)</li> <li>- Delta (<math>L/A^{0.5}</math>)</li> <li>- USACE<sup>41</sup> index (<math>L^2/A</math>)</li> </ul>	<ul style="list-style-type: none"> <li>- Lemniscate ratio</li> <li>- Area comparison</li> <li>- Inscribed versus circumscribed diameters ratio</li> <li>- Elongation-compactness-orientation</li> <li>- Radial-linear ratio</li> </ul>
SIZE	<ul style="list-style-type: none"> <li>- Interbasin area</li> <li>- Catchment area ratio or law of stream areas (<math>R_A = A_w/ A_{w-1}</math>)</li> </ul>	<ul style="list-style-type: none"> <li>- Rectangle equivalent</li> </ul>
HEIGHT	<ul style="list-style-type: none"> <li>- Relief ratio (<math>RR=R/A^{0.5}</math>)</li> <li>- Relative relief</li> <li>- Incidence number</li> <li>- Geometry number</li> <li>- Slope of the terrain orthogonal to the isohypses</li> <li>- Maximum slope of the valley hillslopes</li> <li>- Slope index</li> <li>- Dihedral angle between the valley sides</li> <li>- Terrain mass volume</li> </ul>	<ul style="list-style-type: none"> <li>- Hypsometric curve</li> <li>- Hypsometric integral</li> </ul>

Abstraction, in other words, the quantity of precipitation that does not immediately form surface runoff due to interception by vegetation, evapotranspiration, surface retention, or percolation by infiltration, is accounted for in estimations integrated using different methodologies (Ferrer, 1993). The most widespread method, known as the Soil Conservation Service (SCS) method for obtaining the runoff curve number (SCS, 1972) considers the type of farm management methods used in the USA (with or without terracing). This variable was substituted in Spain by the slope of the basin terrain as a morphometric parameter (Témez, 1987), assigning separate runoff threshold values to the subareas of the catchment between zero and three degrees and those with slopes greater than three degrees.

The travel time of water in the basin, an essential element in the estimation of characteristic times for hydrographs such as time of concentration, depends on the distance it must cover and the flow velocity. To estimate average flow velocities of surface water in the basin in its unchannelized stage, some organizations, such as the Texas Highway Department (1970), have proposed tables in which the input variables are the land cover type and the slope of the catchment area (in percentages). Within this morphometric variable four intervals are differentiated: 0%–3%, 4%–7%, 8%–11% and >12% which indicate very different flow velocities.

### Drainage networks

The size and layout of the drainage network are even more important in the genesis and propagation of floods. The shape of the network determines the velocity and degree of incorporation of the rainfall and runoff from the drainage network's watersheds. As with catchment areas, a series of morphometric measurements and relationships (Gardiner, 1974) have been established that have proved useful in evaluating their impacts on flood hydrology (Table 4). Most of the relationships between the parameters and indices and the magnitudes of floods

<sup>41</sup> US Army Corps of Engineers.

**Table 4.** Morphometric parameters of the drainage network which affect flood hydrology.

<b>BASIC MEASURES</b> , obtained from direct observation of the network mapping: <ul style="list-style-type: none"> <li>- Total length of the streams in the network (L)</li> <li>- Confluence angle of two or more streams in the network</li> <li>- Hierarchical order of the stream within the network (<math>\omega</math>) <ul style="list-style-type: none"> <li>· Systems according to the position of the segment, Horton (1945), Strahler (1952), and the Decimal Classification of Rivers (Centre for Hydrographic Studies [CEH], 1966)</li> <li>· Systems according to the magnitude relative to the segment, Shreve (1967) and Scheidegger (1970)</li> <li>· Systems according to the erosive power and water contribution</li> <li>· Systems according to the evolutionary status</li> </ul> </li> <li>- Number of streams of a given order (<math>N_\omega</math>)</li> <li>- Length of streams of a given order (<math>L_\omega</math>)</li> </ul>
<b>MORPHOMETRIC INDICES</b> , of the relationship between basic measures or between morphometric indices and those of the catchment area: <ul style="list-style-type: none"> <li>- Bifurcation ratio or law of stream numbers, <math>R_B = N_\omega / N_{\omega+1}</math> (Horton, 1945; Strahler, 1952 and 1964)</li> <li>- Stream length ratio or law of stream lengths, <math>R_L = L_\omega / L_{\omega-1}</math> (Horton, 1945)</li> <li>- Relation between stream length and bifurcation ratio (Horton, 1945)</li> <li>- Drainage density (<math>Dd = L/A</math>)</li> <li>- Stream frequency (F)</li> <li>- Drainage intensity</li> <li>- Ruggedness number (<math>HR = Dd \cdot R</math>)</li> <li>- Relative stream density (<math>F/Dd^2</math>)</li> </ul>

**Table 5.** Regression formulas for predicting the magnitudes of flood discharges based on drainage basin morphometry in various hydrogeomorphological areas in the US Symbology: M, basin magnitude; HD, ruggedness number;  $F_1$ , first-order channel frequency; DD, drainage density; RR, relief ratio. Translated and adapted from Patton and Baker (1976).

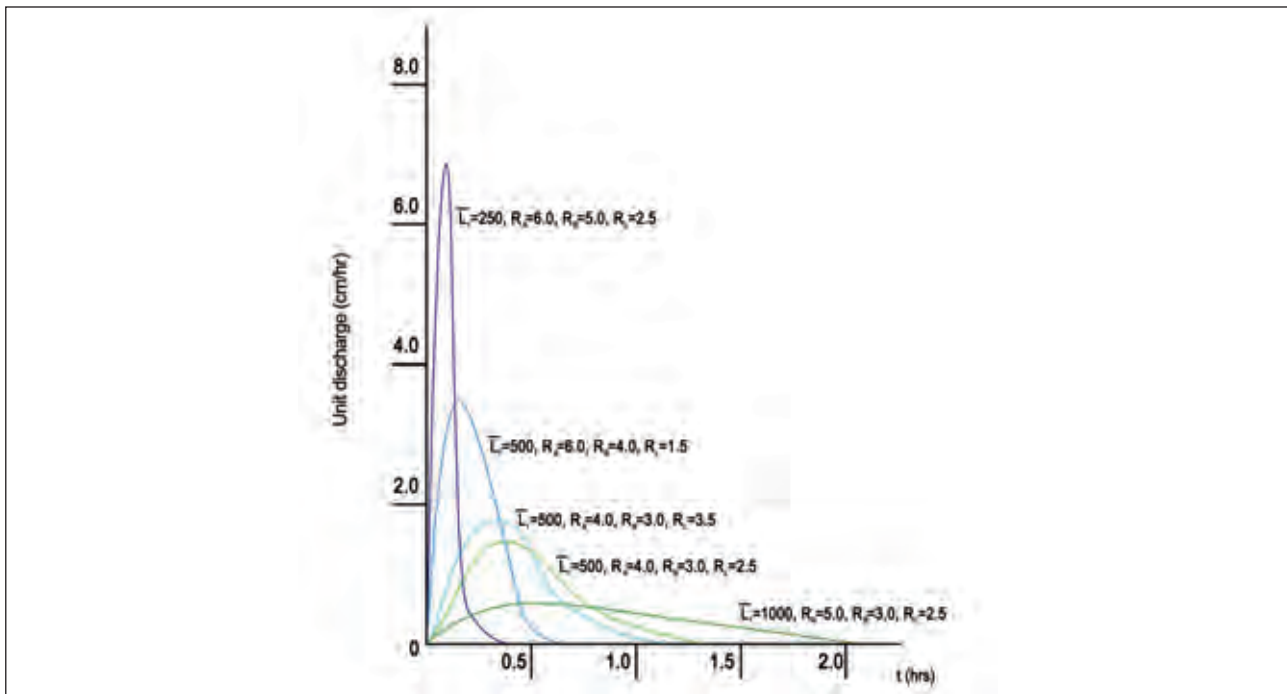
Region	Equation to calculate $Q_{max}$	$R^2$	Probability
Central Texas	$17.369 \cdot M^{0.43} \cdot HD^{0.54} \cdot F_1^{-0.96}$ $36.650 \cdot M^{0.64} \cdot RR^{0.54} \cdot Dd^{-1.68}$	0.85 0.74	0.001 0.01
Southern California	$155 \cdot M^{1.04} \cdot HD^{-0.83} \cdot F_1^{-0.73}$ $380 \cdot M^{0.89} \cdot Dd^{-1.87}$	0.85 0.86	0.001 0.0001
North-central Utah	$23 \cdot M^{0.90} \cdot HD^{1.19} \cdot F_1^{-1.58}$ $38.618 \cdot M^{2.20} \cdot RR^{2.51} \cdot F_1^{-3.73}$	0.72 0.83	0.005 0.005
Indiana	$424 \cdot M^{0.46} \cdot HD^{0.73} \cdot F_1^{0.21}$ $424 \cdot M^{0.82} \cdot RR^{0.67} \cdot Dd^{0.56}$	0.67 0.66	0.01 0.05
Appalachian Plateau	$100 \cdot M^{0.79} \cdot HD^{0.19} \cdot F_1^{-0.29}$ $38 \cdot M^{0.89} \cdot Dd^{-0.50}$	0.92 0.91	0.0001 0.0001

in the catchment areas and networks (especially peak discharge) have been established through regression formulas applied to specific regions (Patton and Baker, 1976). It is doubtful whether they can be extrapolated to other physiographic systems, and the correlation indices are not very meaningful (Table 5), making them simple mathematical devices.

These types of analyses have also been done on basins and subbasins in the south-central mainland Spain in the drainage areas of the Tajo and Guadiana rivers (Potenciano, 2004 and 2008).

However, many of these parameters are of such hydrological significance that some authors have developed the so-called geomorphological instantaneous unit hydrograph [GIUH] (Rodríguez-Iturbe and Valdés, 1979; Valdés *et al.*, 1979, Gupta *et al.* 1980 and 1986), the characterization of is based on the measurements and in-





**Figure 33.** Geomorphological instantaneous unit hydrographs simulated for a third-order basin with constant flow velocity (2.5 m/s) but with varied morphometric characteristics:  $L$ , average lengths of first-order channels in meters (Rodríguez Iturbe and Valdés, 1979).

dexes of the basin and network in which a flood event is produced. Rodríguez-Iturbe and Valdés (1979) and Willgoose *et al.* (1994) have found relationships between a stream's hierarchical order number (the so-called Horton laws or indexes  $R_A$ ,  $R_B$  and  $R_L$ ; see Tables 3 and 4) and its hydrological response (instantaneous unit hydrograph [IUH]). Important parameters such as the hydrograph's peak discharge or time to peak can be obtained from expressions like:

$$q_p = \frac{1.31 \cdot v}{L_\Omega} R_L^{0.43}$$

$$t_p = \frac{0.44 \cdot L_\Omega \cdot R_B^{0.55} \cdot R_A^{-0.55} \cdot R_L^{-0.38}}{v}$$

where  $v$  is flow velocity and  $L_\Omega$  is an internal scale parameter (Figures 33 and 34). The indices can be obtained by representing  $N$ ,  $L$  and  $A$  on a logarithmic scale (ordinates) against the order of the stream or basin ( $\omega$ ,  $x$  axis). The slopes of the regression lines fitted to each scatterplot will be the values of the  $R_B$ ,  $R_L$  and  $R_A$ , indices, respectively (Valdés *et al.*, 1979, Figure 35).

A dimensionless ratio  $IR$  which is constant for each watershed may also be defined, independent of the storm characteristics; it is intimately connected to the geomorphology of the basin and to the structure of its hydrological response.

$$IR = 0.58 \left( \frac{R_B}{R_A} \right)^{0.55} \cdot R_L^{0.05}$$

This ratio can be considered a measurement of the geometric similarity between two catchments. In this vein, Rosso (1984) established the relationship between the cascade of linear reservoirs, or the Nash unit hydrograph method, and the Horton morphometric theories. Along these lines, a monograph was recently published on the geomorphological unit hydrograph of deposits as a basis for calculating design hydrographs in average-size basins (López *et al.*, 2007).

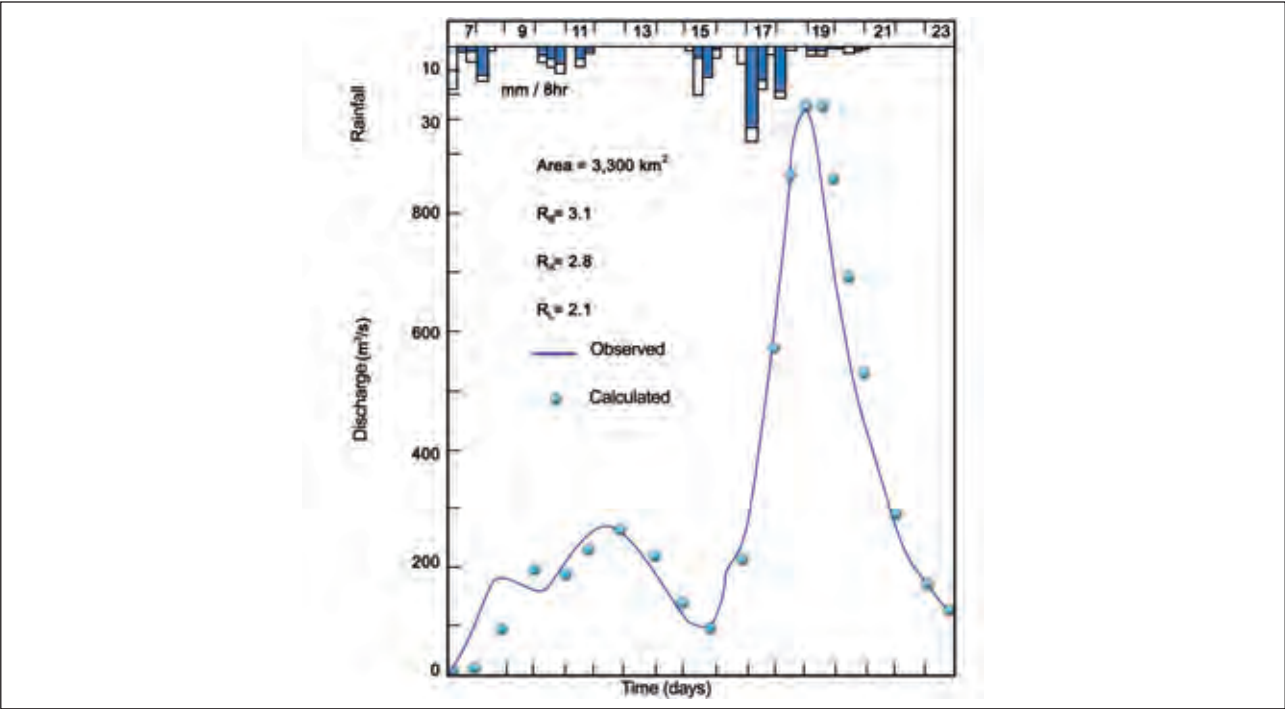


Figure 34. Hydrograph calculated and graphically fitted to the actual observed hydrograph for the Vermillion river in Danville, USA. Adapted from Gupta et al., 1980.

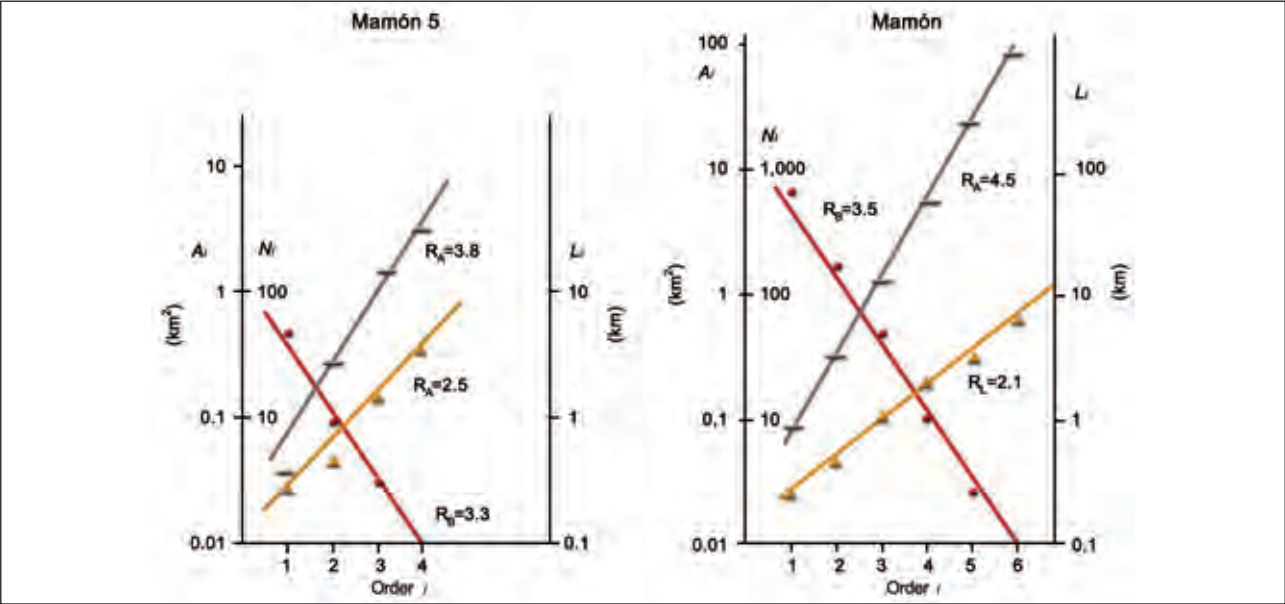


Figure 35. Representations of the basin areas ( $A_i$ ), flow lengths ( $L_i$ ), and their number ( $N_i$ ) in relation to the order ( $i$ ) to obtain morphometric indices  $R_A$ ,  $R_L$ , and  $R_b$ . Carried out for Mamón basin and Mamón 5 subbasin (Venezuela) by Valdés et al. (1979); copyright American Geophysical Union.

The Shreve (1976) method of ordering streams can be a highly descriptive parameter in relation to the hydrological response of the stream network. More importantly, the Shreve Magnitude (number of first-order streams) has been used to correlate it with peak discharge (Patton and Baker, 1976).

Finally, the incorporation of water from the basin’s slopes into the channels during a flood also depends on the





arrangement and morphometric characteristics of the network. Therefore, parameters such as total length of streams in the network ( $L$ ) determine the discharge incorporated into the fluvial system. The reason is, when the surface flow has a discharge  $q_0$  per unit of width, the discharge which reaches the network will be  $Q = q_0 L$ . Considered in terms of its relationship with the drainage area (basin), the drainage density ( $Dd$ ) allows us to obtain a measurement for the average length of surface flow on the slopes ( $L_0$ ), assuming the streams are fed by Hortonian overland flow from their entire contributing area:  $L_0 = 0.5 Dd$

### Streams

As regards individual streams or isolated reaches thereof, the morphometric parameters are those which define the hydraulic geometry of the stream and which are considered in the three orthogonal dimensions in space (Table 6).

Indexes and ratios can be defined between these parameters as well, with the most characteristic being:

- Hydraulic radius,  $A/P$
- Ratio of wetted perimeter to top width ( $P/P_b$ )
- Channel fall,  $C = z_0 - z_b$  (m)
- Bed slope or gradient,  $S_0 = C/L$  (dimensionless)
- Water surface slope ( $S_w$ )
- Sinuosity,  $s = L_t / L_v$
- *Braiding* parameter

**Table 6.** Morphometric parameters which can be defined in a stream or reach thereof (modified version of Pedraza and Díez, 1996; Díez Herrero 2002a).

<p><b>SECTIONS OF THE CHANNEL OR CROSS SECTIONS</b></p> <ul style="list-style-type: none"> <li>- Surfaces: <ul style="list-style-type: none"> <li>· Channelfull area (<math>A</math>)</li> <li>· Bankfull area (<math>A_b</math>)</li> </ul> </li> <li>- Boundaries: <ul style="list-style-type: none"> <li>· Wetted Perimeter (<math>P</math>)</li> <li>· Perimeter of the bankfull section (<math>P_b</math>)</li> </ul> </li> <li>- Elevations: <ul style="list-style-type: none"> <li>· Depth (<math>d</math>)</li> <li>· Relative height between two points (<math>h</math>)</li> </ul> </li> <li>- Separations, amplitudes and widths: <ul style="list-style-type: none"> <li>· Separation between banks or bank escarpments (<math>l</math> or <math>w_b</math>)</li> <li>· Water surface elevations (<math>w</math>)</li> <li>· Top width of the channel (<math>B</math>)</li> </ul> </li> </ul>
<p><b>PLANFORMS OR PATTERNS</b></p> <ul style="list-style-type: none"> <li>- Configuration measures: <ul style="list-style-type: none"> <li>· Thalweg length (<math>L_t</math>)</li> <li>· Valley envelope length (<math>L_v</math>)</li> </ul> </li> <li>- Stream azimuth, angle of the stream with respect to magnetic north (<math>^\circ</math>)</li> </ul>
<p><b>LONGITUDINAL PROFILES</b></p> <ul style="list-style-type: none"> <li>- Linear definitions: <ul style="list-style-type: none"> <li>· Stream length (<math>L</math>)</li> <li>· Depth (<math>y</math>)</li> </ul> </li> <li>- Elevations: <ul style="list-style-type: none"> <li>· Initial altitude (<math>z_0</math>)</li> <li>· Altitude of the river mouth or base level (<math>z_b</math>)</li> </ul> </li> </ul>

Close relationships have also been established between these measurements and indices and their hydrological consequences, as is the case with the influence of stream length (L) and the channel slope ( $S_0$ ) with respect to the characteristic times obtained through synthetic unit hydrographs:

- The lag-to-peak calculated according to the hydrometeorological methodology of the SCS (1975) depends exclusively on both morphometric parameters of the stream in which the flood is propagated and the curve number of the watershed.
- The average time (in hours) according to the equation proposed by the US Army Corps of Engineers (USACE, 1957) depends on the length, slope, and distance along the main channel, from the point nearest to the basin's centre of gravity to the basin outlet ( $L_c$ , in km):

$$T_m = 0.164 \left( \frac{L \cdot L_c}{S_0^{0.5}} \right)^{0.38}$$

- The time of concentration proposed by Témez (1991) based on a comparison between various Spanish catchments also depends on the length of the main channel and its slope:

$$T_c = 0.3 \left( \frac{L}{S_0^{0.25}} \right)^{0.76}$$

- The basin lag ( $t_p$ , in hours) from the Snyder unit hydrograph (1938) depends on the length of the main stream in km (L), the distance from the basin outlet to its centroid ( $L_c$ ) and a coefficient based on nearby instrumented basins ( $C_t$ ):

$$T_p = 0.75 \cdot C_t (L \cdot L_c)^{0.3}$$

Some of this unit hydrograph's parameters have been regionalized; they are dependent on morphometric variables (Espey *et al.*, 1977).

Moreover, emphasis should be placed on the influence of a stream's morphology on the parameters needed to calculate flood propagation in channels (US Army, 1960; Ferrer, 1993) – both on hydraulic parameters (solution of the Saint-Venant equations) and hydrological parameters (Puls, Muskingum or Muskingum-Cunge). With the Muskingum method, the K parameter or storage index is estimated by a simple ratio between the length of the established stream reaches (L or  $\Delta x$ ) and the celerity of the flood wave (C). The latter value depends on other morphometric parameters, such as the channel width (B), depth variation (y) and in discharge of the reach (Q):

$$K = \frac{L}{C} \quad C = \frac{1}{B} + \frac{dQ}{dy}$$

The modification introduced by Cunge (1967), which brought about the Muskingum-Cunge method, further clarifies the relationships between the physical characteristics of the channel (morphometry) and the calculations needed for the analysis of propagation, such as the dimensionless parameter X:

$$X = \left( \frac{1-Q}{B \cdot S_0 \cdot C \cdot \Delta x} \right) \cdot 0.5$$

In composite flood propagation models (random linear reservoirs), the storage constant K has also been related to the Horton stream order of the drained subarea.

In the formulation of kinematic waves, the TETIS hydrometeorological distributed modelling program uses geomorphological parameters from the stream or flow line on which each pixel, or its continuity, is located.



Finally, and at the channel section scale, the stream's morphometric parameters, such as slope or hydraulic radius, intervene in the hydraulic computation of the depths that certain flood discharge reach. A typical example is the Manning equation for one-dimensional flow in a uniform regime (see Section 2.1.1). In this context, indices are defined such as the conveyance factor of the catchment area ( $\Phi$ , Espey *et al.*, 1977), a function of the roughness of the main channel (Casa Planes, 2007) and of the percentage of impermeable cover of the catchment area, and the relationships between the specific topographical configuration and channel roughness, useful for hydraulic models (Casas Planes, 2007).

## RIVER TYPES

Another aspect of fluvial morphology that has traditionally been linked to the characteristics of floods in streams is the type of rivers. This not only refers to the plan view of the channel or channels but also their associated elements (plain, bars, valley) and deposits. An initial criterion for classifying rivers is to consider the characteristics of the material which forms their channel bed. Because bedrock rivers are entrenched into the rocks of the substrate, the dynamics and geometry of their channel are determined by the nature of the substrate's rocks, the fragments that fall on it, and its flow or discharge. Unlike bedrock rivers, alluvial-bed rivers are those whose channel is entrenched into the very sediment transported by the river, which is why the geometry of the channel is as dependent on the movement of water as it is on the movement of sediment. Bedrock channels are much more stable over time, while the morphology and position of alluvial-bed rivers change more rapidly over time. This is due to the fact that alluvial-bed rivers were formed by erodible sediment and since forces from water flow can exceed the resistance to sediment drag.

Numerous classifications have been proposed for streams with alluvial beds, but they can be grouped into two

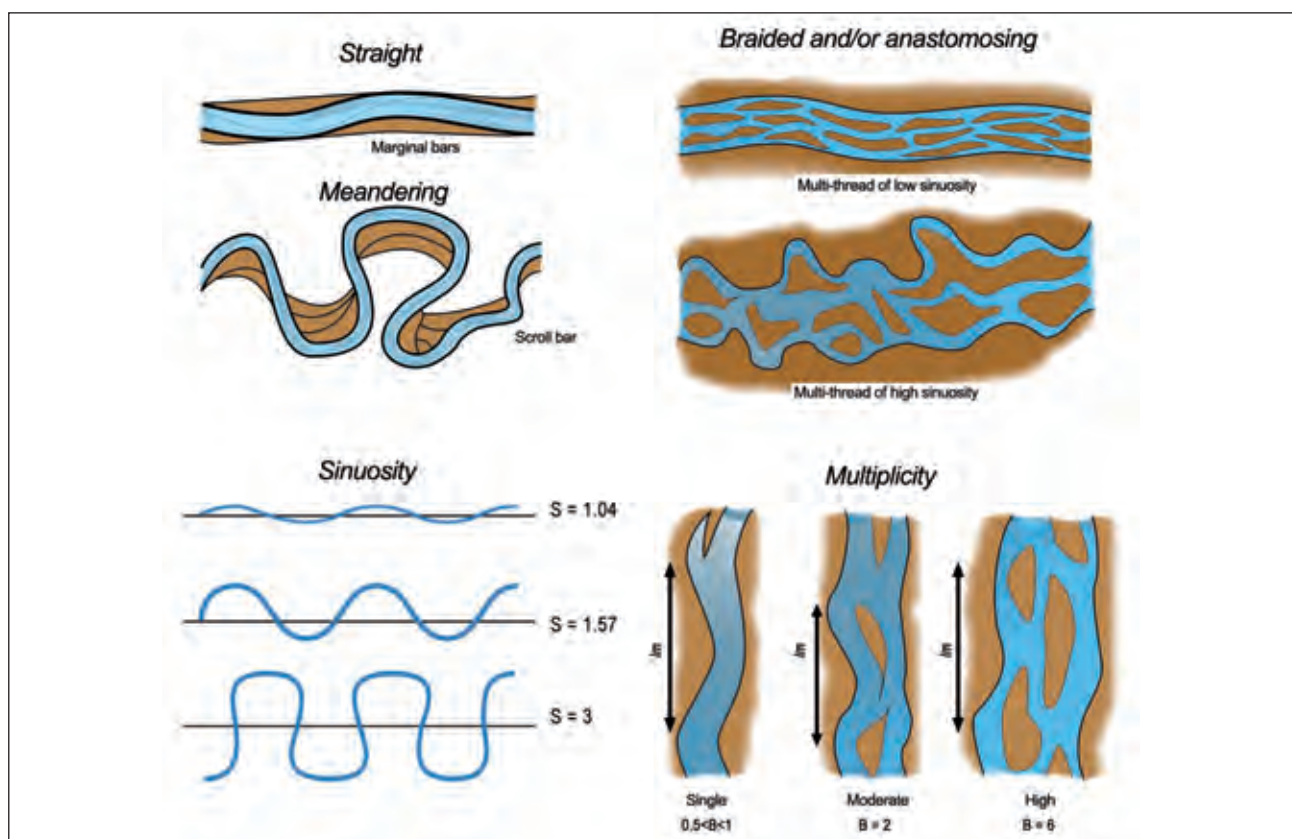


Figure 36. Basic classification of river types based on the number of stream channels and sinuosity. Based on Díez and Pedraza (1996).

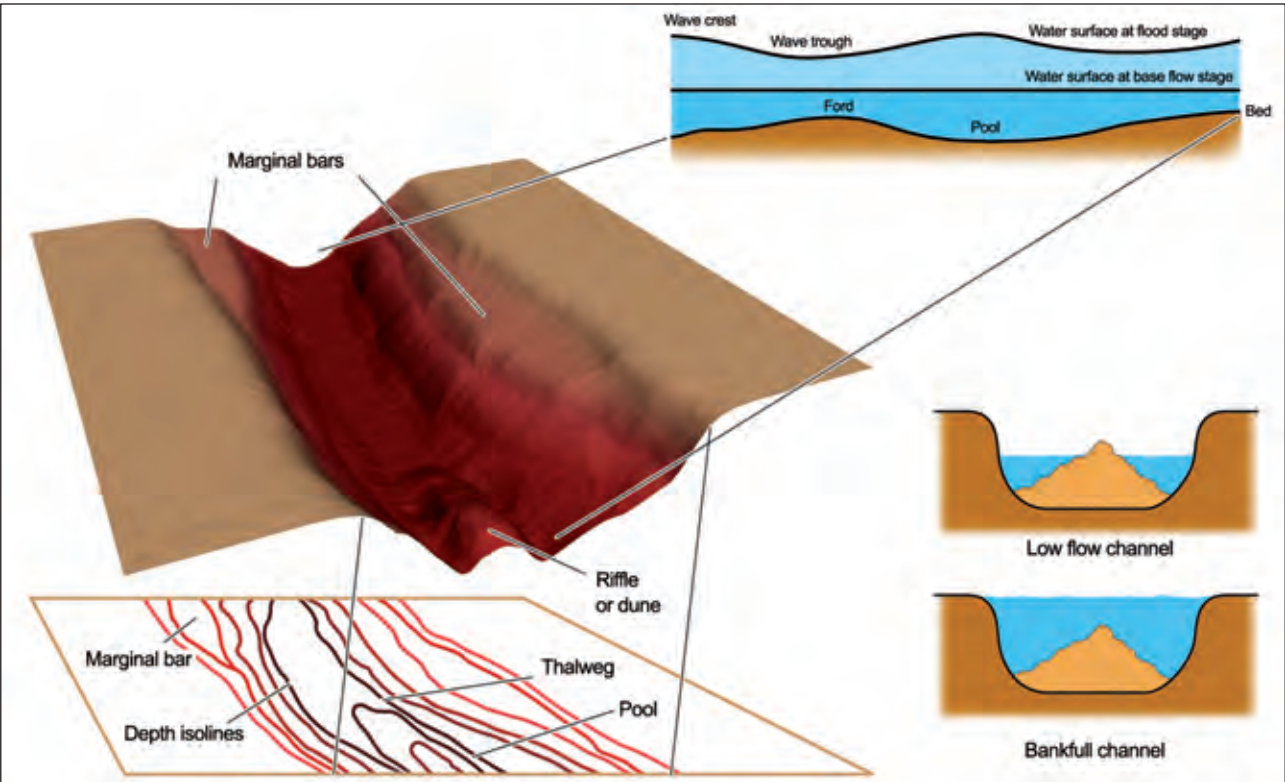


Figure 37. Characteristic forms of a straight river. Based on Díez and Pedraza (1996).

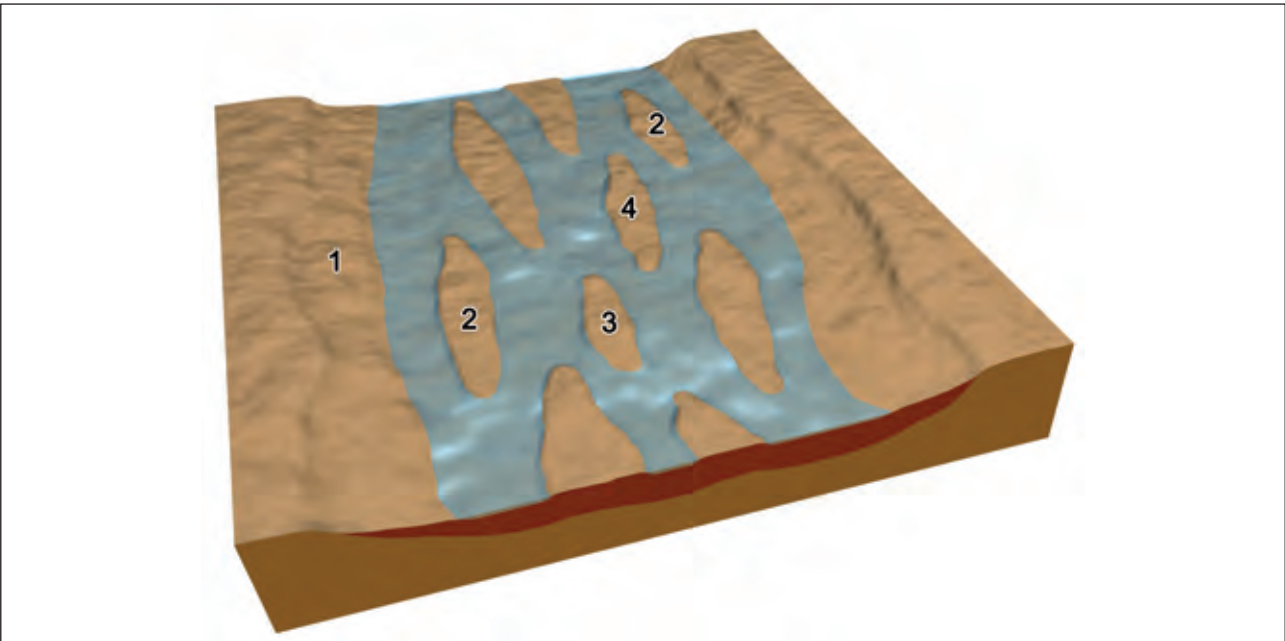
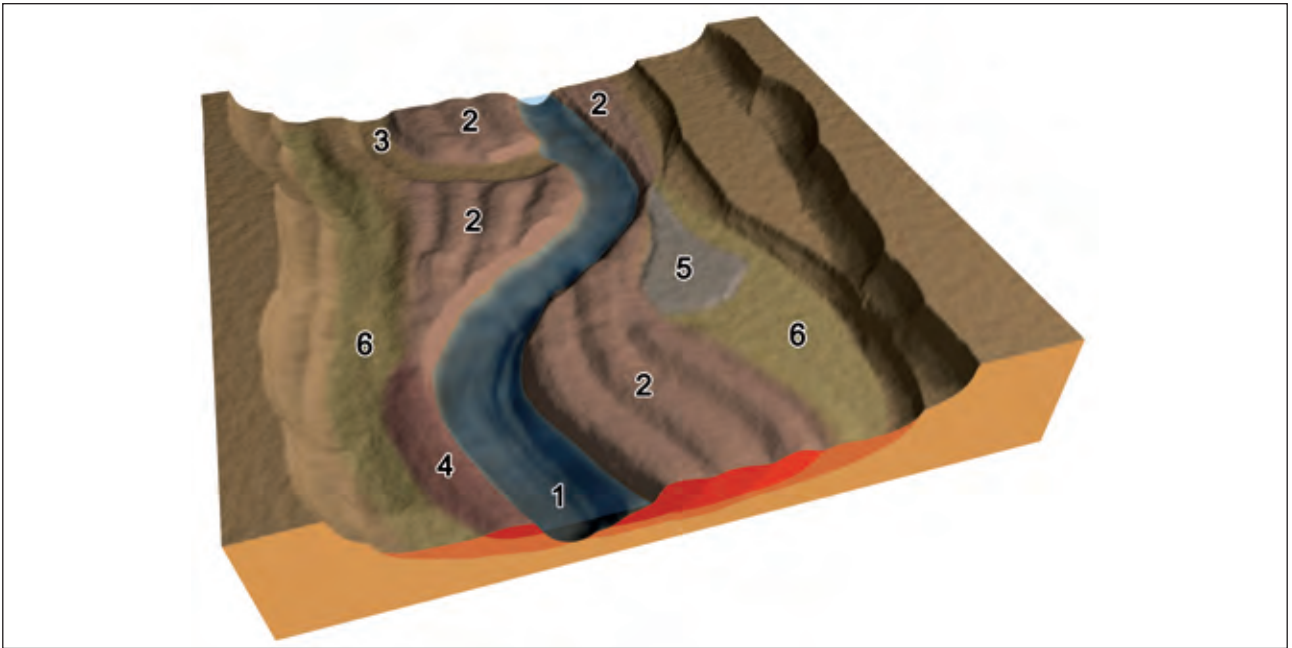


Figure 38. Characteristic forms of a braided river: 1, sandy plain or flood plain; 2, lateral or marginal bars; 3, central longitudinal bars; 4, central diagonal bars. Based on Díez and Pedraza (1996).

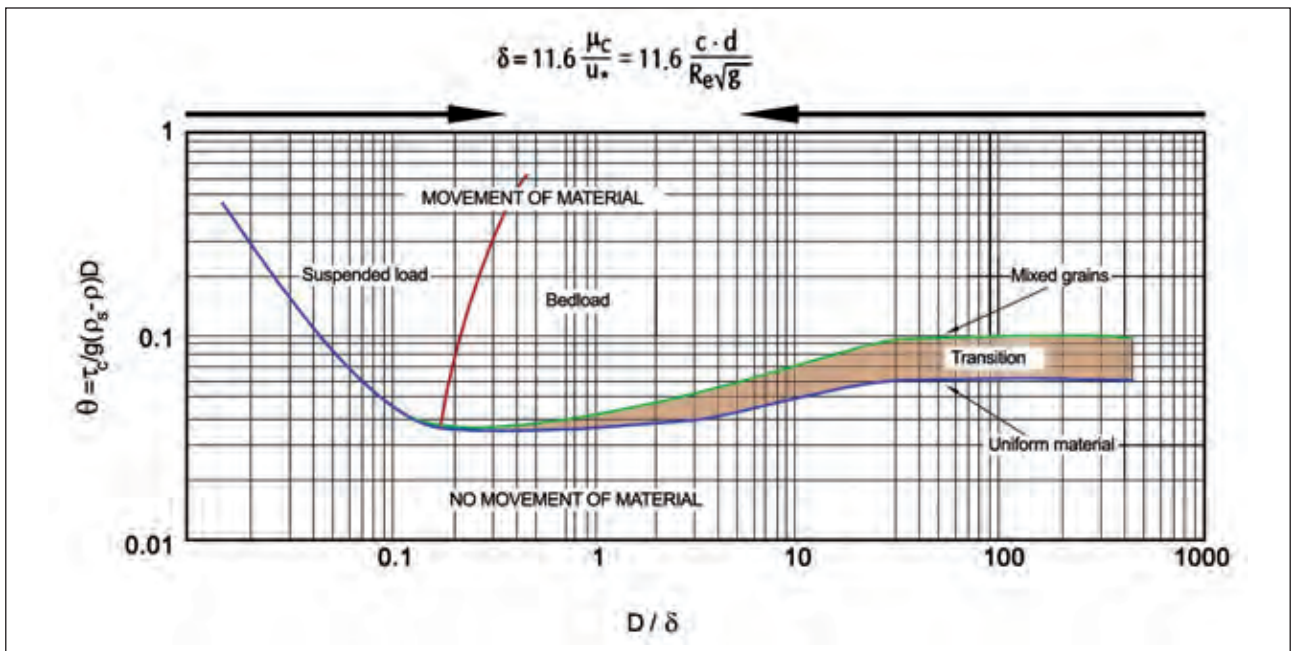
essential sets: Geomorphological, which place particular emphasis on the pattern, using parameters such as the sinuosity, number of channels, and braiding; or sedimentological, which relate the stream’s morphology to its dynamics (load and stability) and characteristic sequences of deposits. A noteworthy geomorphological classification system was Leopold and Wolman’s (1957) proposal in which three types of channels are differentiated:







**Figure 39.** Characteristic forms of a meandering river: 1, functional channel; 2, point bars with their ridges; 3, abandoned channel; 4, natural dike or seawall; 5, floodplain; 6, residual ponding and overflow areas (marshes and peat bogs). Based on Díez and Pedraza (1996).



**Figure 40.** Shields Diagram. Based on Díez and Pedraza (1996).

straight, braided and meandering. Of the sedimentological systems, there is the one by Schumm (1981), with its 14 models integrated in three groups (A, B and C) organised by load and which also take into account fundamental flow variables (channel gradient and width-depth ratio) and the channel's relative stability. In recent decades, both classification systems seem to have converged, resulting in derivative classifications which integrate both criteria. Some good examples are those in Rust (1978), a function of sinuosity and number of channels, and that of Miall (1977), a function of sinuosity and braiding. Both include four basic types (Figure 36):



straight (Figure 37), meandering, braided and anastomosed. Another alternative is the Rosgen classification system, as a function of channel slope, channel material, width-depth ratio, sinuosity, and the entrenchment ratio.

With respect to stream's relationship with the types and effects of floods, a basic flood pattern can be defined in each type of stream. While floods in braided rivers involve a successive occupation of the channel system through the connection of the threads of contiguous streams by order of their elevation (Figure 38), meandering rivers are associated with a rapid occupation of the floodplain (Figure 39) and of the scrolls of the point bar. In the same way, the stream's type affects the flood hydrograph, levelling it in the case of meandering and anastomosed rivers (fluvial floods), and propagating it rapidly in the case of straight rivers (torrential floods).

Another important aspect related to the type of the channel is the stability of the bed over time and the types of morphological changes that can occur. Rivers with straight channels are usually very stable, since their banks are usually of silt and clay that do not erode easily. And if there is bedload, it is translated in the form of bars which migrate downstream and subject the banks to alternating degrees erosion. In meandering and anastomosed rivers in which suspended loads are predominant, the banks' stability is also high, but translation or lateral migration may occur downstream from the meanders, which can end up getting choked. Although the channels of all these types of rivers with predominantly suspended loads are generally stable, if a deposit in the form of a natural dike or dike is generated on its banks, a rupture could occur during a flash flood, causing the channel to suddenly deviate to a new position (avulsion).

The increase in total sediment load and the proportion of bedload, coupled with the unstable processes which characterise meandering rivers, create other types of instabilities in the channel. This also leads to meanders being cut off by overflow channels or chutes. The migration of channel bars causes constant changes in the flow and, consequently, changes in where the banks are eroded. Rivers with braided channels are even more unstable. The thalweg and the bars migrate constantly, causing significant erosion of the banks. Avulsion, or a sudden change in the course of the channel to a new position, is a very frequent phenomenon.

## FLUVIAL MORPHODYNAMICS AND MORPHOLOGICAL EVOLUTION

### *Fluvial action during floods*

During a flood event a notable change is produced in the stream's velocity fields, which involves a modification in the spatial distribution of the points where the basic, fundamental actions of fluvial processes (erosion, transport, and sedimentation) and their concatenations are produced. The well-known Hjulström (1935) empirical graph explains how, with uniform channel bed particles, an increase in stream velocity similar to that which would occur during a flood causes a shift from the prevalence of sedimentation or transport to the prevalence of remobilisation-erosion.

But not only is there a change in the basic action at each point of the fluvial channel; the ways in which the action is produced also change. Erosion occurs by means of abrasion, corrasion and cavitation, with corrosion being relatively less important. For uniform particle size, transport tends to change as velocity increases from an area in which translation and traction are prevalent towards saltation and suspension, with a decrease in the ratio of fall velocity to friction velocity ( $v_f/u_*$ ). Deposition is basically produced by load abandonment, when settling and precipitation are restricted to areas of ineffective flow where water normally is not circulated.

Similarly, Lane's proportionality ratio (1955;  $Q_s D_{50} \propto QS$ ), when applied to a flood event, means that an increase in discharge ( $Q$ ) corresponds with a decrease in channel slope ( $S$ ), or more likely, to an increase in sediment load. This can be quantitative (increase in solid flow,  $Q_s$ ), or qualitative (increase in diameter of material transported,  $D_{50}$ ).



### *Fluvial landforms associated with floods*

During floods, characteristic landforms are produced in streams and their banks. These morphologies can be grouped according to two basic criteria: plan of the space in which they are characterized (plan view, profile or section of channel; Table 7); or erosion type: deposition and mixed (Figure 41).

The first group includes grooves caused by over-digging in the bed (linear channels, smooth surfaces, scars, flute marks) and overhangs created by the sapping of the banks or bank escarpments and natural dikes, both due to the temporary increase in water velocity on the outer meander banks, steps in the bed or plan view narrowings that produce the onset of supercritical flow. For more detailed information on these morphologies see Baker (1988). This erosive capacity increases the stream's load, which is already high due to the evacuating effect of material pre-"prepared" in the channel (due to landslides, weathering, alluvial cones, etc.; Garzón, 1985), and consequently changes its hydraulic parameters (such as density) causing its erosive action to be more effective in a characteristic feedback effect.

Basically, sedimentary landforms are located in channel banks, inside the river bed, such as crevasse splays, sand ribbons, sedimentation layers (termed "tarquín" [silt] in Spanish), the migration and growth of longitudinal, lateral and transversal bars with straight or undulating ridges, or the formation of accretions associated with obstacles to streamflow. See the compilation by Baker and Kochel (1988) or local studies by Moya *et al.* (1998) and the McKee *et al.* classic. (1967).

One of the most characteristic mixed morphologies of streams as far as floods are concerned is the inbank capacity or bankfull channel, supposedly associated with a given flood discharge or bankfull discharge. There have been countless studies seeking to characterize the morphology of this channel section based on minimum width/depth ratios, characteristic escarpments on the banks, changes in the vegetation along the banks, or by the granulometry (grain sizes) of the channel, or hydrological determination by assigning a given return period to the bankfull discharge (Lewin, 1989). This channel section receives such a label since it is assumed to play a dominant role in the channel's morphological configuration (self-forming) and is the one with the most load-bearing capacity and efficacy (particularly bedload; Batalla and Sala, 1994). Although it has a notable spatial variability in the mid-latitude regions, a return period of 1.58 years is usually associated with this discharge. In other words, it occurs an average of twice every three years. In Spain it has been made the equivalent of the maximum ordinary flood elicited in the Spanish Water Act<sup>42</sup>, with the return period varying between 1.1 and 9.8 years with an average of 3.7 years and a standard deviation of 0.6 (CEDEX, 1994).

At the mesoscale, some floods usually modify the channel's geometry. For this to take place, certain thresholds must be surpassed (limit conditions) that can cause the system (alluvial plain) to go outside its metastable equilibrium (Díez and Pedraza, 1996). Within the section, concatenated effects can be compensated for and yield results quite similar to those of the initial state. However, from the plan view the consequences are more significant, causing meanders to be cut (cut-offs and bottlenecks), avulsions, changes in the channel pattern, as well as modifications in some elements of the channel, such as breaches of natural dikes or occupation of abandoned channels in the plain. The type of process depends on the type of the channel, as previously explained.

### SPATIAL LAYOUT OF FLUVIAL FORMS: THE FLUVIAL SYSTEM AND ITS ZONES

According to the classic Davis models, the evolution of a fluvial system in time involves a shift from torrential stages to wide floodplains. The network's morphometric parameters and indices vary progressively with time, modifying the types and characteristics of floods produced and, above all, the flood inundations linked with them. Therefore, the initial stages in the landscape's evolution are linked to torrential floods, with a spatial distribution restricted to the channels and their banks. In contrast, the final stages, corresponding to the peneplain (Davis) or the ultimate plain (Penck) are associated with sheet floods which affect extensive areas of coalescent floodplains that make up a peneplain.

<sup>42</sup> *Ley de Aguas.*

**Table 7.** Classification of fluvial landforms associated with floods, with attention on their impact on the pattern, longitudinal and/or cross-sectional profile (Díez 2001-2005 and 2002a).

PLANE		MESOFORM	MICROFORM AND/OR ACTION			
X-Y PATTERN	Straight channels	Restored channels (decreased S index)				
		Channels with undulating walls				
	Meandering channels	Meander bends moved due to ...	Extension			
			Rotation			
			Translation			
			Variation in $\lambda$			
		Meander bends abandoned by ...	Cutting off			
Constriction						
Avulsion channels						
Braided channels		Highly braided channels (increase in B index)				
Anastomosed channels		Highly anastomosed channels (increase in B and S)				
X-Z PROFILE	Uniform	Flat beds				
		Rapids				
	Irregular	Steps				
		Pools	Pools and fords			
			Cascade pools			
			Step-pools			
Y-Z CROSS-SECTION	EROSION LANDFORMS	Macroforms ( $> Dm$ )	Innermost or inner channels			
			Canyons			
			Expansion of bank escarpments			
		Mesoforms ( $> m$ )	Smooth and faceted	Smooth surfaces		
				Faceted boulders		
			Scour marks	Scroll bars		
				Giant potholes		
			Armour surfaces			
		Microforms ( $< m$ )	Flutes			
			Microfacets			
			Transverse landforms			
			Flute marks			
			Pits			
			Striations			
			Potholes			
			Erosive escarpments			
	DEPOSITIONAL LANDFORMS	Microforms ( $< dm$ )	Ripples			
			Linear deposits (level marks)	Silt lines		
				Float bands (inflows)		
			Desiccation cracks			
		Mesoforms ( $> dm$ ) and Macroforms ( $> Dm$ )	Bars and benches	Side	Longitudinal	
					Meander (point)	
				Central and diagonal	Longitudinal	
					Transverse	
				Obstacle	Lee-side	
					Stoss side	
			Natural dike		Linear	
					Splayed	
			Dunes and megaripples		Straight-crested	
					Undulating crest	
			Beds and laminae (cross-stratification)			
			Lobes, splays, and belts		Fan-shaped	
					Elongated	
			Fans and cones		Tributary confluence	
					River mouth	







a) Pebble and cobble bar or bench with a characteristic armour layer and imbrication of clasts, indicating the direction that the stream took during the flood (from right to left).



b) Bench or bed of large metric boulders and rocks deposited in a widening of the valley after a debris flow.



c) Metric boulder or rock mobilized by traction during a debris flow and stopped by vegetation crushing and covering it.



d) Cobble and pebble crevasse splay lobe formed after a flash flood by the dismantling of the railway embankment (bottom of the photo).



e) Inner channel due to excessive digging in the clayey deposits of the bed of the floodplain after a flood.



f) Deposit of a pebble and boulder splay lobe with the characteristic reverse grading, in other words, the finer materials in the lower part and the larger material in the upper.

**Figure 41.** Fluvial landforms and deposits associated with floods (reproduced from Díez 2001-2005 and Díez-Herrero, 2002).





g) Secondary flood channel with a sandy bed where undulating crest megaripples can be seen with submetric amplitude; these indicate the direction of the bottom current in the foreground of the photo.



h) Sand bar in the form of a cohoide deposited after an obstacle to the flood flow (tree stump), indicating the flow direction from left to right and the minimum depth that the water level reached.



i) Mixed deposition-erosion formation on a floodplain equivalent to a small, smoothed escarpment (centre of the photo) between two terrace flats (left and right).



j) Linear float band deposit composed of vegetation detritus (known as "arribazones" [beds] in certain regions of Spain); marks the minimum level reached by the water table during the flood, and successive sublevels of stabilization.



k) Alluvial cone in a confluence between two tributary streams with the characteristic sub-triangular morphology generated in a single flood event and where the damming of the highway (bottom left) marked the base level of deposition.

**Figura 41.** (Continuation)







**Figure 42.** Examples of the three types of fluvial landscapes where floods are produced: torrent headland in Venero Claro (Ávila, left); middle reach of the river Guadalquivir in Alcolea (top right); and its mouth in Doñana (bottom right).

The fluvial system is formed by a set of landforms related to one another in an orderly fashion (i.e., the catchment and its stream network) and is usually divided into classifications (Schumm, 1977) of zones dominated by the production of sediment (erosion) in the headlands, the transfer of sediment load (transport) in the middle reaches, and the deposition of sediment at the river mouth. The extent of spatial development and the geomorphological processes that occur in each of these zones produce the three basic types of geomorphological contexts in which inundations are produced during floods and play a very decisive role in determining what types of floods they are (Figure 42):

- a) This is the characteristic zone of the upper reaches of the catchment or headlands and, as such, it usually occupies relatively mountainous regions. This zone is composed of slopes that drain toward torrents, streams, and riverbeds, which generally have bedrock beds or are braided. The prevailing processes here are water catchment and sediment production, with little development of the transfer zone and almost no deposition area. The floods typical of this zone are called “upstream floods” and affect the upper parts of the basin exclusively and are usually produced by intense rains of short duration over a more or less small area. While their effects can be significant, they affect only a limited area of the catchment and usually do not produce overbank flows in the main rivers with which they converge downstream. This type of phenomenon often happens suddenly (flash flood). Floods resulting from rapid snowmelt due to a sudden increase in temperature, sometimes accompanied by rain, in the months of spring and late winter are also characteristic of these zones.

- b) Fundamentally composed of a set of main streams or channels that transport water and sediment from zone a) to zone c). This is the characteristic zone of the middle reaches of drainage catchments and usually occupies the interior, flat regions. Therefore, the transfer zone is prevalent here, with the headland sediment production being less frequent. Typically, it contains alluvial stream channels, the most common of which are meanders. Flooding occurs in the transfer zone itself due to the overflow of a single, main channel which inundates an elongated floodplain in which two areas can be distinguished: outlet of intense flow (effective flow or floodway) and margins with ineffective flow (fringes). Examples of this type of floods are those produced by large rivers in middle reaches: Ebro in Zaragoza, Duero in Zamora, Tajo in Aranjuez, Guadalquivir in Seville, etc.
- c) Area largely reserved for the deposition of the system's transported sediment load. It is the characteristic zone of the lower reaches of catchment basins and usually occupies piedmont areas, inner basins or coastal areas. In other words, areas near the mouths of rivers draining to the sea, a lake, or an inner playa. The sediment load is usually limited to finer fractions extending over wide regions with a very gradual slope and which constitute alluvial fans of large dimensions, deltas, and estuaries. The channels are meandering or straight and can split downstream into several distributary channels. Floods that are produced in the depositional zone are laminar, shallow, and have a low flow velocity, affecting wide expanses. The floods of the Ebro delta or those produced in the Guadalquivir marshes are characteristic examples.

The floods most typical of zones b) and c) are those termed "downstream" and are those produced by prolonged sustained rainfall phenomena which saturate the soil and produce a significant increase in the basin system's runoff. While the overflows in the small headland tributaries are not particularly significant, the runoff from all of them converges in the main channel or channels, producing a single flood wave characterized by a hydrograph with a relatively long concentration curve and an even longer depletion curve. Overflows of the main channels in these zones (middle and lower reaches) can last several days.

This general regime can be marked by a multitude of variants. When zone a) suddenly opens onto to a more flat area (alluvial plain, a higher-order river or a piedmont plain), it can give rise to the formation of a limited deposition area, i.e., a zone c) characterized by an alluvial cone or fan, with hardly any sediment transfer reach, or zone b. The resulting flood in the sedimentation zone is thus very sudden (flash flood), and there is frequent avulsion of the distributary channels and flooding due to semi-laminar flow in active lobes. An example of this type of flood is the one produced in the alluvial cone of the Arás ravine (Biescas, Huesca) during the flash flood event in August of 1996.

Another similar instance occurs in mountainous regions near the coast, where there can be almost immediate transitions from zones a) to c). In such cases, a fan delta or alluvial fan is usually formed. This scenario is very common in several places on the Spanish Mediterranean coast, where torrential rains are combined with mesoscale convective systems (cold droplets). These floods are rather sudden and generally have a significant sediment load, such as the one which occurred at the mouth of the Albuñol gully in 1973 (La Rabita, Granada) or the more recent ones in Almuñecar of 2007.

### **2.2.2. METHODS AND SOURCES OF DATA FOR THE GEOMORPHOLOGICAL ANALYSIS AND MAPPING OF FLUVIAL LANDFORMS**

#### **LITERATURE ON METHODS AND PROCESSES IN FLUVIAL GEOMORPHOLOGY**

Extensive literature exists on fluvial geomorphology that is applicable to the descriptive research, analysis, and mapping of fluvial landforms and deposits associated with floods that can be consulted for the application of geomorphological methods in flood hazard research.

Some of the books available in Spanish were written by Spanish authors, such as: Sandoval (1991), Pedraza *et al.* (1996), Muñoz (1992) and Gutiérrez Elorza (1994 and 2008); as translations of manuals and classic foreign



treatises of general geomorphology including chapters dedicated to fluvial geomorphology, for example, the works of Passarge (1931), Holmes (1960), Martonne (1964-68), Bloom (1974), Strahler (1974), Derruau (1978), Rice (1983), Tarbuck and Lutgens (1999).

English-language literature is more abundant, of which classic books on fluvial geomorphology should be noted, such as: Leopold *et al.* (1964), Morisawa (1968 and 1985), Schumm (1977), Knighton (1984), Baker *et al.* (1988), Beven & Carling (1989); or those from French-speaking authors, such as Pardé (1955).

There are other interesting articles, book chapters and journals which specifically focus on the classification and use of the fluvial landforms of floods in Spanish case studies. Some examples follow: La Roca and Carmona (1983), López and Gutiérrez (1983), Puigdefábregas (1983), Durán *et al.* (1985), Martínez *et al.* (1986-87 and 1987), Moya *et al.* (1998), Díez (2001-05 and 2002), Ortega and Garzón (2002 and 2006), Ortega (2003 and 2007). Numerous other local studies can be found in the database compilation "*Documentación sobre Inundaciones y Riesgos asociados de España*" (Documentation on Floods and Associated Risks in Spain), made available and updated at <http://www.riada.es/>.

To obtain information on aspects of regional geomorphology and a bibliographical compilation of the area under study, refer to the collective work "*Geomorphology of Spain*" (Gutiérrez Elorza, 1994), the "*Geomorphological Map of Spain*" and its report (Martín-Serrano, 2005) and the "*Physical Guide to the Rivers of Spain*" (Arenillas and Sáenz, 1987).

## FLUVIAL GEOMORPHOLOGICAL MAPPING METHODS AND PROCESSES APPLIED TO FLOOD HAZARDS

The geomorphological characterization of fluvial landforms associated with floods (Table 7) is accomplished by means of classic methods of mapping and description of landforms and deposits, using both vertical aerial stereoscopic pair photo interpretation (different dates and scales) and interpreting basic mapping (morphometry, hydrographs, toponymy) and thematic mapping (geological maps, geomorphological, surface formations, active processes). In addition, characterization requires field runs to check the mapping to resolve problematic regions, evaluate the level of activity of active processes, and determine the power and origin of surface formations, particularly those of fluvial-torrential origin. At the same time, the required geological-lithological characterization of zones, assessment of the climate and soil context, and analysis of the surface and groundwater hydrological dynamics are done.

The specific development of geomorphological maps and the application of specific techniques such as stereo photo interpretation and landform identification in the field can be read about in books such as: López-Vergara (1988), Morisawa (1976), Garzón (1978), Herrero (1988), Pedraza *et al.* (1988), Centeno *et al.* (1994), and Peña Monné (1997).

In simplified terms, the preparation of sound geomorphological map for use in flood hazard mapping requires two steps which are consecutive but complementary: delimiting cartographic units and elements and assigning them hazard levels or one of their parameters (recurrence level, severity, temporal distribution).

### *Delimiting of geomorphological elements*

The first aspect, demarcating mapping units and elements on the geomorphological map, can be done in very different ways and styles, giving rise to the different types of geomorphological maps (Peña Monné, 1997). There are two broad groups of geomorphological maps:

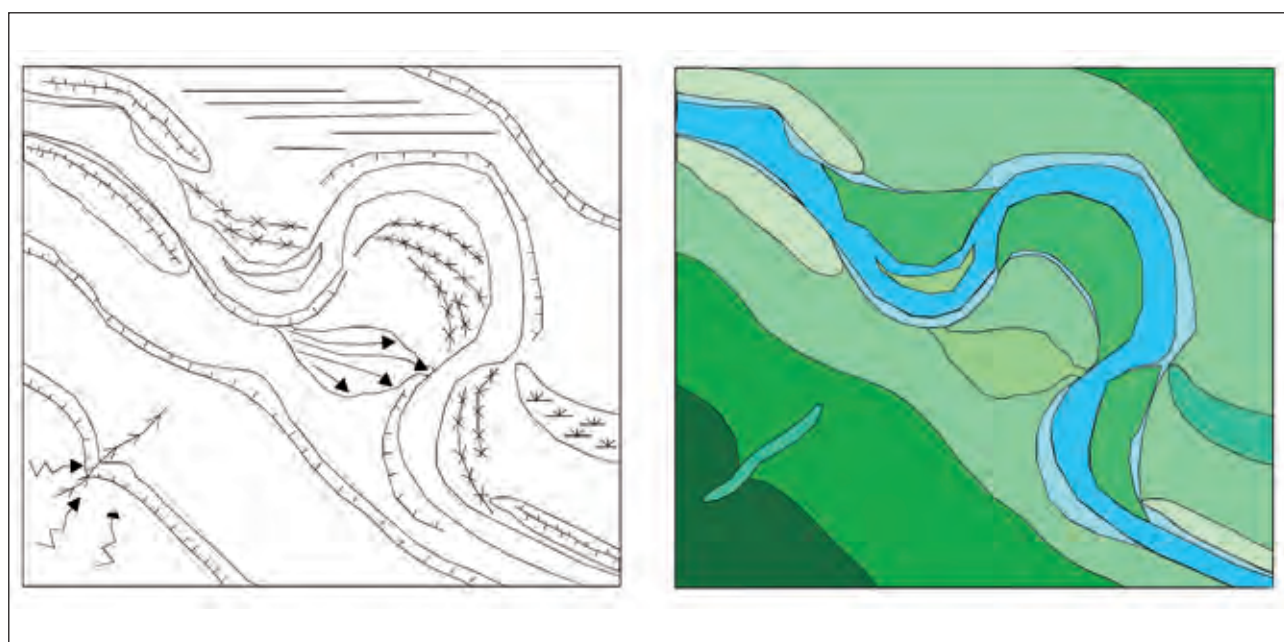
- Maps based on the morphogenetic classification of the terrain and done with an analytical focus, for which there is essentially a representation of elements.

- Maps based on the physiographic classification of the terrain, generally done with a derivative approach and on which there is usually a representation of units, either hierarchical or not.

The maps that are most useful for hazard mapping are physiographic-derivative since they are usually more appropriate for applied purposes (Martín Duque, 2000).

The better applicability of physiographic geomorphological maps, which represent detailed homogeneous geomorphological units (landforms), are worthwhile in that the elements they contain (for example, “land system” processes) cover the entire terrain with polygonal units (enclosure with area), which you can couple with other environmental variables. Moreover, a hazard rating can be assigned to a group belonging to a zone with apparent homogenous behaviour. For example, a characteristic unit of this mapping system would be the floodplain of a river which, within itself, has an areal entity and topological relationships with other contiguous units. The first maps of this type were done at a regional scale for areas of the USA between the late 19th century and the early 20th century. They attained maximum development and popularity for their application in Australian regions in late 1960. In Spain, physiographic geomorphological maps have not been used much. However, of note are the projects carried out by the University of Cantabria (Cendrero *et al.*, 1976; Díaz de Terán, 1985) and the University of Madrid [UCM] (Martínez de Pisón *et al.*, 1977; Pedraza and Garzón, 1978; Pedraza *et al.*, 1986 and 1997; Martín Duque, 1997), all essentially for the purposes of land planning and environmental and landscape design. Of particular interest are physiographic geomorphological maps that have been used to prepare hazard and susceptibility maps related to geological processes (Martín Duque *et al.*, 2003; Santos *et al.*, 2006).

The other area of geomorphological mapping, with a more analytic and morphogenetic focus, is usually centred on academic and research activities, and is much more widespread and established in Spain. The resulting maps are usually very well documented and complex and include data on morphometry, morphography, morphogenesis, morphochronology, morphodynamics, as well as lithology and hydrography (Garzón, 1978; Peña Monné, 1997; Martín-Serrano *et al.*, 2004-08). This type of mapping combines point, line, and areal elements, with the first two not necessarily needing to be included, nor needing to contain homogenous units.



**Figure 43.** Sections of two idealised geomorphological maps of the same zone: one with a morphogenetic focus (left) and the other physiographic (right). Note the point, line, and polygonal elements in the first map, while the second only has polygonal elements.



**Table 8.** Example of equivalences or correspondences between elements and units of morphogenetic geomorphological mapping and those of physiographic mapping for some flood-related landforms and deposits. The numbers in parentheses following after each morphogenetic map element correspond to their code in the legend proposed by Peña Monné (1997).

MORPHOGENETIC OR ANALYTICAL MAPPING ELEMENT (point, line, or open area)	PHYSIOGRAPHIC OR DERIVATIVE MAPPING UNIT (closed polygon)
Escarpsments in Quaternary deposits (138), dashed lines for slope on the banks of both margins	Low flow or bankfull stage
Abandoned channels (128), outline of the outer boundaries of both margins	Abandoned channel
Lines of lateral accretion (148)	Area of lateral accretion
Lateral erosion of the channel (149)	Section with lateral erosion of the channel
Crest of natural dike or levee	Natural dike, levee, or groin
Change in slope in the levee base	

The areal elements do not have to be closed polygons. This situation creates the need for the establishment of new closed polygonal enclosures using these point, line and open elements (Figure 43). For example, an element of this map could be a polygenic erosive escarpment of a river bank, which would be a simple line with its normal symbology, but for which it is necessary to establish relationships with the opposite bank escarpment (if any) so as to be able to define an areal unit (in this case, the low flow or bankfull stage). This transformation from morphogenetic mapping to the physiographic format is not easy, since there are elements of the former which do not permit immediate assimilation into the latter, and other elements which, for their lack of cartographic boundary definition, would require new reviews through aerial photography, consultation of basic and thematic mapping, and field work. In the case of the basic flood-related fluvial landforms usually covered in these morphogenetic maps (Peña Monné, 1997; Martín-Serrano *et al.*, 2004-08), this transformation can be done through equivalence or correspondence tables (Table 8).

Finally, it should be pointed out that some mapping methods try to combine different focuses and means of representation, for example, the Dutch ITC method (Verstappen and Van Zuidam, 1991). Among these we should mention the methodology proposed by IGME (Martín-Serrano *et al.*, 2004), in which geomorphological mapping was unfolded in a Geomorphological Map (in the strict sense of the word) and in a Map of Active Processes. Both maps were developed with an analytic focus and are based on morphogenetic classifications. A third, more derivative map can be added in the future if desired: a Geomorphological Units Map, comprised entirely of polygonal mapping enclosures with associated information about active processes that can occur in each unit. Accordingly, a dynamic view related to the active processes is added to the static representation of relief landforms and surface formations typical of more traditional geomorphological maps.

The representation scales for delimiting the elements and units will depend largely on the purpose of the study, its scope (detailed, local, regional, etc.) and the initial information available (topographic data, aerial photographs, etc.). Generally, it is preferable to work with the largest scale possible (highest level of detail), even if simplifications and generalizations are made later if the representation scale is smaller. If topographical or photographic information at appropriate scales is available and the objectives and timeframes of the project allow it, the ideal scales to obtain a geomorphological map focused on flood hazards vary between 1:2,000 and 1:5,000. However, the lack of available topographical data with sufficient resolution, or vertical aerial photographs for stereoscopic vision at detailed scales, means that a large portion of the geomorphological maps and diagrams must be done at standardized scales 1:50,000 and 1:25,000 (national topographic maps), 1:33,000 and



1:18,000 (typical scales in vertical aerial photographs), and 1:10,000 (typical for topographic maps for public administrations and orthophotographic maps). However, in recent years commercial satellite imagery has become available which is accessible to the scientific community with spatial resolutions in optical sensors of up to 50 cm (WorldView-1 from the end of 2007), allowing mapping at scales of great detail. Another great advance in satellite imagery is along-track stereoscopy integrated into the images of SPOT-5, ASTER, IKONOS, QuickBird and WorldView-1. This technique allows stereoscopic pairs to be obtained in the same pass, making it easier to correlate them (E. García-Meléndez, pers. com.). There are other sources of information as well which, although they do not support stereo vision (or digital elevation support is not sufficient), can serve as an orientation and reference. These are Google Maps, Yahoo Maps and other aerial imagery servers constantly evolving and developing.

Regarding preferences which information sources to use for mapping, for topographic data, the highest resolution takes priority (larger scale, lower equidistance or smaller pixel size) since the detail elements are better-defined, with the morphometry acting as a fundamental aid in realising the geomorphological map. However, many times higher-detail data, such as from digital elevation models (DEM) originating from LIDAR images (whose resolution can be up to 1x1 m), can contain too much information, which can be counterproductive if 'background noise' is detected or if huge quantities of information render it untenable to work with in optimal conditions, making it necessary to perform generalization or simplification.

Concerning aerial photographs and images, it is always preferable to work in a combination of vertical aerial photograms suited for stereo vision (essential for delimiting landforms) and orthophotographs which, when geo-referenced, permit accurate mapping directly on them. Additionally, in both cases preference should be given to the highest resolution and detail (larger scales and/or smaller pixel sizes) and to the latest update versions. This does not mean one cannot use several sets of photographs and orthophotographs sequenced over time, which shows the temporal evolution of landforms and deposits to be mapped and to deduce their possible future evolution. Further, with a wider range of dates during which there is an absence of vegetation or less anthropic occupation of the terrain, it is easier to identify landforms and their delineation. In this respect, it must be pointed out that the first flights for national coverage, carried out in the forties and late fifties of last century, show a geomorphological state very near the one rivers would show in a natural hydrological regime. This is because they are presented before or at the same time as the large hydrological regulation projects, such as dams, and the extensive hydrological-forestry reforestation of the catchment headlands. Therefore, the analysis of these old photographs is of the utmost interest in the assessment of morphological impacts on the channel and its metamorphosis.

All things being equal, colour photograms and images are preferable to those in greyscale, since some deposits and lithologies of the substrate are more easily identifiable and distinguishable and the colours of the vegetation can be useful to a certain extent. However, there are usually problems relative to the grain quality or size of photograms, since the emulsions used for panchromatic photographs in black and white allow much better image quality than those used for colour photographs. For this reason, many geomorphologists prefer classic panchromatic photographs in greyscale, since experience has shown that their use and the high quality images that they produce enable better identification of landforms and deposits based on characteristic textures and tones.

### *Assigning hazard levels to geomorphological elements*

The difficulty of assigning a hazard level to every mapped geomorphological unit and element has been the age-old Achilles' heel of geomorphological methods. However, several assessments and investigations show that not only is it possible to assign a hazard, or at least one of its parameters, there is a better correspondence between this assignment and empirical evidence (flood frequency, velocities, and depths, etc.) than when other methods are used.



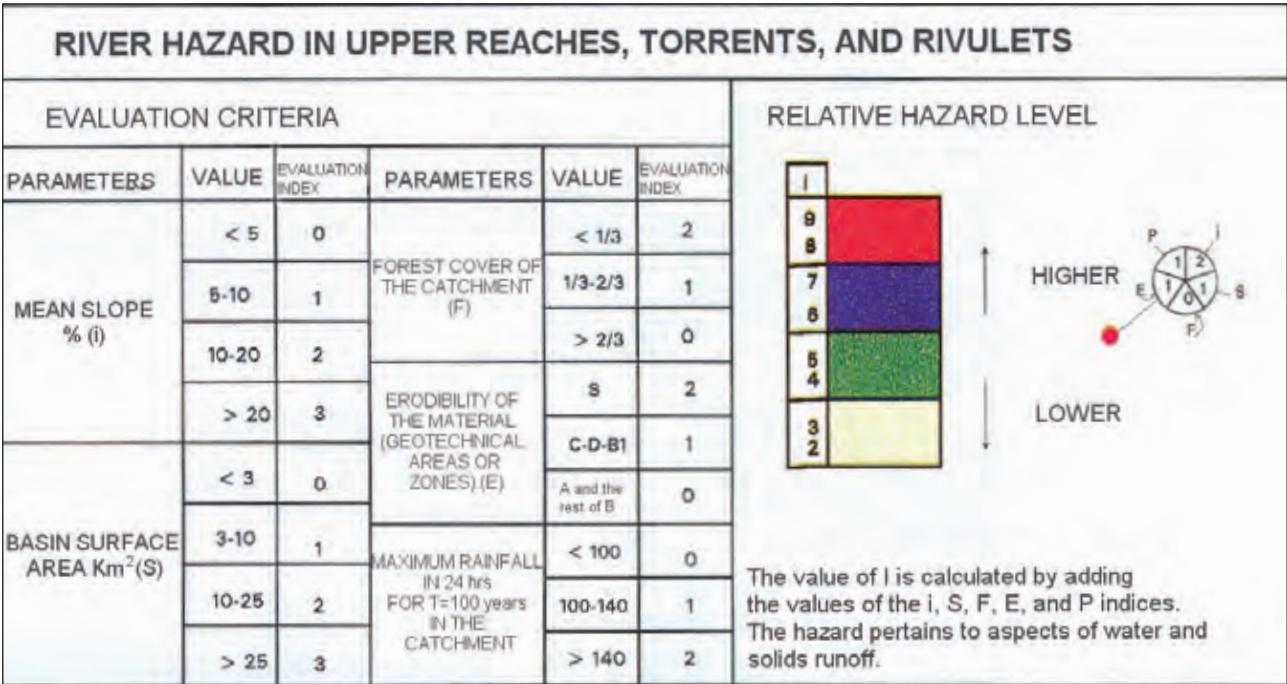


Figure 44. Section of the flood hazard map legend for rivers in upper reaches, torrents, and rivulets of the Central Pyrenees of Huesca (Mulas and Fresno in Ríos, 2001). In this legend a qualitative hazard valuation is carried out based on different parameters.

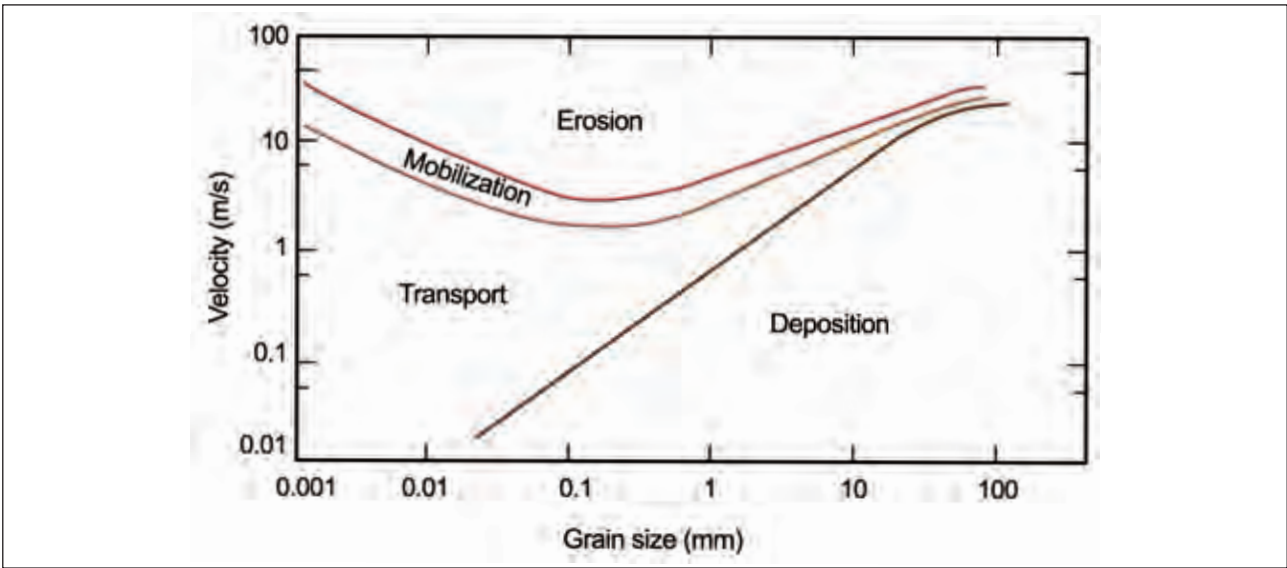
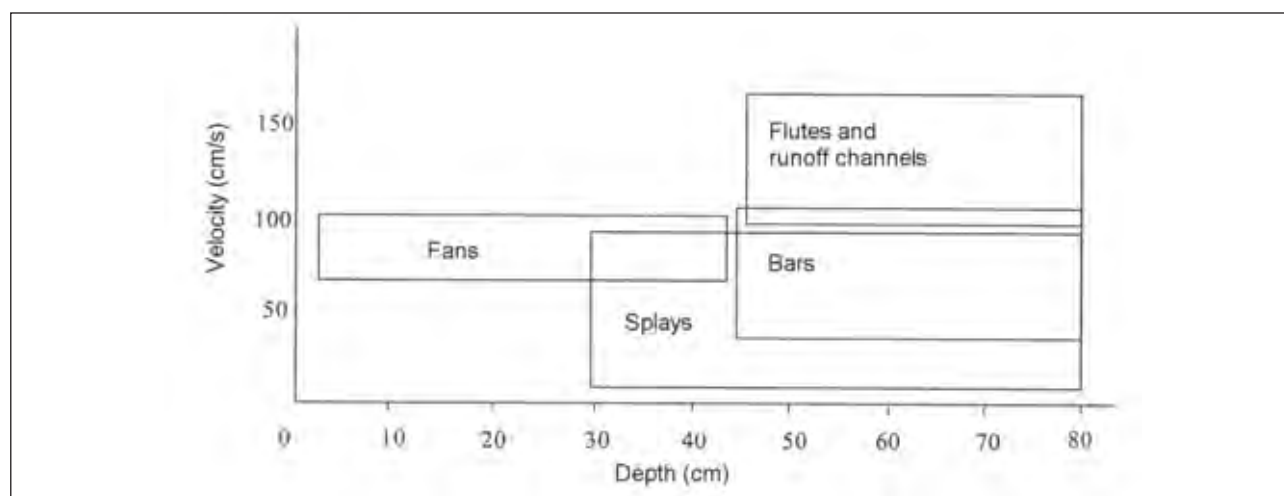


Figure 45. The Hjulström diagram (1935).

Broadly speaking, there are two approaches to assigning hazards: qualitative, attributing only some generic and relative degrees of hazard (high, medium, low) to each unit; or quantitative, testing indices which allow parameters to be fixed such as frequency, velocity, depth, sediment load, etc. or at least their minimum and maximum thresholds and variation ranges.

For the first approach, the qualitative assignment of flood hazards to the units of a geomorphological map, the technician must have significant experience with an extensive background in these assessments, as well as a comprehensive view of the entire area to be studied, in order to establish relative scales. For this purpose, lev-



**Figure 46.** Graph with stability boxes on a velocity-depth graph for sedimentary landforms produced by the inundation of the Rivillas river in three analyzed reaches (Ortega and Garzón, 2006).

els of detail of the active processes maps are especially useful (Martín-Serrano *et al.*, 2004-08) and the criteria used in them (Figure 44).

The quantitative approach is of far greater interest, since certain mapped landforms and deposits, depending on their position, size, lithological and textural composition, and level of conservation and vegetation colonization, make it possible to delimit parameter ranges such as stream velocity and depth, flood event durations, sediment load transported, or an area's flood frequency.

For the estimation of velocity and depth ranges, graphs and tables are particularly useful since, as they are often obtained in laboratory tests in design channels, they establish stability ranges for landforms and deposits (from the classic Hjulström graph (Figure 45) for modern sedimentological studies (Figure 46). More useful yet are studies in which these ranges are established for natural landforms and deposits, in which geomorphological studies coupled with detailed hydraulic modelling render patterns closer to the physical reality of the process (Magilligan *et al.*, 1998; Ortega and Garzón, 2006).



**Figure 47.** Physical models to scale can be useful for the study of sediment load transport and deposition. For example, the embankment formed by discarded concrete is an excellent analogy for all channel types and depositional landforms in torrential floods (channels, natural dikes or dikes, lobes, etc.).

Sediment load transported during different types of flood events that can affect an area can be inferred as much by observing the configuration of deposits in the different units as by their lithological and textural distribution. Likewise, in mapped depositional units, sedimentological sequences can be established to interpret depositional media and environments and, based on the reconstruction of the flood's dynamics, to reconstruct sediment load (Benito *et al.*, 2003b). For example, the presence of climbing ripples allows a minimal content in sediment load transported to be deduced.

To assign a flood frequency or recurrence level to each unit, qualitative scales of the landforms' conservation levels can be used, depending on how "degraded" the geomorphological elements most sensitive to erosion are (distinct escarpments, sharp ridges and troughs...) in relation to the rate of action of other geomorphological processes (diffused arroyo flood, wind, ice) that affect them after they are formed during the flood (Salazar and Martín-Serrano, 2006).

Of course, this assignment of flood frequencies and recurrence intervals to each unit of the geomorphological map is done with great accuracy when these methods are coupled with other techniques, such as historical-documentary data gathered from surveying local inhabitants (Marquínez *et al.*, 2006a and b; Lastra *et al.*, 2008), historical flood databases (Barnolas and Llasat, 2007), or coupled with botanical methods using distribution patterns of ages, species and/or covers (Díez-Herrero *et al.*, 2008a).

### 2.2.3. METHODS FOR ESTIMATING SEDIMENT LOAD TRANSPORTED BY A STREAM

In Spain, most rivers manifest torrent dynamics due to both the steep slopes of the channels and the rainfall regime. Nearly all victims caused by overbank flows of natural watercourses are produced precisely in small catchments where steep slope conditions converge with the torrentiality process, and where the volume of sediment transported by the stream plays an essential role in the destructive capacity of the flood.

The incorporation of sediment load in a stream aggravates the overflow situation, as much through the effects of the impact of sediment load and the injuries caused to people and infrastructure as through the increase in flow density, which produces a feedback effect by contributing greater transport capacity and greater erosive capacity. If indeed part of this sediment load incorporated into the flow comes from the channel bed itself (which theoretically implies an increase in the stream capacity to evacuate the flood discharge), it is also true that the incorporation of sediment into the stream increases the flow's viscosity and the roughness of the bed, which ultimately gives rise to a very sharp rise in the water surface elevation compared to that which would be produced in conditions with clear water and fixed bed.

There are three major groups of methodologies for approximating sediment load transported by a stream:

- Equations and models rooted in hydraulics (see Section 2.1.2)
- Empirical methods of erosion and sediment yield
- Qualitative estimation methods

#### EMPIRICAL METHODS OF EROSION AND SEDIMENT YIELD

There are several ways to approximate the quantity of sediments that a stream can entrain as a flood event develops. One of the most widely used methods is known as MUSLE (Modified Universal Soil Loss Equation [Williams, 1975]), which is based on the following equation:

$$Y = 11.8 \cdot (Q \cdot q_p)^{0.56} K \cdot L \cdot S \cdot C \cdot P$$

Where:

$Y$  is the sediment yield of the catchment (t).

$Q$  is the volume of storm water runoff in cubic meters ( $m^3$ ).

$q_p$  is the maximum discharge velocity ( $m^3/s$ ).

And the other factors are the same as in the Universal Soil Loss Equation (USLE):

$K$  is the soil erodibility factor. It is the rate of soil loss per unit erodibility index (EI) for a specific soil, measured in a portion of standard terrain (22.13 m in length, 9% slope, in cultivated, continuous fallow).

$L$  is the slope length factor, proportion of soil loss along a specific slope with respect to a standard slope (22.13 m).

$S$  is the slope magnitude factor, the proportion of soil loss of a surface with a specific slope with respect to that of a standard slope of 9%, with all other factors identical.

$C$  is the cropping management factor, the proportion of soil loss of a surface with specific vegetation and management with respect to a surface identical in cultivated, continuous fallow.

$P$  is the erosion-control practice factor, the proportion of soil loss with an erosion-control practice such as contour farming, live barriers, or terracing, with regard to those cultivation methods along the direction of the slope (Food and Agriculture Organization of the United Nations [FAO], 1994).

The  $Y$  units are converted to t/ha when  $Q$  is in mm and  $q_p$  is in mm/ha. The runoff factor ( $Q \times q_p$ ) supplies a source of energy and as the runoff rate per surface unit decreases proportionally to the increase of surface drainage, the model gives a rate of implicit soil loss. MUSLE is useful for catchments with surfaces of around 100 km<sup>2</sup>.

This methodology has been successfully tested and calibrated in Spanish catchments, where variations of little or no significance between the empirical estimations and actual rates measured are observed (Bodoque *et al.* 2001).

## QUALITATIVE ESTIMATION METHODS

Other implementation methods which are less costly, but effective in terms of qualitative results of the relative probability that flood hazard factors will be triggered by sediment load can include the gathering of evidence from channels subject to frequent debris flows (Santos and Menéndez, 2006) or following multivariate analysis procedures by means of GIS (IGME, 2007). This last procedure establishes the probability of geological landforms producing sediment (in terms of theoretical capacity) susceptible of being incorporated as sediment discharge in a flood event. It involves using a weighted reclassification of lithological maps and surface formations derived from the geological map and various routines for estimating the slope values of the streams to be analyzed (maximum flow length and maximum and minimum depths of the catchments analyzed, derived from a DEM). Once the sediment load is estimated, it is compared with the slope in the form of a hazard matrix (or a flood aggravating factor).

### 2.2.4. LITHOLOGICAL INFLUENCE ON THE RAINFALL-RUNOFF TRANSFORMATION PROCESS

The formation of soil (in the edaphic sense) and its textural and compositional characteristics which determine its drainage capacity, is controlled by several factors which can be summarized as: Characteristics of the bedrock terrain slope, type and extent of vegetation cover, and evolution time.

To the extent the bedrock is the lithology of the substrate, the petrologic composition of a terrain determines





the type of potential soil which can be formed, and therefore its behaviour in the rainfall-runoff transformation process. However, this determining factor is neither linear nor univocal, and different types of geological substrates can give rise to soils with similar hydrological properties and vice versa. A single type of rock from the substrate can create soils with very different hydrological behaviours.

In an attempt to characterize the hydrological response of the soils which could potentially come about over specific lithologies, it is important to start by identifying the textural characteristics of the alteration products of these rocks, in other words, the characteristic regoliths of their physical-chemical weathering processes.

In this way, acidic igneous rocks (granite series, rhyolite), tend to form sandy regoliths rich in quartz yielding soils with high drainage capacity by infiltration. Unlike igneous rocks, mixed sedimentary rocks, such as marls, usually form clay-loam regoliths with very poor drainage properties. To quantify this determining factor using the system of classifying soils according to their hydrological behaviour designed by the SCS (1972), we would first have a Type A soil, while the second would correspond to a Type D soil. Depending on the slope and vegetation or type of cultivation method, this can cause the runoff threshold to vary, even in the order of magnitude.

The so-called surface formations deserve separate mention. These are lithological bodies normally comprised of recently formed (Quaternary) and poorly consolidated detrital sedimentary rocks. Oftentimes, due to their thinness, irregular geometry, and low spatial continuity, they are not properly represented on geological maps, especially those of small scale (scant detail). Nevertheless, owing to their position on the uppermost surface of the crust, they are the principal determining factor of hydrological behaviour of the substrate and of the potential soils that form over them. It is therefore not surprising that apparent discrepancies between the lithologies appearing on the map and the actual hydrological behaviour of the zone should arise, given that the presence of a surface formation over this lithology was not taken into account.

In light of the foregoing, one of the partial or sectorial hazard maps that can be constructed consists of a reclassification of lithological maps based on the hydrological behaviour of the potential soils which could form over these lithologies (e.g., A, B, C, and D, according to SCS, 1972). Obviously, this would only make sense in the absence of a soil map (edaphic) with classes adjusted more closely to their hydrological behaviour.

#### **2.2.5. HYDROGEOLOGICAL CRITERIA FOR THE ASSESSMENT OF FLOODS CAUSED BY RISING WATER TABLE**

One of the most common types of surface flooding, which is relatively little studied, is the covering of low-lying areas and depressions due to the rise of an aquifer's water table above the land surface.

An aquifer can be defined as a geological formation capable of storing and transporting groundwater in significant enough quantities for it to be used. Depending on the hydrostatic pressure of the water contained in them, they can be classified as: unconfined (free, phreatic), confined (artesian), or semi-confined. In the case of unconfined aquifers, the upper boundary of the groundwater contained in the geological formation forms a surface that is in contact with the air contained in the unsaturated zone, at atmospheric pressure, which is referred to as the phreatic surface or water table. The distance between the land surface and the water table determines the water table's elevation.

A rise in the water table above the land surface results in groundwater flooding. This rise can be annual (seasonal), year-to-year (wet and dry climate sequences), or one-time caused by sporadic events.

In general, zones where the water table is near the surface and, in particular, the areas of aquifer discharge which often coincide with the low lying areas, are places prone to such phenomena. The discharge areas are characterized by a piezometric level increasing in depth and the possible presence of water wells or springs that indicate an excess of moisture. Rainfall which produces a rapid recharge and, therefore, a rise in the water table, causes flood inundation from ponding on the land surface.



**Figure 48.** Application of hydrogeological analysis techniques for the risk assessment of groundwater flooding in Villacañas (Toledo), by IGME: measuring the piezometric level using a water level probe (left) and measuring the in situ conductivity (right).

This type of flooding occurs as much in detrital aquifers as in carbonate rock karst aquifers. These carbonate aquifers, which are depressions such as poljes (e.g., Zafarraya), dolines, uvalas, etc., comprise areas prone to these types of processes. They can also give rise to the formation of lakes, lagoons, or accumulations of small bodies of water, such as pools, swamps, bogs, marshes, mires, etc. in the lowest lying areas of endorheic zones with unconfined aquifers and surface water tables.

Obviously, the use of the proper criteria and techniques of hydrogeology is of fundamental importance in the analysis and mapping of this type of flood. For this reason, at a minimum, and in a very condensed fashion, a geological and hydrogeological map should be constructed which identifies the aquifer levels of interest and how they are related in the event two or more levels are superimposed. Additionally, an inventory of water points of the zone should be taken (water wells, pools, piezometers, etc.) in an attempt to extract all possible information (lithological columns, levels, discharges, sample analyses, etc.; Figure 48). Based on this information, systematic measurements of the water table depth should be established that reference the correct topographical levelling, which allow piezometric maps to be created at different stages and whose interpretation will make it possible to identify the movement of and model groundwater flow.

This basic hydrogeological information, in conjunction with sufficient knowledge of surface hydrology and the distribution, duration, intensity, and frequency of precipitation will permit an assessment of these types of risks.

## ***2.3. Historical and palaeohydrological Methods***

### **2.3.1. HISTORICAL METHODS**

Historical methods involve the use of historical documentation (manuscripts and printed matter from archives, libraries, and periodicals collections), oral and audiovisual testimonies (photographs, drawings, historical map-

ping, etc.) and markings on artificial elements (buildings, communication paths, public works, etc.) or natural elements (rocks and trees) along a river's banks in order to reconstruct the area covered or height reached by the waters in a flood which occurred during the historical period. This methodology is based on the assumption that if water has reached certain levels once, it can also reach them in the not too distant future, making this a 'historical flood' zone. Rather more sophisticated are studies which use hydraulic models to transpose these levels to streamflows and assign them a certain probability, allowing them to be introduced as complementary data (non-systematic) into the frequency analysis of actual streamflows measured using standard methods.

There are essentially three phases in utilizing these information sources: searching for and compiling the documentation; analyzing and interpreting the information, and integrating the data into a flood frequency analysis.

## SEARCHING FOR AND COMPILING HISTORICAL DOCUMENTATION

The main sources of historical information are archives (civil and those kept by churches), periodicals collections, libraries and surveys and interviews, where one can find files, press items (Figure 49), books, and audio-visual testimonies, respectively. From all of the available sources, a selection must be made based on reliability, credibility and how the information is organized (Barnolas and Llasat, 2007). There are also markings and plaques (Figure 50) placed by witnesses or victims on natural elements (rocks or trees) or buildings and infrastructure (bridges).

One problem, at the outset, is the actual definition and concept of historical flood, since various professional

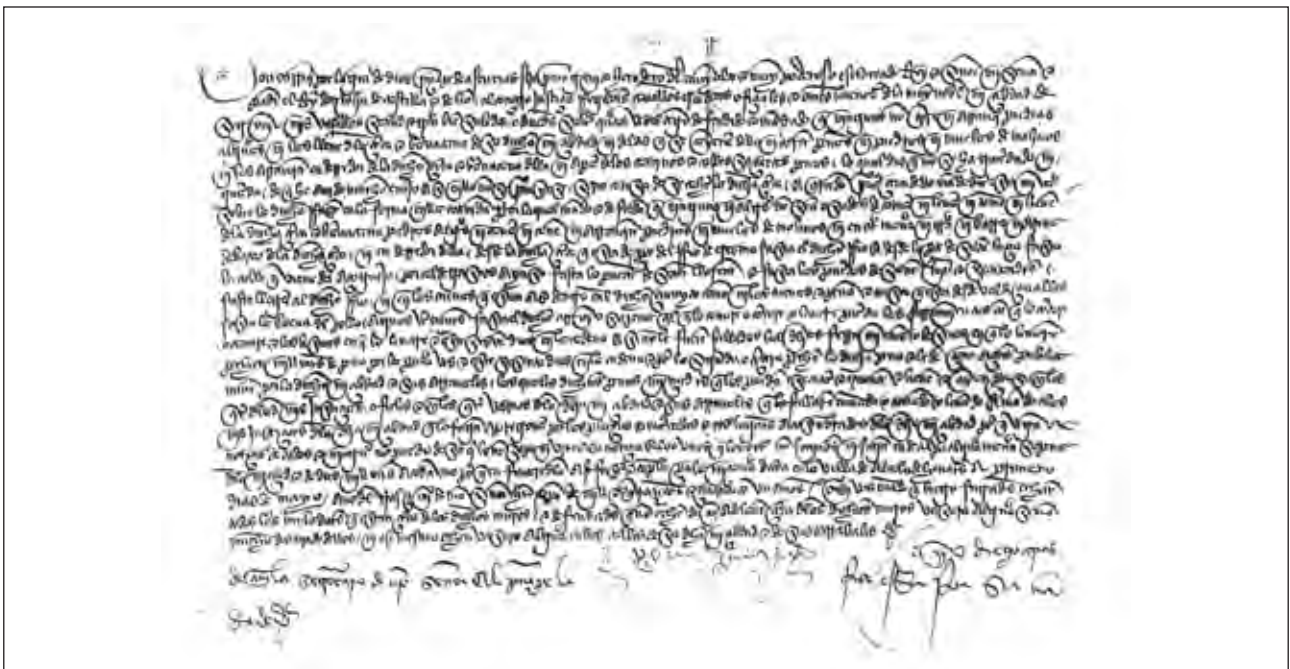


Figure 49. Example of a news item featuring a historical flood of the Alberche river, taken from the El Diario de Ávila newspaper archives.





**Figure 50.** Historical flood markings and plaques placed on anthropogenic elements: a) Virgen de la Poveda Sanctuary (Villa del Prado, Madrid); b) interior of a church in a suburb on the banks of the Duero (Zamora); c) door of Sandeman cellars (Oporto, Portugal); d) arcades of the Casa Consistorial in Burgos; e) the Torre del Oro (Seville).



**Figure 51.** Archival document signed by Enrique IV in the mid-15<sup>th</sup> century which dictates norms for avoiding the effects of natural disasters. Example of an historical information source which, to be understood, must be transcribed using palaeographic techniques.

groups (historians, engineers, geologists) and different periods in history have varying degrees of perception and tolerance thresholds as to what should be considered an historical flood. Furthermore, variations in the extent of anthropic use of river banks over the course of history may also lead to erroneous interpretation for lack of information from eras during which the floodplain was used little, or – quite the opposite – overemphasized interpretation due to intensive use of the same area (Llorente Isidro, *et al.* 2007).

An excellent, up-to-date compilation of research on historical floods in Spain can be found in Barriendos and Rodrigo (2006) and Barnolas and Llasat (2007).

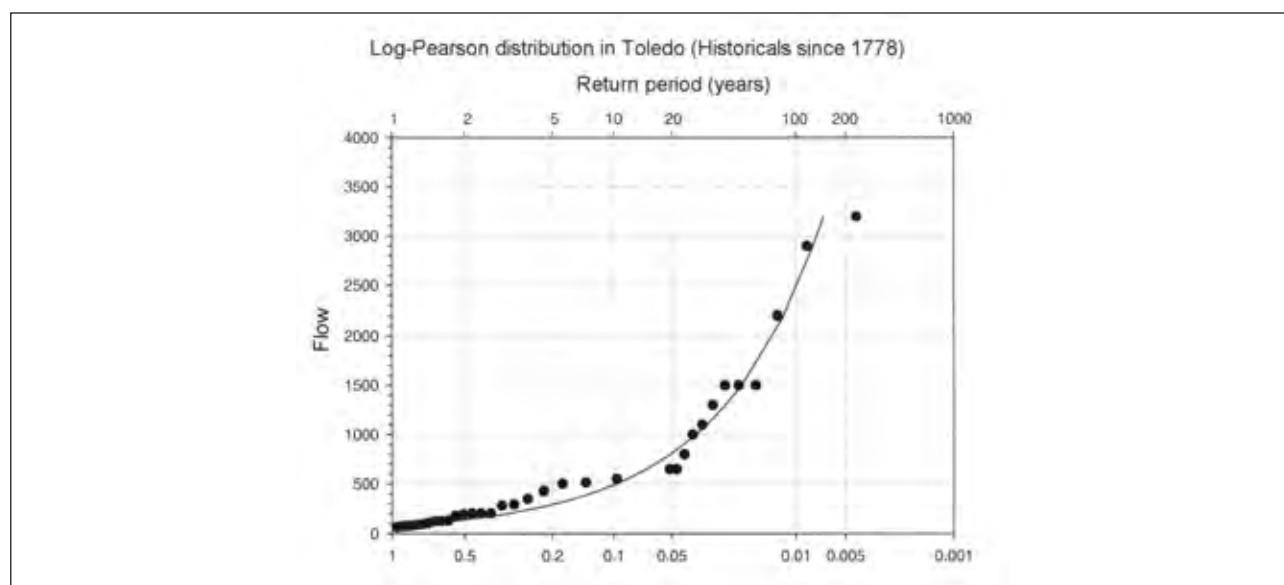
## ANALYSING AND INTERPRETING HISTORICAL INFORMATION

Once the meaning of historical flood is understood, delimiting the time period to be considered and the aforementioned perception threshold, the flood's magnitude can be assessed. This is achieved by studying its impacts (Barnolas and Llasat, 2007): direct, such as damage to housing, mills, bridges, walls, streets, etc., or indirect or deferred, such as rises in transport and communications costs, problems with crops, supply shortages, rogations, etc.

Information that could possibly be obtained from documentary record is: dating of the flood, dating of the phenomenon which triggered the flood, identification of the cause, a quantitative and qualitative description of the phenomenon, and a quantitative and qualitative description of the impacts and effects. Complementary information can also be compiled, whether conventional (historical mapping, records from construction, fire fighting and government activity) or non-conventional (epigraphy, oral history, photography, video recordings; Barriendos and Coeur, 2004; Barnolas and Llasat, 2007).

Initial processing of the information involves gaining an understanding of the texts and documents, which requires mastering palaeographic techniques for writing types which differ from modern ones (Figure 51), understanding different levels of writing quality (formal, informal and cryptic) and being familiar with lexical aspects.





**Figure 52.** Fitted frequency distribution function for the peak discharges of the Tajo river in Toledo, incorporating the flows of historical floods since the late 18<sup>th</sup> century into the systematic series (Uribe Larrea *et al.*, 2004).

Next, it is crucial that the dates be converted, both in terms of chronology (when eras and calendars other than our own are used) and metrology (when measurement units which differ from the international system are used). To that end, the annexes in Barriendos and Coeur (2004) containing compilations of chronologies, measurement units (equivalencies between those most commonly-used in the western Mediterranean and the international metric system) and conversion charts between different calendars are particularly useful.

Finally, the floods must be classified according to their behaviour, magnitude and the impacts they produce. One qualitative classification system accepted internationally is the one proposed by Barriendos and Coeur (2004): ordinary flood, any event without clear proof of overflow; extraordinary flood, event with proof of overflow but without damages, or with reports of mild damage to some hydraulic infrastructure; and catastrophic flood, an event with proof of overflow producing serious damage or complete destruction of some type of city infrastructure. Subcategories have been established between these three, depending on the case being studied and the availability of information (Barnolas and Llasat, 2007).

All of the information obtained and properly analysed and processed is stored for integrated analysis using database management systems (Pascual and Bustamente, 2008), and sometimes georeferencing the references by connecting to geographical information systems (Díez *et al.*, 1998; Díez *et al.*, 2003; Barnolas and Llasat, 2007).

Finally, quantitative magnitudes (flow, velocity, energy, water surface level) are obtained from the direct impacts (and, to a lesser extent, from the indirect ones) using hydraulic methods and models (see section 2.1.2), although in a manner adapted to specific use with historical data (Lang *et al.*, 2004).

## INTEGRATING THE DATA INTO FLOOD FREQUENCY ANALYSES

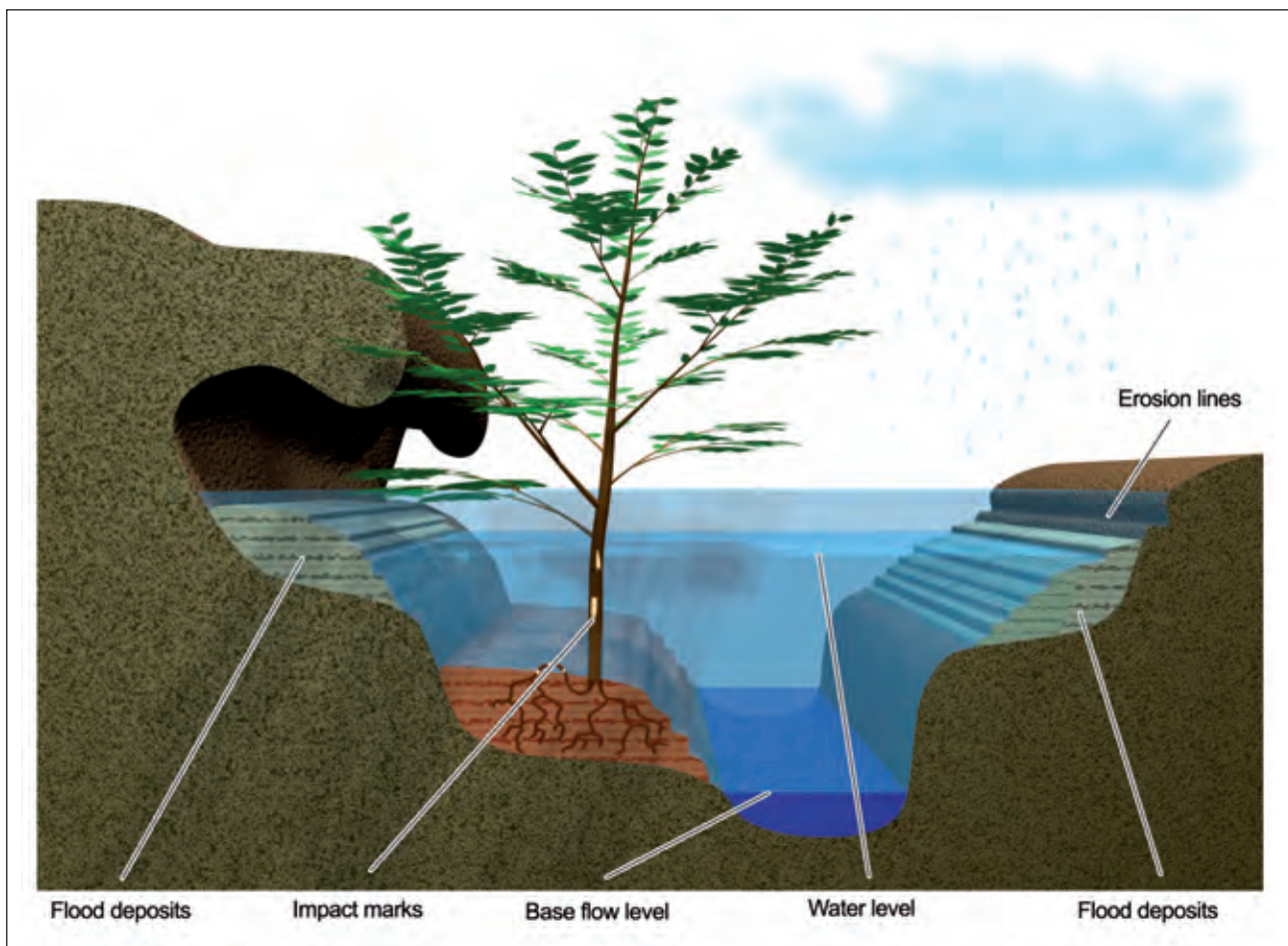
The quantitative and qualitative information about the historical flood events and their relative frequency can be integrated into flood event frequency analyses in very different ways. From the simplest techniques, which used empirical formulas to assign different sample frequencies to historical data in respect of data obtained from systematic flow records (USWRC, 1981; Figure 52), to the modern methodologies which use specific fre-

quency distribution functions for non-systematic information (Francés, 2004a), remarkable advances have been achieved in this field in recent decades.

The analysis starts with the classification of the non-systematic data by type (Francés *et al.*, 1991; Francés, 2004): EX (exact flood value), LB (exceeds a lower boundary), UB (did not reach an upper boundary) or DB (known upper and lower boundaries). Next, the data are fitted to a stationary statistical model, with its distribution function and parameter estimation method. Many of these distribution functions are based on the establishment of thresholds on water level and then estimating the degree and frequency of their exceedance. A few noteworthy examples are ETEV, LN4 and EV4 (Francés, 2004a).

### 2.3.2. PALAEOHYDROLOGICAL METHODS

From an etymological point of view, any analysis and information source of past flood events (gauging station records, historical floods, dendrogeomorphological and lichenometric data, etc.) can be considered part of the scope of Palaeohydrology. However, in scientific literature the term palaeoflood and the use of paelohydrological methods are usually restricted to the study of sources of information drawn from geological-sedimentological records. These records may include reconstructions based on flow competence and which utilize Palaeostage indicators. This does not necessarily imply that palaeofloods studied using these methods have to have occurred thousands of years ago; to the contrary, historical and recent floods for which there is no other systematic or documentary information can be studied.



**Figure 53.** Places where deposits and markings useful for palaeohydrological purposes are often found. Modified version of G. Benito.





**Figure 54.** Slack-water deposits as an overlap or shelter in the wall of Duratón canyon (Segovia), with a close-up shot of the sedimentary structures characteristic of these deposits (Díez-Herrero et al., 2005).

#### METHODS BASED ON FLOW COMPETENCE

These methods are based the relationship between the characteristics of the sediments and deposits generated during or after a flood event and the characteristics of the flow during the same event (Benito, 2002). Some of the most frequently established relationships are the correlations between the size and shape of sediments and transport capacity, from which are inferred such parameters as velocity, drag force, etc., which in turn are used

to estimate palaeodischarges using hydraulic models. There are also formulas which relate these sizes to the critical shear stress or critical discharge necessary to mobilise them.

Normally, for the study of palaeofloods, very thick particles are used, such as pebbles, boulders and large boulders, and among them, those with the greatest volumes or sizes (diameters; Carling, 2002). Nevertheless, there is no univocal, simple relationship between hydraulic power and these measurements. There are unknowns resulting from other factors, such as the shape of the particles, armouring, fluid density, roughness, etc. (Benito, 2002).

## METHODS BASED ON PALAEOSTAGE INDICATORS

Commonly referred to in international literature as PSIs, palaeostage indicators include accumulations of sediments, dendrogeomorphological and botanical evidence, erosion lines and other geological evidence. In general, the information obtained with these palaeostage indicators corresponds to the minimum height reached by the water table during the flood which produced the indicators. However, some of these indicators (clay lines, accumulations of small amounts of organic matter, slackwater deposits) are formed in areas of the bank very near the maximum flood level and indicate rather precisely the maximum height reached by the waters during the palaeoflood (Figure 53).

Of all the PSIs, slackwater deposits stand out for their usefulness and broad temporal span. They normally consist of sequences of fine detritus sediments (sand, silt and clay), slightly hardened, and with thicknesses ranging from a few millimetres to several meters. These sediments appear by forming accretions (benches) in ineffective flow areas, such as tributary mouths at the main channel, confluences, channel expansions, meander curves, cavities and rocky shelters along the banks (Figure 54), among others. To study them, standard fluvial sedimentology tools and processes are used, such as differentiating between stages or units, describing trends in sediment grading and sedimentary structures, identifying sequences, interpreting depositional environments and sub-environments (Benito *et al.*, 2003b), identifying palaeoevents, etc. (Benito *et al.*, 2004a).

This is achieved by means of taking highly-detailed sediment columns and profiles (Figure 55), peels (Figure 56), sediment grading samples, etc. For the dating of each of the deposit levels, there are different radiometric dating methods which are useful for the Quaternary ( $^{14}\text{C}$ ,  $^{137}\text{Cs}$ , TL, OSL), both archaeological and palaeontological remains, correlating palaeopalynological sequences, etc. Although these indicators only show minimum levels reached by the flow, various studies have demonstrated that its height is close to that of the water table at flood peak (Benito, 2002).

With these palaeostage indicators, the flood's discharge and other physical are reconstituted using hydraulic formulas and models (see section 2.1.2), factoring in particularities arising from the necessity for the boundary conditions (topography, roughness) to have remained constant in time (Benito, 2002). Once the flows and their dating are determined, in order to incorporate the data into the flood frequency analysis along with the systematic records, frequency distribution functions and procedures similar to those used for factoring in historical flood data are used (section 2.3.1).

These techniques and methodologies have already been used with noteworthy success in terms of their ability to reproduce the frequency and magnitude of the probable floods in each period when applied to various areas in Spain: Tajo basin (Benito *et al.*, 2003), Segura basin (Benito *et al.*, 2006), Llobregat basin (Thorndycraft *et al.*, 2004, 2005a, and 2005b; Rico Herrero, 2004) and Guadiana (Ortega Becerril, 2007).

## PALAEOHYDROLOGICAL METHODS AND VARIABILITY INTRODUCED BY GLOBAL CHANGE

Where risk analysis and its representation in cartography are concerned, most legislation and recommendations in the last few decades place special emphasis on taking into consideration the uncertainties associated with the variations global change is producing and shall continue to produce in the future.



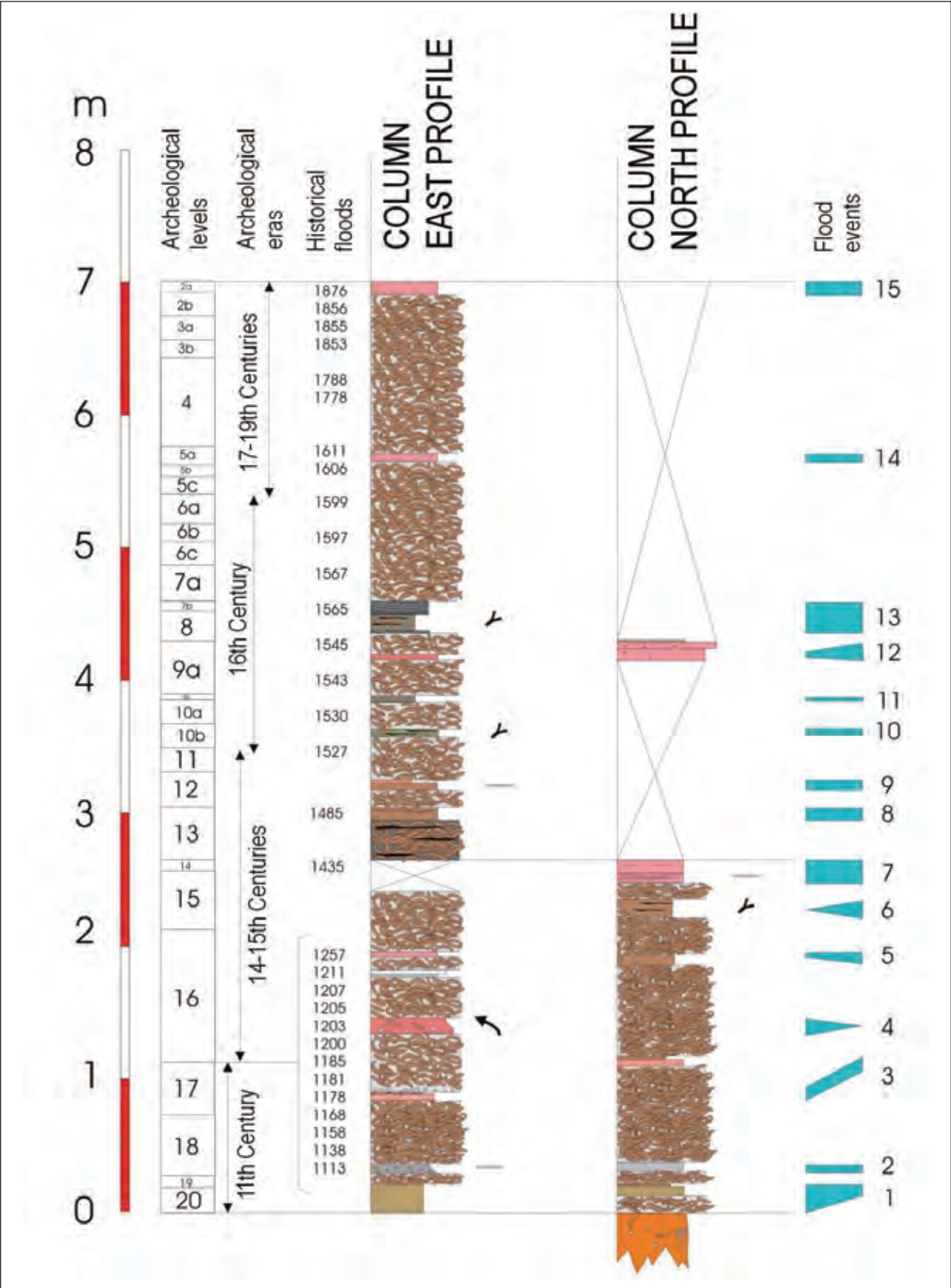


Figure 55. Steps involved in taking a peel of slack-water deposits for a sedimentological study. Rambla Mayor (Guadalestín basin, Almería-Murcia).



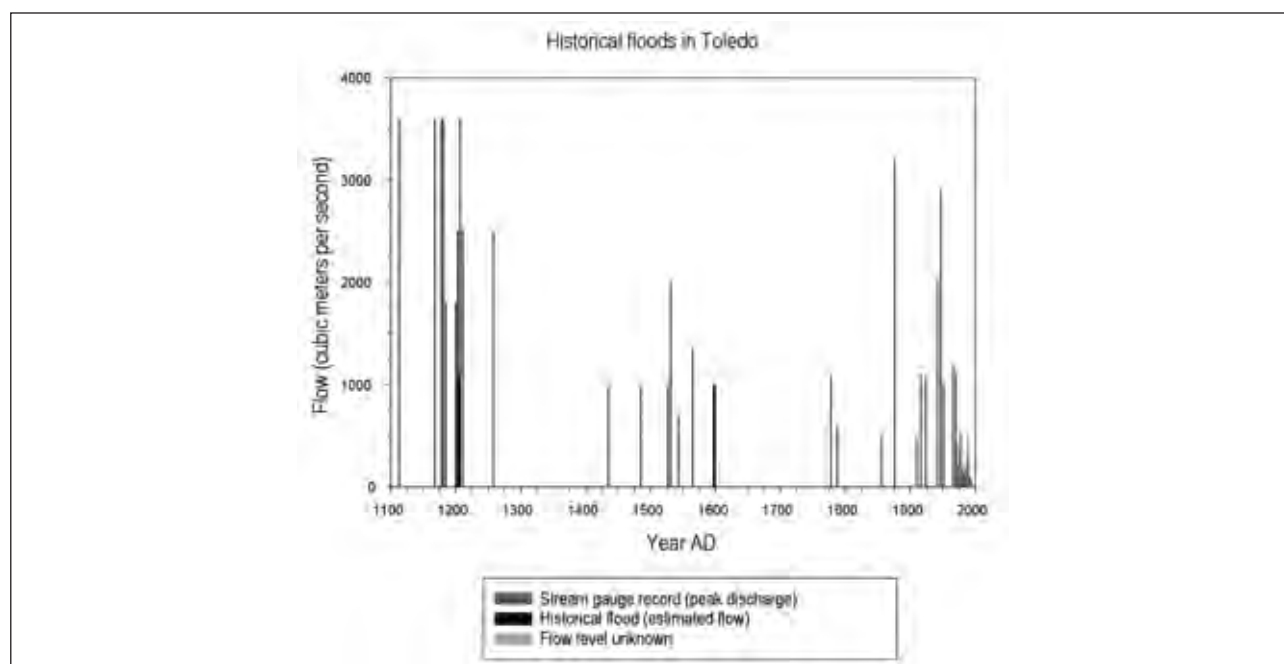




**Figure 56.** Steps involved in taking a peel of slack-water deposits for a sedimentological study. Rambla Mayor (Guadalentín basin, Almería-Murcia).

The process of considering these variations has yet to be resolved from a scientific-technical point of view, owing to the fact that uncertainties concerning the change's magnitude and tendency are compounded by a lack of understanding of how complex natural systems will respond to it (such as fluvial basins).

Some countries have decided to tackle this challenge by factoring a percentage of error in the estimation of risk analysis and associated maps, usually maximizing hazard (in this case, flood hazard), so as to err on the side of caution. This is true for certain central European countries, which increase design flows or calculation by 10-20% in order to take into account a potential future increase in the frequency and magnitude of floods. Another alternative, provided for in part by the European directive on the assessment and management of flood risks, is periodic review.



**Figure 57.** Variability in the frequency of historical floods in the past millennium in the Tajo basin in Toledo (Benito *et al.*, 2003a).

However, these broad-brush, simplistic approximations are not used in Spain's case, given that the enormous diversity of the types of basins, climatic situations and streams adds a spatial variability factor to the predictable effects of climate change. That is why a linear increase in calculation flows, although permitting us to remain on the safe side in some cases, could result in an overestimation of the hazard zones (flood hazard), which would be inappropriate for mapping intended for land-use planning, watershed management, civil protection and insurance systems.

As an alternative to this linear increase or overestimation, a study has been proposed on the frequency and magnitude behaviour of floods in historic or prehistoric time periods analogous to the forecasts by the IPCC for the next half-century, that is, to study floods from periods in which there was a temperature increase similar to that predicted for upcoming decades, for example the beginning of the so-called Medieval Warm Period (Figure 57), or the beginning of the Roman Warm Period (Llorente Isidro, 2007).

To study the frequency and magnitude of historical and prehistoric floods (palaeofloods), there are many methodology handbooks which can be applied to Spain in general or regions with analogous behaviour (Atlantic and Mediterranean watersheds). The works by Benito *et al.* in which contain summaries of the methodologies are worth consulting (2004).

An initial approximation which generally applies to all of Spain can be found in the article by Benito (2006), in which he concludes that modifications have been detected in the magnitude and frequency pattern of extreme flood events based on analyses of floods in the past 2500 years. Most of the changes occur in moments of climatic transition like the current one. Several periods in the Mediterranean watershed (1580-1620 and 1840-1870) and the Atlantic basins (1590-1610, 1730-1760, 1780-1810 and 1870-1900) are worth noting. What is more, in the 20<sup>th</sup> century, there are multiple signs of periods of increase in the frequency and magnitude of floods in the two watersheds, a clear indication of today's climate change.

In short, by observing the variations (increases or decreases) in the frequency and magnitude of the floods in different Spanish basins or watersheds for historical periods analogous to the predictions for upcoming decades, it is possible to estimate the percentage of variation (increase or decrease) of the design flows and associated

potentially flood-prone areas, all of which should be taken into account in flood hazard mapping. For large regions, the results of these studies may be an asymptote of maximum design discharge (similar or assimilable to the PMF), an increase or decrease percentage in peak flow values (and thus flow depths and velocities), or an oscillation range of the boundaries delimiting the hazard zones.

## **2.4. Other methods, techniques and information sources**

### **2.4.1. THE HYDROLOGICAL-HYDRAULIC METHOD BASED ON GEOMORPHOLOGY**

When hydrological-hydraulic criteria are to be used in a generalized, rapid manner using physical parameters as a basis, there is a useful, verified method which uses the relationship or ratio between the peak discharges associated with different return periods ( $Q_T$ ) and the overflow or bankfull discharge ( $Q_b$ ) as a qualitative indicator of the flood probability at a given point in the stream network (Díez and Garrote, 2008).

#### **DEVELOPING THE CRITERIUM CONCEPTUALLY AND METHODOLOGICALLY**

According to the definition in *The Basic Directive of Civil Protection Planning on Flood Risk*<sup>43</sup> (Official Gazette 14 February 1995), *flooding is the submersion of normally dry lands*. In the case of floods associated with river flows, this submersion implies that once the evacuation capacity of the river or stream's natural channel is exceeded, it overflows and the banks are overflowed. Therefore, from a conceptual perspective, river flooding is produced when the discharge exceeds the natural channel's drainage capacity, and it will be more frequent and of greater magnitude as this exceedance increases.

#### *Bankfull or overflow discharge*

A natural channel's drainage capacity is determined by the discharge which fits in the channel between geomorphological elements called escarpments or banks, escarpments measured in meters and located – in varying degrees of morphological definition – on both shores. This discharge is therefore called 'bankfull discharge' in scientific publications ( $Q_b$ ), since it equals the bank's topographical height and fills the basin. Any discharge which surpasses it results in the overflow of the banks, which normally occupy a relatively flat area referred to as a floodplain.

Bankfull discharges have other names or have other associated terms and definitions (Díez, 2001, 2003, 2004 and 2005a), such as:

- *Channel-forming discharge* ( $Q_c$ ); since the maximum geomorphic capacity in relation to the flow volume is attributed to it, that is, when this discharge is reached, the river is at maximum load and sediment transport capacity, thus causing morphological changes to the channel (see works by R. Batalla; ex. Batalla and Sala, 1994).
- *High-flow discharge*; as opposed to low-flow discharge, which defines the stream channel's lowest level.
- *Overflow discharge* (CEDEX, 1994); since it marks the limit beyond which the water overflows the channel capacity, inundating the banks.
- *Maximum Ordinary Flood*; this term, essentially defined from a hydrological perspective in the Spanish Water Act and the Regulations on Hydraulic Public Domain, has also been assimilated to the concept of overflow or bankfull discharge, and thus is included the geomorphological criteria referred to in the abovementioned legislation. However, this correlation gives rise to numerous problems, particularly in the channels of Spain's Mediterranean watershed, as has been evidenced in the studies and reports on the subject (CEDEX, 1994).

<sup>43</sup> *Directriz Básica de Planificación de Protección Civil ante el Riesgo de Inundaciones.*

Estimating overflow or bankfull discharge must be done using detailed hydraulic models, using topographies and bathymetries suited to the scale of the task, in addition to modelling hypotheses which are appropriate for the boundary conditions. Nevertheless, to simplify estimation, a plethora of scientific works have attempted to assimilate its value to that of different return period quantiles estimated from flood frequency analysis using series of stream gauges, and even hydrometeorological methods.

Conducted in the English-speaking world and only valid for the streams of the British Isles and the east coast of the US, the first works assigned values of one to three return period years for this discharge (1.58 Dury; 1.24<2.69 years, Woodyer); more specifically, some manuals put forward a value of 2.33 years of return period as a standard figure.

However, the studies carried out for the streams in the Iberian peninsula clearly demonstrate the enormous variability in these values depending, logically, on the stream's geomorphological characteristics (gradient, plan view arrangement, quantity and type of sediment load), as well as its feeding and hydrological regime. In this respect, the works carried out by CEDEX (1994) attempt to delimit and quantify the variability in the values of Spanish rivers and propose formulas like the following for estimating them:

$$\frac{Q_b}{Q_m} = 0.7 + 0.6 \cdot C_v$$

$$T(Q_{MCO}) = 5 \cdot C_v$$

Where:

$Q_b$  is bankfull discharge

$Q_m$  is the mean of instantaneous discharges throughout a 24-hour period

$C_v$  is the coefficient of variation

$T$  is the return period in years

$Q_{mop}$  is the maximum ordinary peak discharge.

In the latest version of the Hydrological Planning Instruction<sup>44</sup> (CEDEX, 2007a), these formulas and approximations for characterising flood regimes are ratified (pages 71 and 72). In particular, to characterize channel-forming discharge ( $Q_G$ ), which is equated to bankfull discharge ( $Q_b$ ), and to the maximum ordinary peak discharge ( $Q_{mop}$ ). This draft Instruction stipulates that the statistics must be calculated based on a series in natural regime which representative of the river's hydrological regime, with at least 20 years of data.

These calculations and spatial variability have been used and calibrated with excellent results in the studies IGME is conducting in the framework of the RICAM (*Flood Risk Analysis in Castilla-La Mancha for the Special Civil Protection Plan*) project. These variables were estimated for all of the maximum mean daily and instantaneous discharge series ( $Q_d$  and  $Q_{id}$ ) available for the gauging stations set up at non-regulated reaches (normally the headwaters) of the Tajo, Guadiana and Júcar river basins: the discharge return period values range from 3.5 to 6.3 years (IGME, 2007).

These formulas are thus proposed for each spatial area where flood zones are mapped (subbasin or a reach thereof), in accordance the requirements set forth in the Directive (page 72) while, wherever possible, validating the discharge value with hydraulic modelling of a representative reach for which precise information is available (above all topographical).

### Peak discharge for different return periods

Estimating peak discharge for different return periods, in the natural flow regime, can be approached using different methodologies, such as the regional analysis of estimated peak discharge frequencies (Mediero and Jiménez, 2007). But in order to obtain this data for a broader territory rather than a specific location, including

<sup>44</sup> Instrucción de Planificación hidrológica.





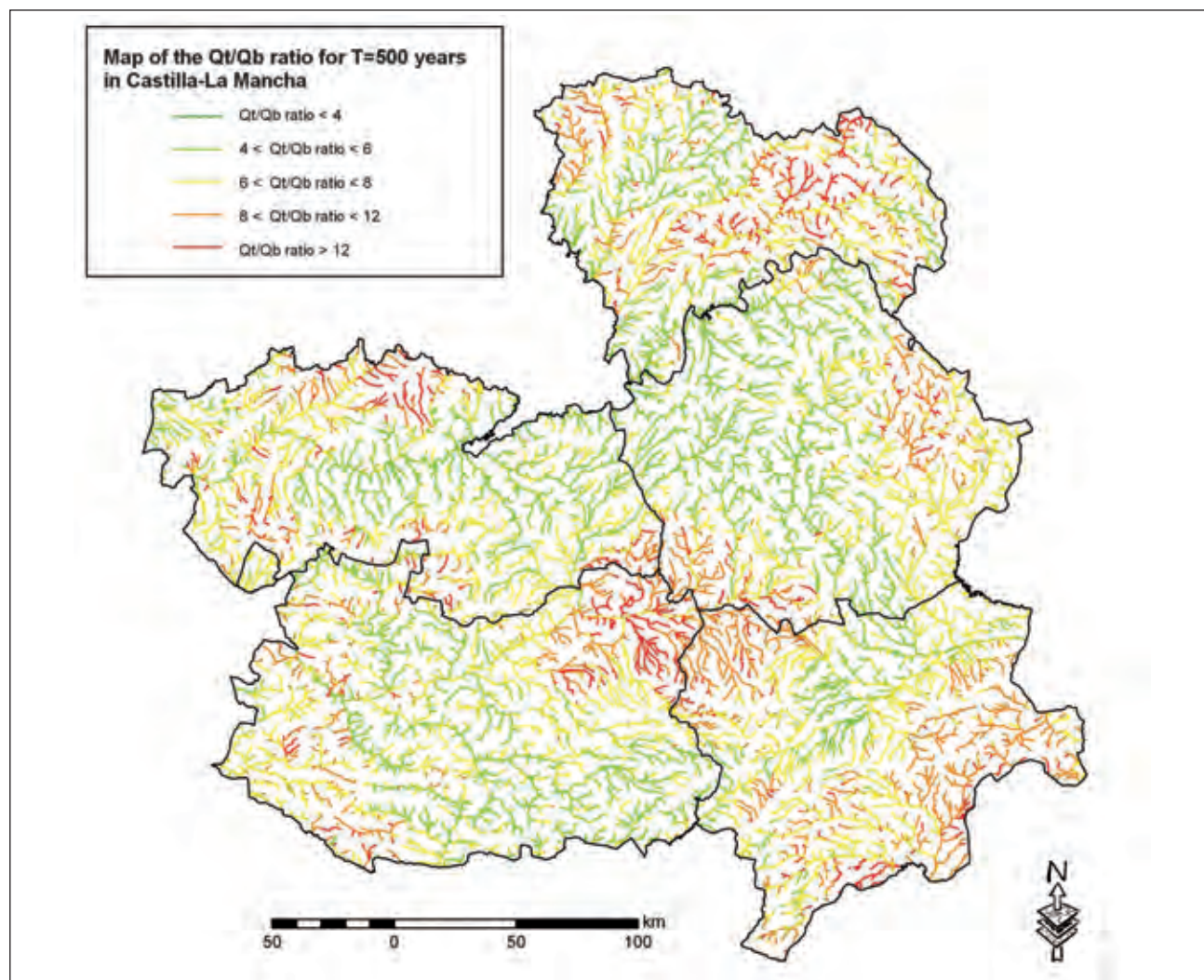
for ungauged catchments, perhaps the most feasible approach is to use hydrometeorological methods and the functionalities of geographical information systems to determine the spatial distribution of the initial abstractions and rainfall intensities and aggregate them.

This procedure was used to estimate peak discharge in natural flow regime, first for the Tajo basin, and then for the other intra-community basins (CEDEX, 2007b). It was also used to estimate peak discharge ( $T_{50}$ ,  $T_{100}$ , and  $T_{500}$ ) in natural flow regime for all streams in Castilla-La Mancha, both at points in the vicinity of population centres and at evenly-spaced points on the drainage network (IGME, 2007).

This estimation methodology is therefore perfectly valid for carrying out the estimation of  $Q_T$  values at the drainage network analysis and mapping points.

#### *The ratio or relationship between $Q_b$ and $Q_T$ values*

The relationship between the bankfull discharge values and the discharge quantiles for different return periods is a perfect indicator of the probability and magnitude of the overflow which will occur at each point of the stream network.



**Figure 58.** Map showing the relationship between the 500-year return period flood and bankfull discharge ( $Q_b$ ) based on 19,655 estimation points in the Castilla-La Mancha stream network. This is indicative of the risk of overflow in extraordinary floods (Díez et al., 2008b).

This ratio has already been used to measure the hazard associated with floods in different countries and regions around the world (Miller, 1997) and reproduced in many of the most widely-distributed books on natural risks (Ayala and Olcina, 2002). Today, though, it is being used in greater detail to categorize the flood hazard of sectors of the stream network in the context of the RICAM project, which has been quite successful (Díez *et al.*, 2008b; Figure 58).

Therefore, the goal is to estimate this relationship for each reach needing to be mapped in the territory, establish categories or classes of values for the ratio, and use these to assign a bankfull capacity to the point or reach, for example, of a given geomorphological unit or element (floodplain up to the first terrace, entire floodplain, or point bars only).

## **2.4.2. BOTANICAL TECHNIQUES AND INFORMATION SOURCES**

### **DENDROGEOMORPHOLOGY**

Applying traditional hydrological-hydraulic techniques to torrential basins in mountainous regions entails enormous scientific uncertainties related to the availability of the initial data (given the scarcity and even absence of meteorological and stream gauge stations), spatial-temporal validity (taking into account the irregular altitudinal distribution or concentration in urban centres in low-lying areas) and the temporal discontinuity of the series, and statistical representativity, when there are fewer than thirty data samples.

In such cases, in order to complete the systematic data records, non-systematic information, both historical and palaeohydrological, from geological records is typically used. Nevertheless, many of the areas analysed, especially in mountainous regions, do not have documentation on historical floods as they are far from administrative centres and places where documents are produced. Nor do they have records of flood deposits, since no detrital materials can be found in the source area, or places where they are likely to be deposited (due to the high speeds of the torrential dynamics) or kept in place. In light of this lack of initial data to build upon, it is very difficult to apply reliable statistical analyses or hydrometeorological modelling which is sufficiently calibrated and validated.

In these mountainous regions, fair amounts of wooded masses have been conserved because of soil-climate conditions and difficult access for land clearing. This, in turn, makes it easy and common to find arboreal vegetation – riparian or other species – in the torrential channels near the banks. With respect to distribution pattern and in individual specimens, the growth of these plant formations is affected by the interference of torrential floods which occur in these channels and their banks (Figures 59 to 61).

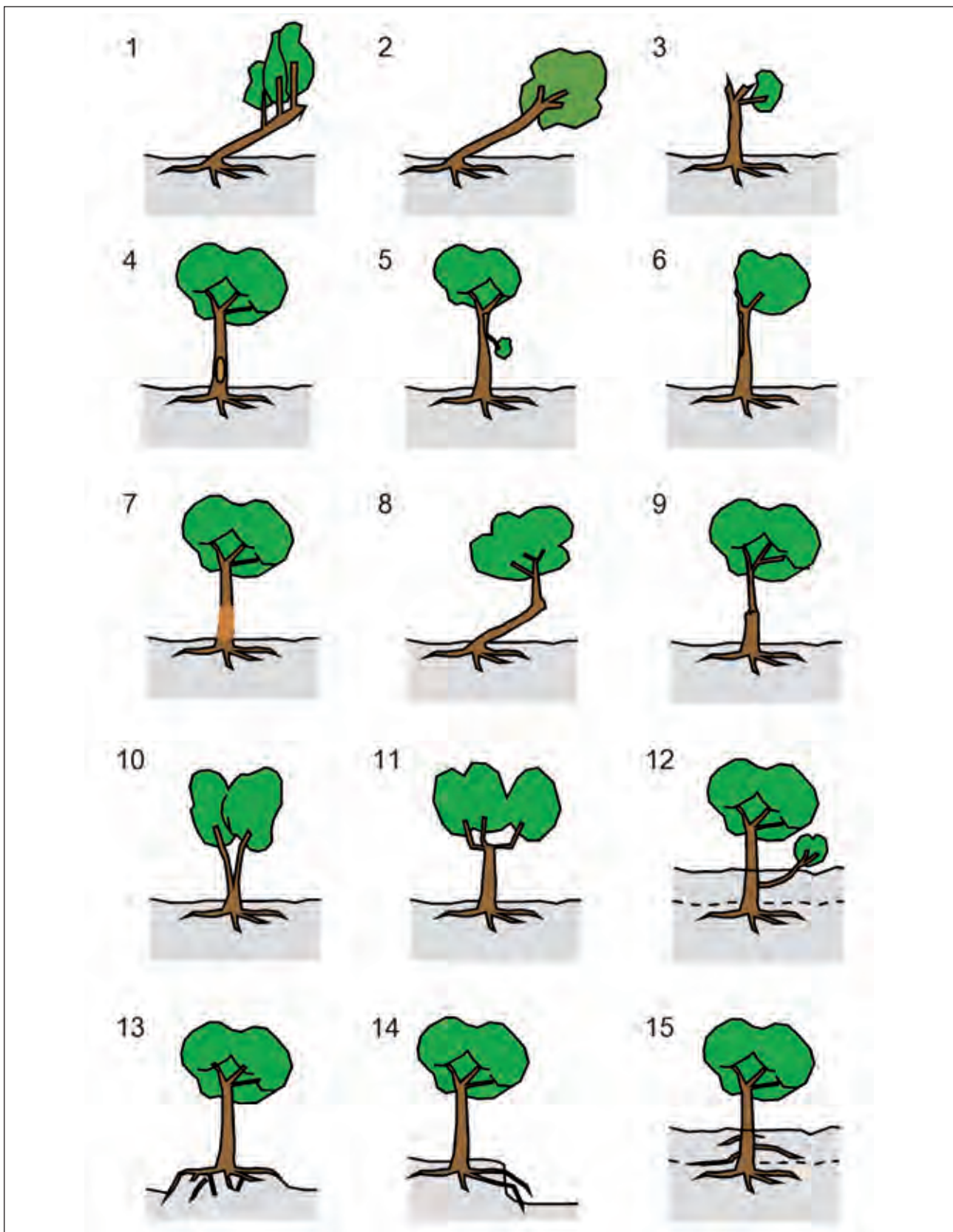
Dendrogeomorphology is a young scientific discipline which, taking advantage of information sources recorded in the roots, trunks and branches of the trees and bushes (Table 9) located in certain geomorphological positions (escarpments, river banks, longitudinal bars, floodplain, etc.), complete (and event supplement) flood hazard studies with information about the records concerning the torrential floods which have occurred at the stream under study, as well as quantitative and qualitative information about magnitude parameters, such as extent, water surface elevation, sediment load, energy and duration (Table 10).

However, applying dendrogeomorphological data to the study of torrential floods necessitates the use of a combination and integration of techniques and methods from the domains of dendrochronology (botany, ecology, physiology, plant anatomy, histology) and the sciences devoted to the study of fluvial dynamics (hydrology, hydraulics, geomorphology).

### **LIQUENOMETRY**

Another group of techniques rooted in botany-ecology – or rather, another source of information about past flood events and the dynamics of fluvial systems – is lichenometry. Applying lichenometric dating to forms and de-





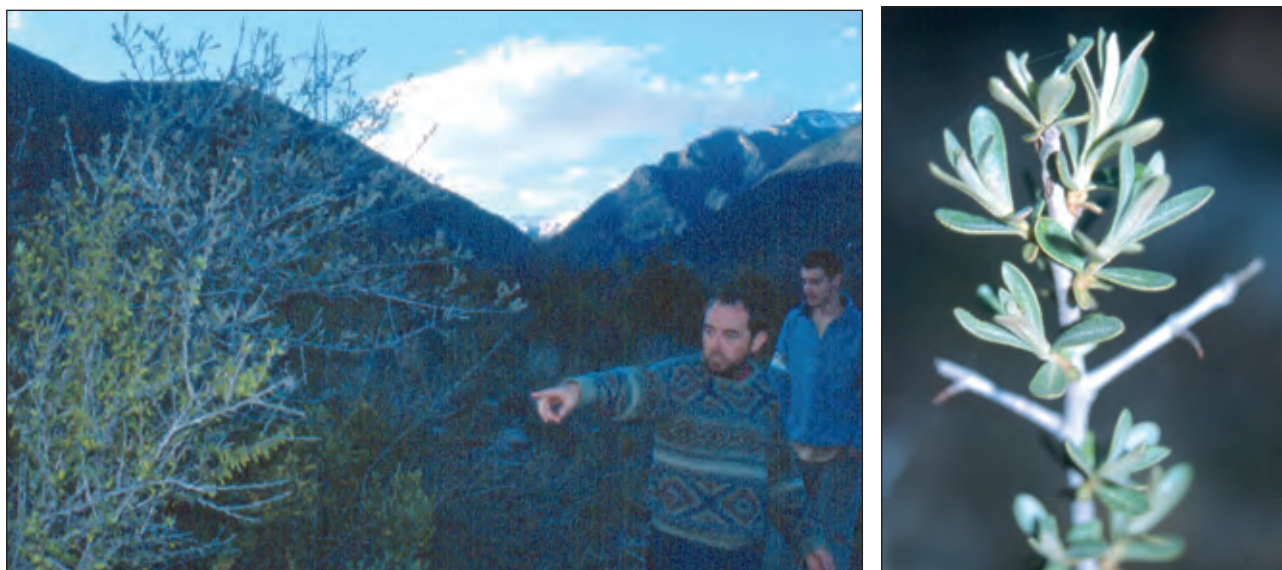
**Figure 59.** Types of the main individual macroscopic dendrogeomorphological indices useful in the study of torrential floods. 1.) “can-delabrum” growths; 2) Tilted with feet tipped over; 3) Decapitated; 4) Impacted by sediment load; 5) Branches torn off; 6) Grazing by other falling boles; 7) Erosion on the trunk; 8) Trunk bends and angles; 9) Sudden narrowing of trunk; 10) Bifurcations; 11) Bends and angles in branches; 12) Regrowth from buried trunks; 13) Exposed roots with stripped bark and eroded surface; 14) Roots aloft without contact with substratum; 15) New roots from buried trunks. (Díez-Herrero et al., 2008a).





**Table 10.** Use of the dendrogeomorphological evidence types and their combinations for the study of the frequency and magnitude of flash floods and floods (Díez-Herrero et al., 2008b). Type of information conveyed and its degree of utility for each sign or combination thereof in the study of flood hazard: green, high utility; orange, medium; red, none.

Relationships between macroscopic and meso-microscopic evidence (IDs) and their application in flood risk studies								
ID/IDs		Temporal considerations		Magnitude considerations				
		Unique events						
		Dating	Seasonality	Extent	Flow depth	Sediment load	Energy	Duration
ID 1								
ID 2								
ID 10								
ID 23	ID 3							
	ID 4							
	ID 5							
	ID 6							
	ID 7							
	ID 8							
	ID 9							
	ID 11							
	ID 12							
	ID 13							
	ID 14							
	ID 15							
	ID 16							
	ID 19							
ID 20	ID 17							
	ID 18							
	ID 5							
ID 7/ ID 21								
ID 22 28- 30	ID 17							
	ID 7							
ID 24								
ID 25								
ID 24 -28 27-29	ID 7							
	ID 17							
ID 31								
ID 32								



**Figure 60.** The presence of certain plant species is an indicator of the torrential conditions and the qualitative frequency of the floods which occur in a given location. Such is the case of the *Hippophae rhamnoides* bush in the alluvial fan of the Arás gorge in Biescas (Huesca).

posits generated during or after floods is an innovative tool for areas lacking other documentary, systematic or dendrogeomorphological information sources.

The first step is always to establish a lichenometric growth curve, useful for the lichen species and subspecies used for the area studied (Jacob *et al.*, 2002). To do this, information about the growth rates of the lichen colonies is gathered from tombstones and old monuments (buildings, rocky surfaces, megaliths), making it possible to go back several centuries, even millennia.

Lichen colonies on stony blocks, canyon walls, fluvial terrace deposits and palaeofloods have been used for dating. Firstly, it allows you to determine the date on which the blocks were displaced and deposited, and, hence, the date associated with this process. Next, you can extrapolate the current's standard power function curves to larger boulders (Gob *et al.*, 2003) to get an idea of its maximum competence during floods (Gob *et al.*, 2005). Lichens on canyon walls and terraces can be used to date the incision phases or abrasion phases linked to the floods (Figure 62) and thereby date the floods and their boundaries, which are used in turn to infer magnitudes (Gregory, 1976).

## 2.5. Integrating methods, calibration and selection criteria

### 2.5.1. INTEGRATING AND CALIBRATING THE METHODS

In Spain, a traditional approach to undertaking the analysis and mapping of flood-prone areas would be to estimate the discharges with hydrological criteria and methods (flood frequency analysis and or hydrometeorological discharge calculation), and then to estimate flood-prone areas, depths and velocities using hydraulic methods. However, applying these techniques to the entire country and at any scale poses a series of problems:

- Lack of a topographical database at a scale sufficiently detailed for hydraulic modelling, given that some vast autonomous regions, such as Castilla-La Mancha, do not have topographical databases at scales greater than 1:25,000, clearly insufficient for hydraulic modelling.



a) Candelabrum growth in an example of an alder tree growing on a central gravel bar in the Alberche river (Navaluenga, Ávila).



b) Bifurcations in the trunks of two ash trees growing on the bank of the Cabrera stream (Venero Claro, Ávila). The similarity in their approximate height and age suggest reaction to the same flood event.



c) Stripped bark with callus mark caused by impact of sediment load during flooding. In this case, at least three events can be observed, with their successive callus marks.



d) Example of a Maritime Pine with several instances of dendrogeomorphological evidence left by a flood event: exposed, stripped roots with erosion, which keep it in pedestal position. Stripped areas on trunk caused by impact by sediment load, which tells us the minimum level reached by the water table.

**Figure 61.** Types of dendrogeomorphological evidence of interest in the analysis of the frequency and magnitude of torrential floods (Díez-Herrero et al., 2008a).

- Limited budgets and time frames for preparing maps, since, owing to the pace of the LINDE project and others like it, creating hydrological-hydraulic models for the entire country could last decades and require investments which would not withstand the most basic cost-benefit analyses.





**Figure 62.** Zoning of the density and size of the lichen colonies (*Rhizocarpon geographicum*) according to the frequency and velocity of floods on the smooth channel surface of a mountain torrent in the Chorro Grande (La Granja de San Ildefonso, Segovia).

- Lack of validity of the hydrological and hydraulic models in certain sectors of the territory where the torrential nature of the streams (with steep slopes and high sediment load), or the scarcity of initial data (stream gauges, rainfall), necessitate approximations and extrapolations lacking in scientific-technical rigor.

Normally, the zoning results from the different groups of methods are neither comparable nor capable of being related to one another since each analysis and map has its own objectives and elements. The ideal response would be to establish calibrations between them, but ample experience in the area (Camarasa and Bescós, 2004; Lastra *et al.*, 2008) has demonstrated that, after all is said and done, priority must be given to one or several criteria or methods, with the others being used to complement the results, while occasionally varying the zoning or adding elements to be represented.

### 2.5.2. SELECTING AND PROPOSING METHODS

Traditionally, priority has been given to results drawn from hydrological-hydraulic methods since, being numerical results (flows, depths, velocities), they are viewed as more objective and, above all, less susceptible to being refuted and questioned in terms of their legal implications. However, multiple studies call into question the objectivity of these methods and models, which are based on scarce information sources (gauging stations, rainfall, infiltration parameters) and assume hypotheses which are unlikely in a natural system (Llorente Isidro *et al.*, 2008b). That is why they have on occasion been turned into statistical-mathematical artifices, only to be subsequently invalidated by empirical evidence (Olcina, 2007).

Historical-palaeohydrological and geomorphological methods are based on an irrefutable reality: they are founded on recognizable physical elements on the ground, or on documentation, which are empirical certainties rather than statistical artifices. This, coupled with the role being played by the hypotheses of global change and its impact on fluvial dynamics, has caused these methods to elbow out hydrological-hydraulic ones in recent decades and, at a minimum, has resulted in their being integrated and complemented, all things being equal. Proof of this affirmation lies in the fact that geomorphological criteria take precedence in the new SNCZI<sup>45</sup> zoning system (National Flood Zone Mapping System) and in the modification to the RDPH<sup>46</sup> (Regulations on Hydraulic Public Domain), including in how the public water domain is delimited.

<sup>45</sup> Sistema Nacional de Cartografía de Zonas Inundables.

<sup>46</sup> Real Decreto del Reglamento del dominio público hidráulico.



In light of the foregoing, any proposal or methodological guide must – in addition to referring to publications specialized what methods can be used – recommend the order of priority in which they should be used and define how the results should be integrated or override one another in the event of disparities between them. The limiting factor in the selection of one hazard analysis method over the others will be, without a doubt, the amount of pre-existing data available. If data required for a complete study are available, the study will comprise: a geomorphological analysis, a review of historical floods and palaeoindicators, a hydrological analysis of the basin and a hydraulic model of the area.

The geomorphological study of the terrain's processes and land forms will serve as the basis for the conceptual foundations in the hydraulic model and the hydrological behaviour, making it applicable in all cases. In highly anthropized stretches in which the natural land forms have apparently been lost, a geomorphological study based on the photointerpretation of photos taken in the past is indispensable for reconstructing the natural system and can also be used as a tool for predicting changes in fluvial dynamics. As was indicated earlier, the geomorphological study must be accompanied by a map of polygonal derivative or physiographic units, on an appropriate scale, with an assessment of its hazard.

Historical studies draw upon data from past floods, so it is possible in some cases that this information will be incomplete, irregular in space or time, or simply non-existent. Moreover, one should at times expect the information sources to be derived from the perception of persons affected by the event, who may exaggerate or simplify its significance. But if there is enough information (marks or indications on buildings, publications, press, official reports, historical documents and mapping, etc.), a historical floods map should be created for comparison with the data obtained in the geomorphological study, and data concerning their frequency and magnitude must be incorporated into the flood frequency analysis.

Hydrological methods are used to calculate flood discharges for use in the hydraulic model, or in the  $Q_p/Q_b$  ratio. Picking up where we left off in chapter 2.1, hydrological methods can be divided into hydrometeorological methods and the flood frequency analysis. Hydrometeorological methods are based on pluviometric data, while statistical flow data methods are based on stream gauging stations measurements. If both data sources are available, it is recommended that the two methods be combined, because gauging station series are usually shorter than rainfall series. When the two are merged, the results from the statistical analysis are used as a means of calibrating the hydrometeorological model, which can then be used to estimate flows.

If historical or palaeohydrological (*sensu stricto*, dendrogeomorphology, lichenometry) information or other data sources are available, they will be integrated into the flood frequency analysis to complete the series and improve the adjustment of the distribution function in the low-frequency reach (high return periods).

Within the group of statistical methods there are univariate models (parametric and non-parametric) and regional predictive models. Using regional models resolves the uncertainty surrounding the representativity of a single sample, assuming a region is homogenous with respect to certain statistical characteristics. It is always preferable to use parametric adjustments between the univariate models, while choosing the right distribution function and method for estimating parameters.

The most common analyses among the hydrometeorological methods (lumped, such as the rational method, pseudo-distributed, such as the unit hydrograph, and distributed) have advantages and limitations, depending on the characteristics of the basin studied.

The rational method is used to obtain the peak discharge at the basin outlet. If the subsequent hydraulic model requires the flood hydrograph, or if there are endorheic areas or reservoirs inside the basin which route the discharge, somewhat more complex rainfall-runoff transformation models must be used. One attempt at using peak flow to reconstruct the hydrograph is the isochrones method (section 2.1.1). Moreover, the rational method is only reliable for basins of up to 3,000 km<sup>2</sup> and times of concentration ranging between 0.25 and 24 hours.

To calculate actual hydrographs generated during floods, estimates can be made at a subbasin or a reach of the channel. In the first case, it is recommended that the Clark unit hydrograph or SCS hydrograph be applied, whereas in the second case the kinematic wave equation and the Muskingum method should be used.

$Q_T/Q_b$  methods are only valid as initial approximations in large territories. For studies and maps which consider low-frequency events (return periods of 500 years or more), it may be worthwhile to compare the results of the PMP-PMF program with the incorporation of historical and palaeohydrological data in the statistical analysis of frequencies.

Using the results from the geomorphological, historical and hydrological studies as a basis, the hydraulic modelling can be achieved. The choice of which model to use depends on the characteristics of the reach being studied. Simplifying the flow as one-dimensional is valid when the reach is rectilinear, more or less closed, not affected by confluences with other rivers and free of secondary flows. Two-dimensional models are more appropriate if the channel has pronounced curves or flows through large floodplains, if there are confluences, if there are flows around sizeable structures, if the flow runs over flood protection ditches or levees, if the reach passes through an urban area, or in the case of a shallow alluvial fan, delta or wetland. In some cases, both models can be connected so as to obtain an optimal rendering of each of the simplifications (section 2.1.2). It is also a good idea to estimate, for each channel reach, the relationship between the breadth of the area prone to flooding and the depth, from which point two-dimensional models can be used.

As mentioned in section 2.1.2, one-dimensional flow methods can be broken down by regime: uniform and steady, steady and gradually varied, and unsteady. Two-dimensional hydraulic flow methods belong to the varied regime category. Steady regime models are applicable in cases in which the routing of the flood wave is not a determining factor, where the discharge is constant in time. Otherwise, varied regime models are used. Moreover, the flow can be uniform if depth is constant along the reach, or non-uniform if depth varies. In turn, non-uniform (varied) flow can be gradually varied (velocity, and thus depth, varies gradually in space), or rapidly varied (variation is abrupt). When these possibilities are combined, we have uniform, steady flow in sloped, very long channels in which flow and depth are constant, and gradually varied, steady flow if there are gradual changes in the depth or in the reach. These options are built into the corresponding computer programs. The model used must be that which best fits the physical features of the channel reach we are modelling. There is a lot of research in which comparative studies are made between the one-dimensional and two-dimensional models (Martín Vide *et al.*, 2003; Brufau and Navarro, 2006; Linés *et al.*, 2008).

The results of the hydraulic model will be validated with those of the geomorphological model and the historical data, both in delimiting the area prone to flooding and in determining the flow's depths and velocity.

If there are disparities between them, the results obtained through geomorphology and historical data should prevail owing to their being founded on recognizable physical elements or pre-existing documentation, and an attempt should be made to use all of the results in order to obtain an integrated analysis of flood hazards that is as reliable and realistic as possible.

### 2.5.3. THE SCALE FACTOR

Flood hazard analysis methods are not applicable on just any scale, which is why scale is also a determining factor in choosing which method to apply (see centre table in Figure 72). In section 2.2, we referred to the scales at which these methods are applied, such as the regional scale (hydrographic basin, with scales of 1:100,000 to  $\leq$  1:200,000), sub-regional [*comarcas*, in Spain] (hydrographic network level, from 1:25,000 to 1:100,000) and local (a reach of river flow, from 1:5,000 to 1:25,000). The aforementioned table shows that the most recommendable scales for flood risk mapping purposes are those ranging between 1:1,000 and 1:25,000, since this is the range of scales in which all analysis methods can be applied.

Of the three major method groups described in the previous sections, the hydrological-hydraulic ones are those with the most limited scalar range. Specifically, hydraulic methods apply in detailed analyses in which scale is



not less than 1:10,000. Furthermore, one must take into account the importance of pre-existing data, not only instrumental data (data from stream gauging or meteorological stations) but also from mapping sources (Total Station, GPS, LIDAR, aero-photogrammetric restitution, etc.).

Topography – both of the channel and the floodplain – is the most critical limiting factor in hydraulic modelling as there are considerable variations in the calculation of the water surface elevation and extent of the area flooded depending on how precise these data are. This can be summed up in the phrase “... you can't get results with better output resolution than input resolution” (from Morad and Treviño, 2001).

A study by Casas *et al.* (2004) of a reach of the Ter river where it passes through Sant Julià de Ramis (downstream from Girona) illustrates these distortions in the hydraulic model depending on the map source. In the analysis, the authors use seven digital terrain models created using three different sources: GPS, LIDAR and digital elevation mapping, in which there were 4.5 m variations in the determination of the water depth and an approximate error of 50% in the estimation of the area flooded for the same boundary conditions.

Other research related to topographical precision can be found in: Bates and De Roo (2000); Bates *et al.* (2003); Casas *et al.* (2004); Hardy *et al.* (1999); Horritt and Bates (2001); Lane (1998); Morad and Triviño (2001) Sung-Min Cho and Myung Woo Lee (2001); Walker and Willgoose (1999); Wechsler (2006).

In addition to the mapping source, another factor which influences hydraulic modelling results is the precision of the digital terrain model. The quality of a digital elevation model (DEM) will depend both on the errors contained in the data used to create it and the errors resulting from the different interpolation or generalization methods (linear, inverse distance, splines, kriging).

In the test conducted by Quiñero and Alonso (2007), the basins and drainage networks are calculated based on digital elevation models obtained using different procedures. The results of each are highly disparate. The DEM generated using linear interpolation is what best adjusts to the manually digitalized drainage network, while kriging and IDW interpolation generate rectilinear channels which are not interconnected. This simple calculation is a good validation test of the DEM.

These sources are good references for information on this topic: Felicísimo (1994 and 1999), available at <http://www.sigte.udg.es/jornadassiglibre/2007>; Weibel and Heller (1991), available at <http://www.wiley.co.uk/wileychi/gis/resources.html>; Wood (1996), available at <http://www.soi.city.ac.uk/jwo/phd/>.

Geological-geomorphological methods encompass the greatest range of scales and therefore the widest range of programs, making them a tool with enormous potential. They can be used both at the basin scale and at a stream reach. What is more, their integration with other models makes them a reliable validation source, both for detailed studies, with hydrological-hydraulic methods, and for regional-scale studies, with historical data, if available. Another variant for integrating different methods with geomorphology is the  $Q_r/Q_b$  ratio, a method which, although hydrological-hydraulic, is rooted in geomorphology (explained in section 2.4) and which can be applied to large spatial areas.

One must take into account the fact that the dynamics of flood processes can change the configuration of the river system. The system regains its equilibrium mainly through erosion or sedimentation. The study of geomorphological change is a tool which allows you to detect changes in the dynamics of the area prone to flooding and, therefore, changes in the associated flood hazard.

Like the previous methods, historical methods cover a wide range of scales, from regional to local, and can also be integrated into analyses along with the other methods. This means they, too, are a means of validating hydrological-hydraulic methods.

For an example of this validation, refer to the test conducted by Camarasa and Bescós (2004), in which they create a flood hazard map for different return periods for the Bajo Arga floodplain (Navarra affluent of the Ebro) and a map of three historical floods attributed return periods of 2, 5, and 10 years. A comparison of the maps reveals misalignments, again resulting from a lack of topographical precision. But an increase in error for events of greater magnitude is also observed. Errors in the flood hazard maps with return periods of 2 and 5 years remain on the safe side (their modelling contains overestimations), whereas the flood of greater magnitude showed misalignments between the hazard areas and those which were actually flooded.



# FLOOD HAZARD MAPPING METHODOLOGIES

## BACKGROUND STUDY

### *International mapping experience references*

Internationally, there are many mapping plan and project experiences, not so much in the way of flood risk maps as flood likelihood and flood hazard maps. Although not the first of their kind, the maps associated with the National Flood Insurance Program (NFIP) in the US (Godesky, 2006; Figure 63) and the Flood Prevention Plan (PPRi)<sup>47</sup> in France (Paquier, 2006; Figure 64) have always been considered paradigms and models for many others. Also noteworthy are the central European experiences related to large trans-boundary rivers, such as the ELLA project concerning the Elba and Labe river basins (<http://www.ella-interreg.org>), Germany's mapping of the Rhine basin (<http://www.iksr.org>), the mapping of the Danube basin (<http://www.icpdr.org>), and the mapping carried out in Mexico (National Civil Protection System, 2004)<sup>48</sup>.

Among the many technical committees and groups of experts brought into existence as part of European Union efforts to monitor and introduce the Water Framework Directive, and now the EU Floods Directive, there is the EXCIMAP (European Exchange Circle on Flood Mapping), which has generated a considerable volume of discussion reports, a handbook on good practices for flood mapping (EXCIMAP, 2007b) and an atlas of examples of flood maps from 19 European countries, the United States and Japan (EXCIMAP, 2007a).

### *Mapping experience references in Spain*

Risk mapping, in the strict sense of the term (considering economic loss and personal injury), has not seen widespread use in Spain, it being limited to pilot experiences in specific locations (De Mora and Díez, 2008) and which are applied to land-use planning studies (PATRICOVA<sup>49</sup>; GV, 2002), basin management, and civil protection (Díez *et al.*, 2008b).

<sup>47</sup> *Plan de prévention des risques d'inondation.*

<sup>48</sup> *Sistema Nacional de Protección Civil.*

<sup>49</sup> *Plan de Acción Territorial de Carácter Sectorial Sobre Prevención de Riesgo de Inundación en la Comunidad Valenciana.*

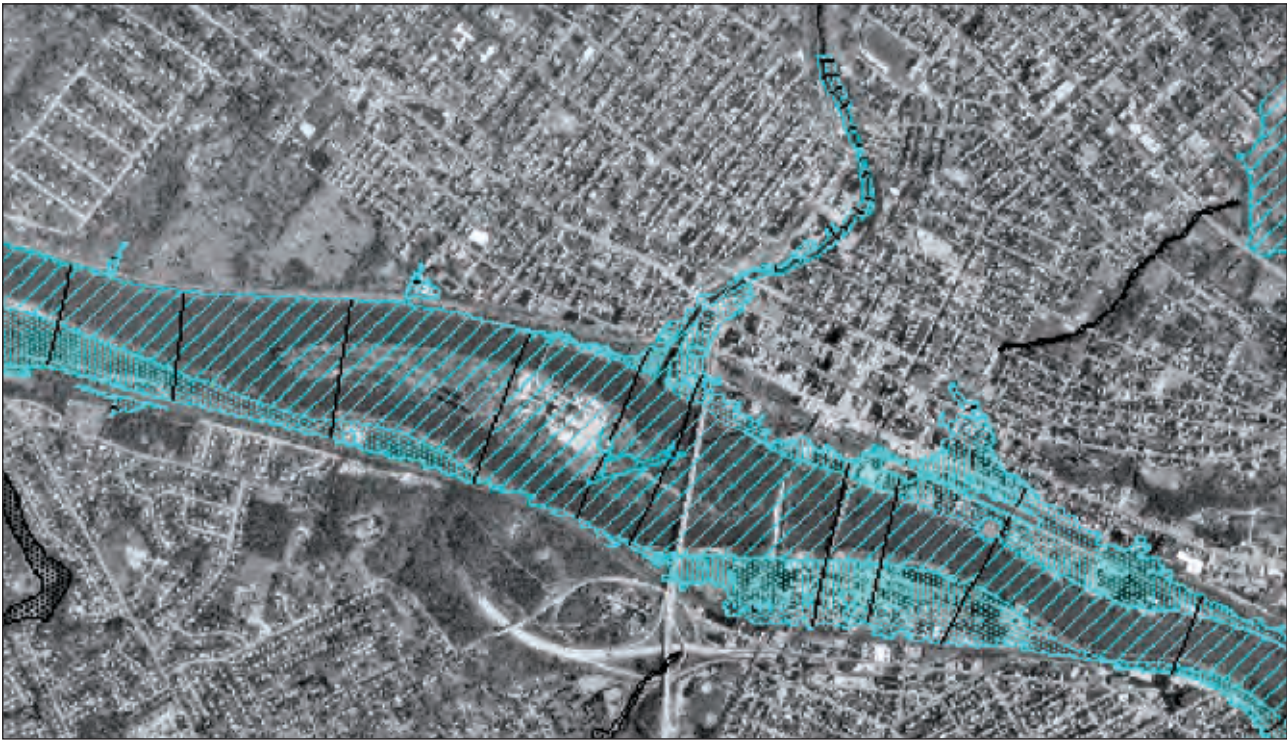


Figure 63. Example of an NFIP flood hazard map (Godesky, 2006).

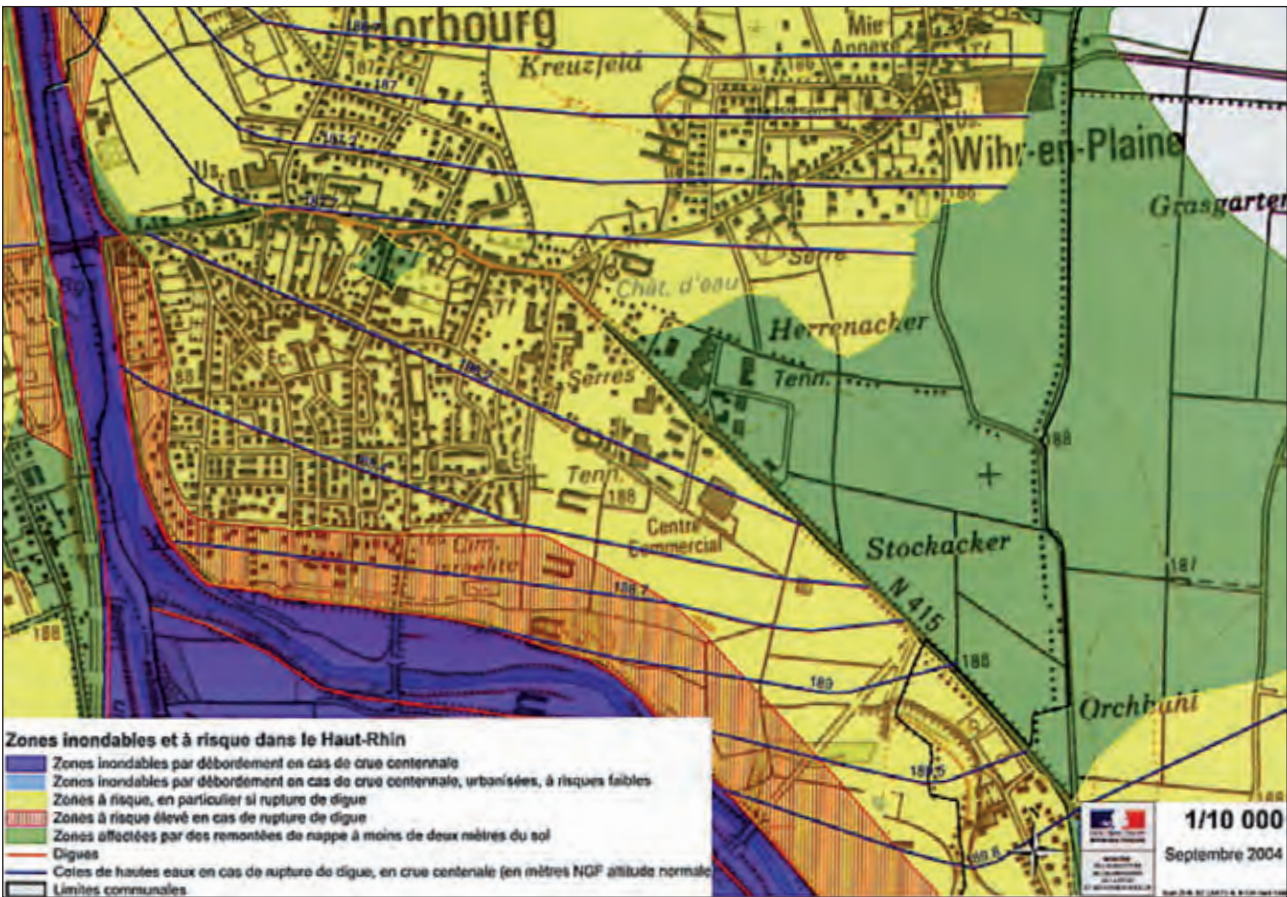


Figure 64. Example of a map of a Flood Risk Prevention Plan (PPRI) for the French city of Horbourg (Paquier, 2006).





As is the case in the other European countries, flood hazard maps are preponderant and more frequently used in Spain (Durán, 1998), with different scales, objectives and elements represented (Díez and Pujadas, 2002). A few examples are standard flood hazard maps for different flows and associated return periods, isobath maps or digital models of maximum depths attained during flooding, and isovel maps or digital models of flow velocities. Flood hazard maps can also show the potential sediment load transported by the flow, trouble spots during flooding, historical floods, or other flood-related phenomena (landslides, scouring and sapping, erosion, deposition, piping) which create risk situations. Various public and private organizations have produced these maps, namely the institutes and centres forming part of the Spanish *Administración General del Estado*, or Public Administration (IGME, DGA, CEDEX, the River Basin Authorities [*Confederaciones Hidrográficas*], the General Directorate for Civil Protection and Emergencies [DGPCE], etc.), organisations in the autonomous regions (water agencies and councils, civil protection, development), county councils [*diputaciones*] and municipal councils [*cabildos*], and some town halls [*ayuntamientos*]. Some universities and research centres (CSIC, IN-DUROT) have also produced flood hazard maps.

In 2005, the Spanish Geological Survey (IGME) presented the new Plan for Geological Risk Mapping (PRI-GEO)<sup>50</sup>, which addresses flood hazard mapping, among other geological risks (landslides, earthquakes tsunamis, volcanism and shoreline dynamics). The scales range from 1:50,000 to 1:10,000, and the planned execution period is ten years (2005-2015). A preview of the proposed criteria and methods had already been presented at the 2006 INUNMAP congress (Llorente *et al.*, 2006, the General Assembly of the European Geosciences Union (Llorente *et al.*, 2007) and the *GEORRIESGOS 2008* Geological Risks Congress in the Canary Islands (Llorente *et al.* 2008b). This handbook aims to further develop them, in keeping with a tradition of over 150 years (Díez and Laín, 1998; Llorente *et al.*, 2006).

The Spanish Minister of Environment and Rural and Marine Affairs recently (November 2007) presented the New National Flood Zone Mapping System (SNCZI), which compiles flood-related projects already carried out and those on the horizon, and which introduces a program designed to facilitate their consultation and management, including over the internet. The project's selected scale is 1:5,000, and it covers a three-year period (Yagüe, 2007). The methodological handbook has not been published yet, although a preview of the criteria and methods does appear in the modification to the Regulations on Hydraulic Public Domain<sup>51</sup> [RDPH] (Marquín *et al.*, 2008).

For their part, the river basin authorities and autonomous water authorities have been working on their own mapping programs in the past two years ago, some of which build upon the established LINDE projects (Viliarroya and Sánchez, 2006), and others which are innovative proposals to zone the stream network (Borrás *et al.*, 2006) or utilize state-of-the art data sources and processing methods (Rodríguez and Delgado, 2006).

### 3.1. Types of flood hazard maps

Flood hazard maps (MPI; Durán, 1998) involve the spatial representation of the different aspects of flood hazards that are analysed, which gives rise to several types of maps (Díez and Pujadas, 2002):

- *Spatial-temporal development*, including areas affected by the natural phenomenon associated with the hazard and the active and residence time of the agent or its effects. A few examples of these maps are:
  - *Maps of areas flooded during a specific flood, or single-event mapping*, are probably the first hazard maps to be carried out and represent the extent and the processes which transpired during a flood. These maps are derived from observations of a flood's effects based on information gathered in the field, photo-interpretation or remote sensing (Llobet, 1963; Calvet, 1983 and 1987; Arbiol *et al.* 1984, Martinez-Goytre *et al.*, 1986; Guerrero and Baena, 1997; Durán, 1998).
  - Maps of potentially flooded areas, whether by rainfall and *in situ* accumulation (Pernía *et al.*, 1987b; Díez and Sanz, 1998b), overflow during floods, transgression or rising groundwater.

<sup>50</sup> Plan de Cartografía de Riesgos Geológicos.

<sup>51</sup> Reglamento del Dominio Público Hidráulico.

- *Maps of areas or points flooded during historical floods and palaeofloods*, for the purpose of stocktaking (DGPC and DGOH, 1985; stocktaking maps, Durán, 1998; Pujadas *et al.*, 2000) or local studies (Martínez Goytre *et al.*, 1986; CEDEX, 1988a and 1988b; Guerrero and Baena, 1997 and 1998; Barnolas and Llasat, 2007).
- *Maps of groundwater residence time* (isochrones) or *seasonality* (CEDEX, 1988b).
- *Maps of the characteristic times* of the hyetograph-flood hydrograph relationship, such as times of concentration, travel, etc. for the drainage basin at each point (Ayala, 1990; Baretino, 1990).
- *Natural phenomena severity*, in the case of floods which are normally quantified based on the agent's physical parameters, expressed as continuous digital models (matrix or vector) or discrete digital models using isopleths, resulting in the following maps:
  - *Water depth maps* (isobaths, or Digital Bathymetric Model, DBM) during an actual flood (Rodríguez *et al.*, 1992) or a modelled flood (Díez and Sanz, 1998; Figure 65).
  - *Water velocity maps* (isovels, or VMs) during an actual or modelled flood.
  - *Sediment load transport map* (bedload, suspended load, or dissolution); Rodríguez *et al.* (1992).
- *Probability of the phenomenon*, normally expressed using the concept of return period or relative frequency, giving rise to the most common maps: *flood hazard maps or maps of flooded areas for a given return period*. The various techniques for estimating the potentially affected area allow us to distinguish between two types of maps:
  - Hydrologic-hydraulic maps, based on the estimation of the depths associated with each flood discharge using hydraulic models and then transposing the data to topographical maps (predictive maps, IGME-ITGE; CEDEX, 1988a and b; Díez and Sanz, 1998).
  - Geological-geomorphological maps, based on the study of earth forms shaped by the floods (terraces and floodplains) or deposits of past floods, making it possible to delimit the geomorphologically active areas with different probabilities (predictive maps, IGME-ITGE; Pujadas, 1993, 1995, 1997 and 1999a and b).
- These flood hazard maps are occasionally accompanied by other maps which attempt to represent the *risks associated with the floods*, particularly fluvial floods, such as gravitational movements which may influence the stability of the slopes:
  - Maps of the risks of damage caused by floods (landslides, erosion and sediment transport, sedimentation, etc.); geological criteria (IGME-ITGE).
  - Permeability and runoff maps, showing the geotechnical behaviour of the basin lithologies (geological criteria, IGME-ITGE).
  - Lithological map reclassified according to excavatability, map of surface formations and map of slope stability (Pujadas *et al.*, 1997).
  - Landslides, rockfalls, and active erosion processes (Baretino, 1990).
  - Modifications in the channel and/or plain following flooding (predictive maps, IGME).

Some flood risk maps only show specific trouble spots, such as: risk points (DGPC and DGOH, 1985; Pujadas *et al.*, 1997) in settled areas with hazard; trouble spots (MJI, 1995) linked to the flood (natural or anthropogenic; Baretino, 1990; Díez, 1999), and problematic spots (Pujadas *et al.*, 1997) which may increase hazard in their vicinity.

Of particular interest in planning for future land use are specific risk maps (Ayala, 1997) which reflect the merging of hazard and vulnerability in areas where there is currently no risk exposure. They make it possible to redirect future cases of risk exposure to persons and properties to areas with less specific risk in view of achieving optimal prevention.

Other authors (Pujadas *et al.*, 1997) prefer to limit the term “integrated maps” to those hazard maps obtained by synthesizing maps carried out using various methodologies and approximations (geological-geomorphological, social-historical and hydrologic-hydraulic) for estimating levels and depths.

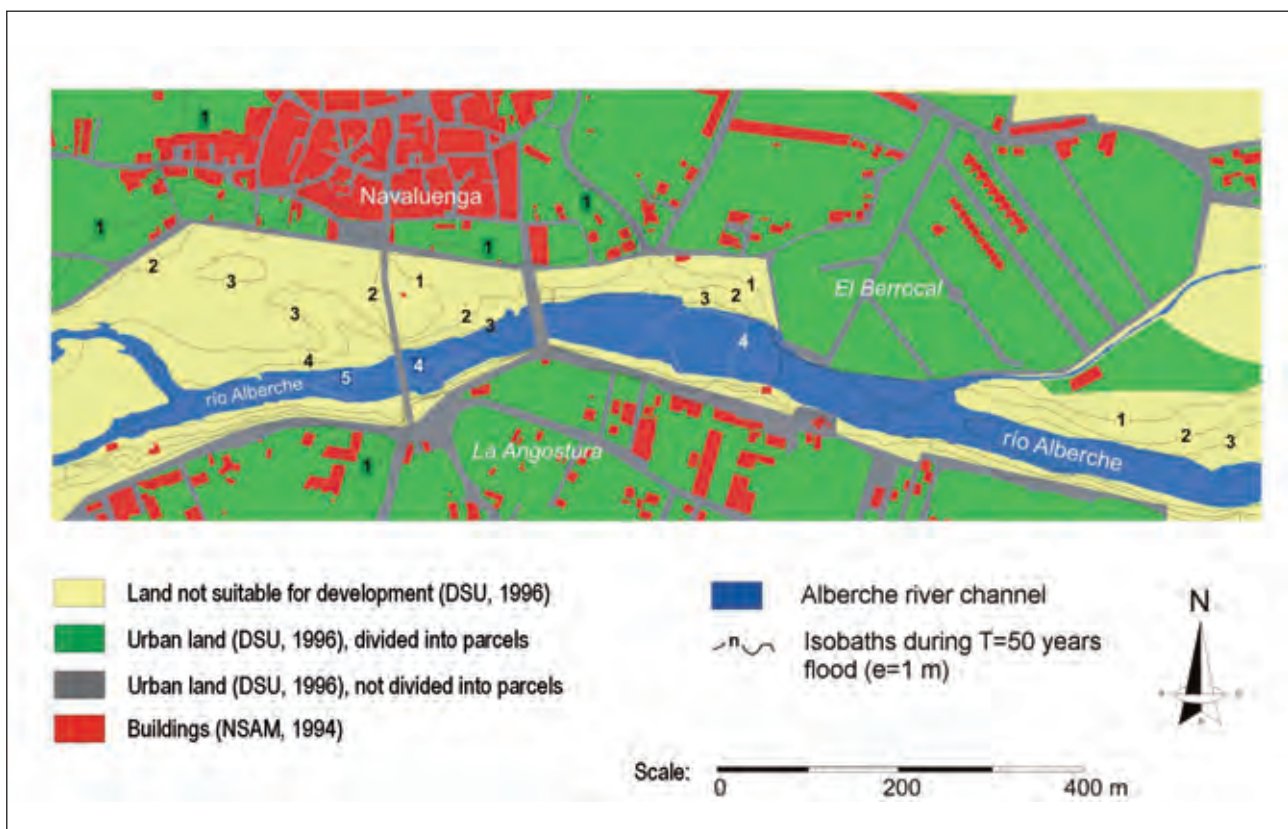
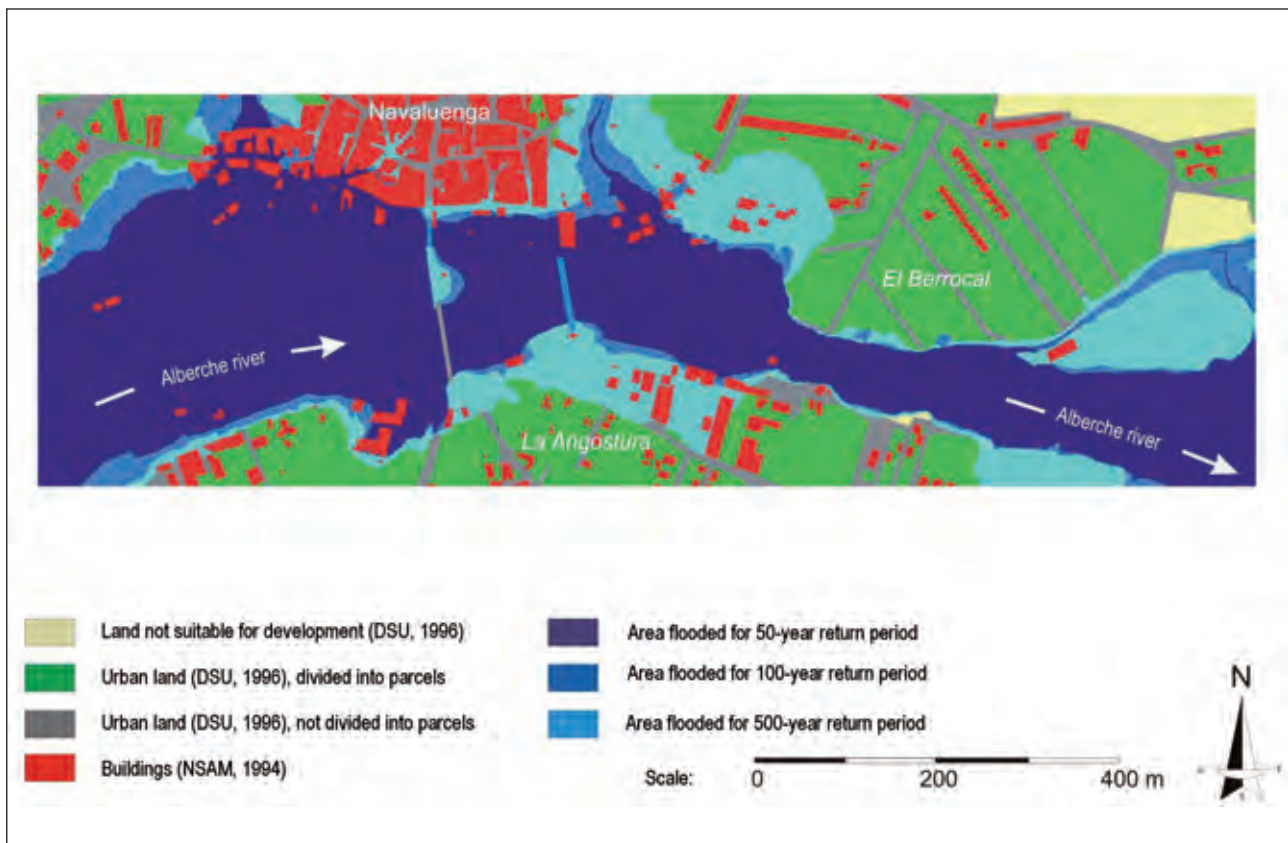
## 3.2. Contents of hazard maps

### 3.2.1. ELEMENTS TO REPRESENT ON THE MAPS

The elements that should be represented on flood hazard maps can be grouped in to three broad groups (Díez and Pujadas, 2002):







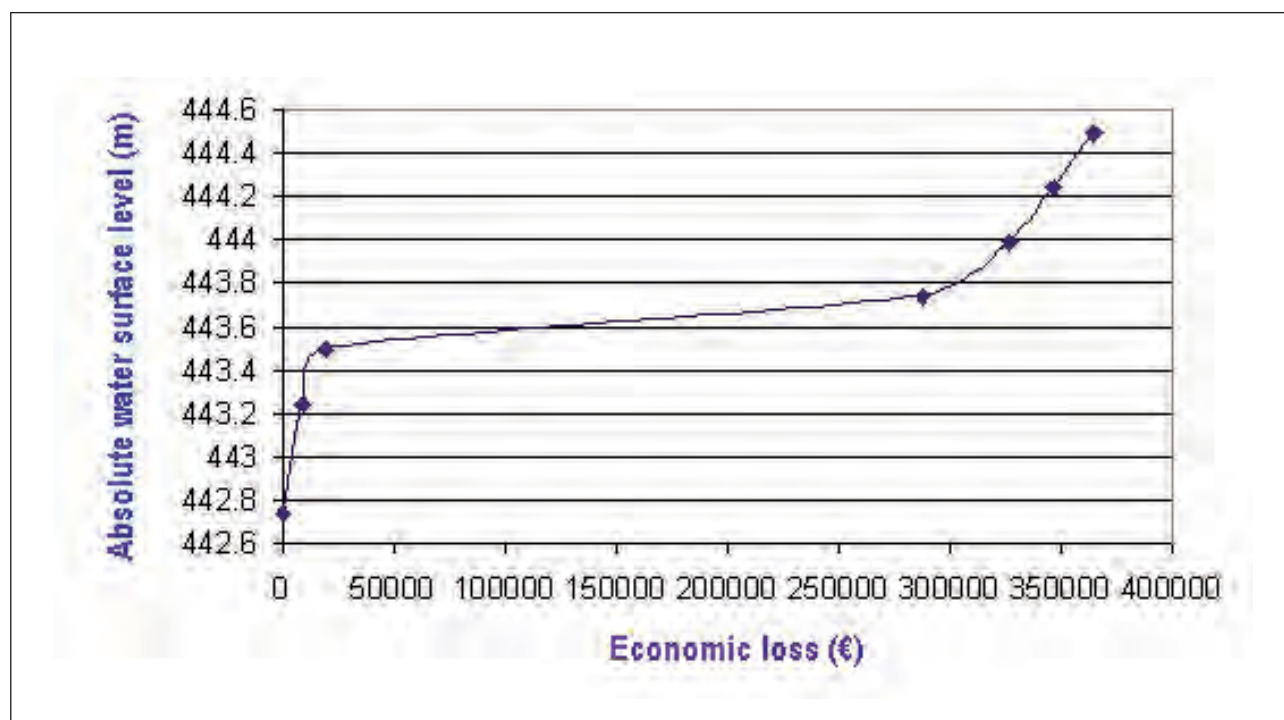
**Figure 65.** Examples of maps of flood hazard aspects (partial or sectorial maps) on which various hazard elements are represented (flood-prone areas for different return periods and isobaths). Alberche river where it passes through Navaluenga, Ávila (Díez, 2001-2003).

- *Descriptive elements or features of past flood events*, such as: the areas covered by one or more past floods, the bathymetric and flow velocity distribution, the flood control points (marks, plaques, documented places), flood trouble spots (narrowings, obstacles, erosion or deposition areas), and temporal dimension (residence time and characteristic times).
- *Elements of future or forthcoming floods* ('design floods'), such as: areas prone to flooding under different hypotheses (frequency or return period - Figure 65 – specific flow values), bathymetric distribution (Figure 65) and flow velocity distribution, potential trouble spots, or characteristic times ( $t_c$ ,  $t_{dp}$ ).
- Derivative elements of past and future situations, such as hazard zones: flood zones which are dangerous to persons, and flood zones which are not; high, medium and average hazard, etc.

From among the variables that should be represented, as long as they are shown with discrete values or closed ranges, an attempt shall be made to choose those which best represent physical features or delimit hazard classes. For example, in the flood-prone areas, standardized return periods must be used, such as 25, 50, 100 and 500 years. The bathymetry shall use isobaths of 0 m (or the equivalent of the dry-wet threshold), 0.4 m, 0.8 m ('table effect'; Figure 66), 1.0 m, 1.2 m (start of asymptotic behaviour) and 1.5 m. For the isovels, values of 0.5, 1 and 2 m/s are to be used (Figures 66 and 67).

To these elements one could add other pertinent elements associated with aspects of exposure and vulnerability (social and economic, individual and collective) in view of completing the hazard map and laying the foundations for a risk map. These could be, among others, the location of residential housing, the population distribution, and the positioning of landmarks (hospitals, learning centres, infrastructures).

The truth is, whether all of these elements should or can be represented on the map depends in large part on the map's ultimate objective (elements of interest to the end user), and, above all, the scale of the work and representation, since many cannot be mapped even when exaggerating their size and spatial distribution.



**Figure 66.** The so-called 'table effect', or significant increase in the volume of economic losses produced during a flood when the depth exceeds the average height of tables and counter tops (0.8-0.9 m). Taken from De Mora and Díez (2008).

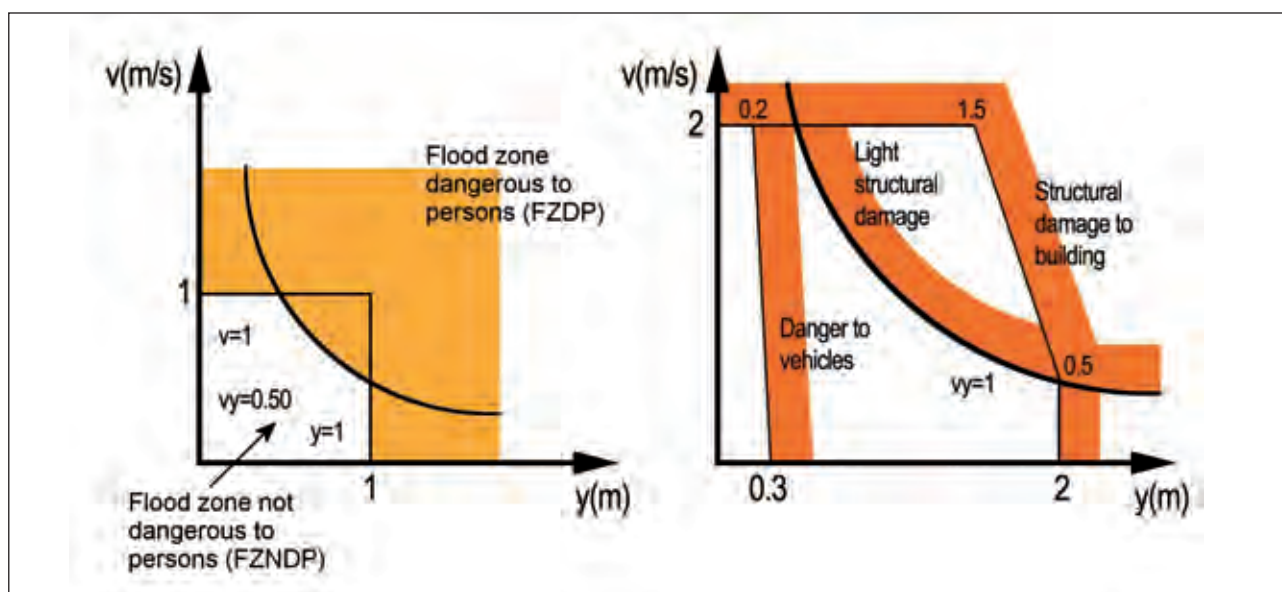


Figure 67. Graphs of estimated classes and values of the different flood areas or damage to persons and property (Martín Vide, 2006).

### 3.2.2. INTEGRATED HAZARD ZONING

Provided they are present within the area of study, three clearly distinguishable hazard zones are shown, with clear boundaries and using different colours (Figures 68 to 71):

- **High Hazard Zone (HHZ, red)**, corresponding to the part of the territory where there is frequent, serious danger to the safety of persons because of the water level (depth,  $v \geq 1$  m), the flow velocity ( $v \geq 1$  m/s), or a combination of both ( $vy \geq 0.5$  m<sup>2</sup>/s). It may also include other flood-related phenomena (transported sediment load, landslides, piping, erosion, deposition) which may produce these damaging effects.. It would be equal to the high probability flood-prone zone, as defined in the European Flood Directive (EFD), and roughly equal to the SNCZI's hydraulic public domain (see modification to the RDPH).
  - In *rivers and fluvial streams*, the main criterion for delimiting the contour of this area is geological-geomorphological, as it should correspond to the flow's natural channel, which is the geomorphological element contained between the escarpments of the river banks (upper part of the escarpment). This would be equal to the bankfull channel, which is filled with the bankfull discharge. In certain conditions it could also be equated to public hydraulic domain or channel in the Spanish Water Act and the Regulations on Hydraulic Public Domain, albeit with the subtle difference of favouring geomorphological criteria over the use of artificial hydrologic-hydraulic delimitation of the maximum ordinary flood (as per the modified line of the RDPH). In places where it may not be possible to identify the river banks with precision, whether because they have been replaced with other geomorphological elements (flood protection ditches, seawalls, or natural dikes – levees, crescent-shaped point bars, or spillage) or because of anthropogenic transformation (urbanization, channelization, dredging), geomorphological criteria can be substituted with other, historical criteria (documentary records from areas affected by past flood events, surveys of the local population), botanical criteria (layout and age of vegetation formations along the channel and banks) and/or hydrological-hydraulic criteria (area flooded by floods with return period of 2 to 9 years, justified according to area of the country). In delimiting the escarpments of the banks and other elements of reference, the channel's dynamic character must be taken into account, with consideration given to the following aspects: possible channel avulsion or capture, bifurcations during floods, meander constrictions and throats, expansion or shifting of meander bends, bar migration and all evolving trends which may be reflected in the channel's spatial-temporal variation.



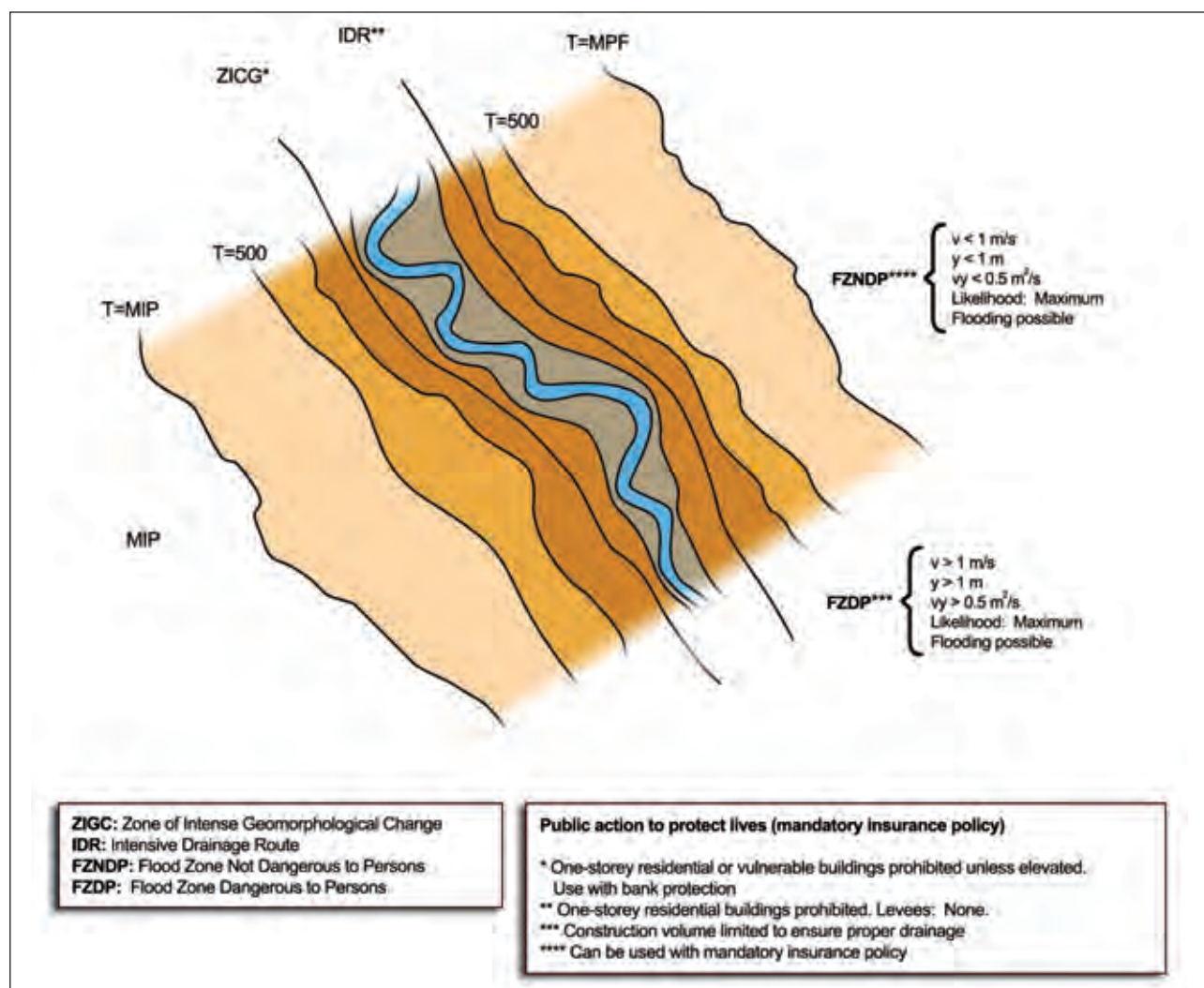


Figure 68. Hazard zoning with hazard criteria for persons (Ayala, 2002).

- In recent, active detrital or alluvial fans, this area is delimited at the apex, all delivery channels (active and abandoned), in spillover lobes and the thalwegs formed by one or more of these lobes – either with each other or with the adjacent slopes, in addition to the low-lying areas between these lobes.
  - In current endorheic and/or aclinal areas, the HHZ will only encompass areas which are seasonally swamp-prone or with recent depositions (Holocene) characteristic of the bottom of flood-prone depressions (lagoons, ponds, plains, mesas, marshes).
- **Medium Hazard Zone** (MHZ, colour orange), corresponding to the area of land prone to frequent flooding but at depths and velocities which do not represent danger to human life ( $y < 1$  m,  $v < 1$  m/s,  $vy < 0.5$  m<sup>2</sup>/s), in addition to areas prone to frequent flooding on the scale of one human life ( $T \approx 100$  years). This would be the equivalent of the floods with medium probability set forth in the European Flood Directive. It must contain the preferential flood zone of the SNCZI (see modification to RDPH) which is not part of the HHZ and which encloses the areas prone to frequent and occasional flooding as defined by the Basic Directive of Civil Protection Planning on Flood Risk (MJI, 1995).
- In rivers and fluvial streams, the main delimitation criterion is also geomorphological, corresponding to the lowest part of the flood plain where there are features which suggest the existence of activity at a less-than-secular scale, such as deposits or forms (spillover lobes, spillover strips, secondary flood flows,





Figure 69. Simplified topographical map of the district of Villanueva de Riaseco, an imaginary place to be used as a pilot area for flood risk and flood hazard maps based on the proposed zoning.

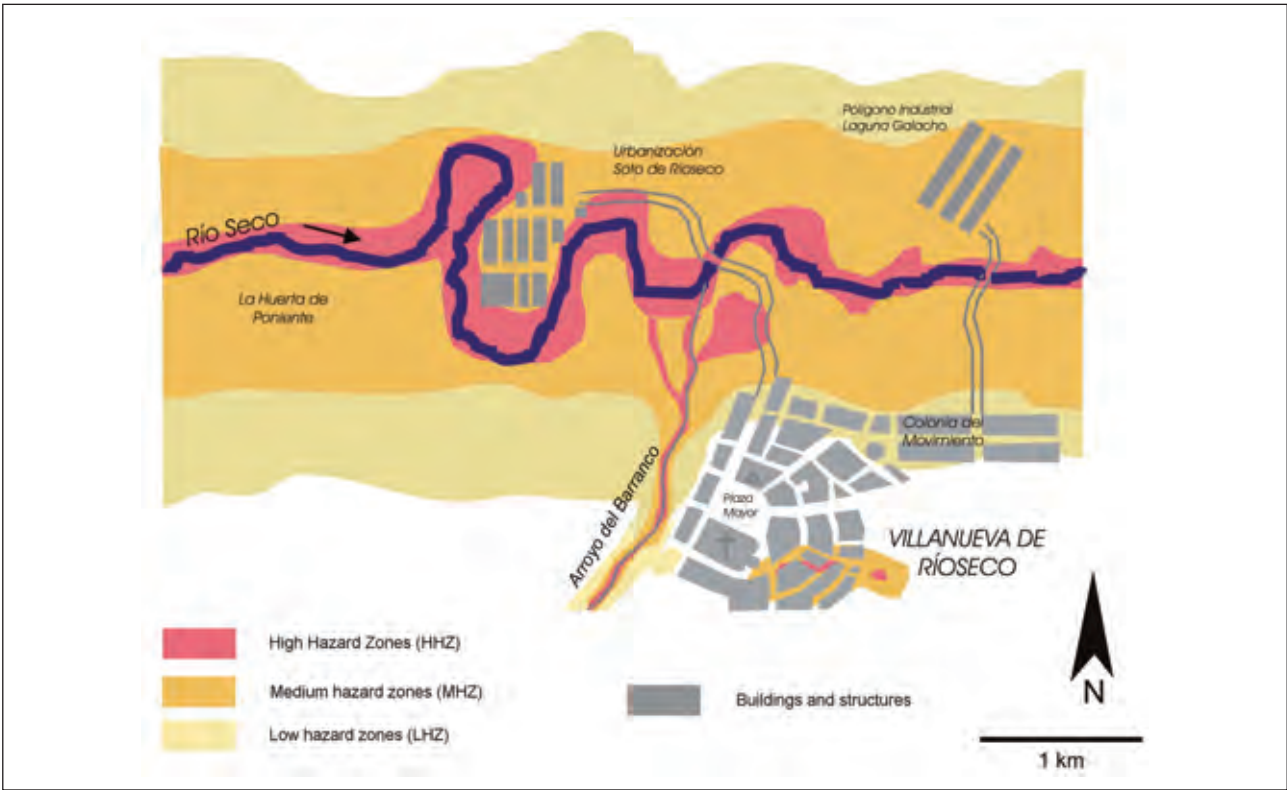
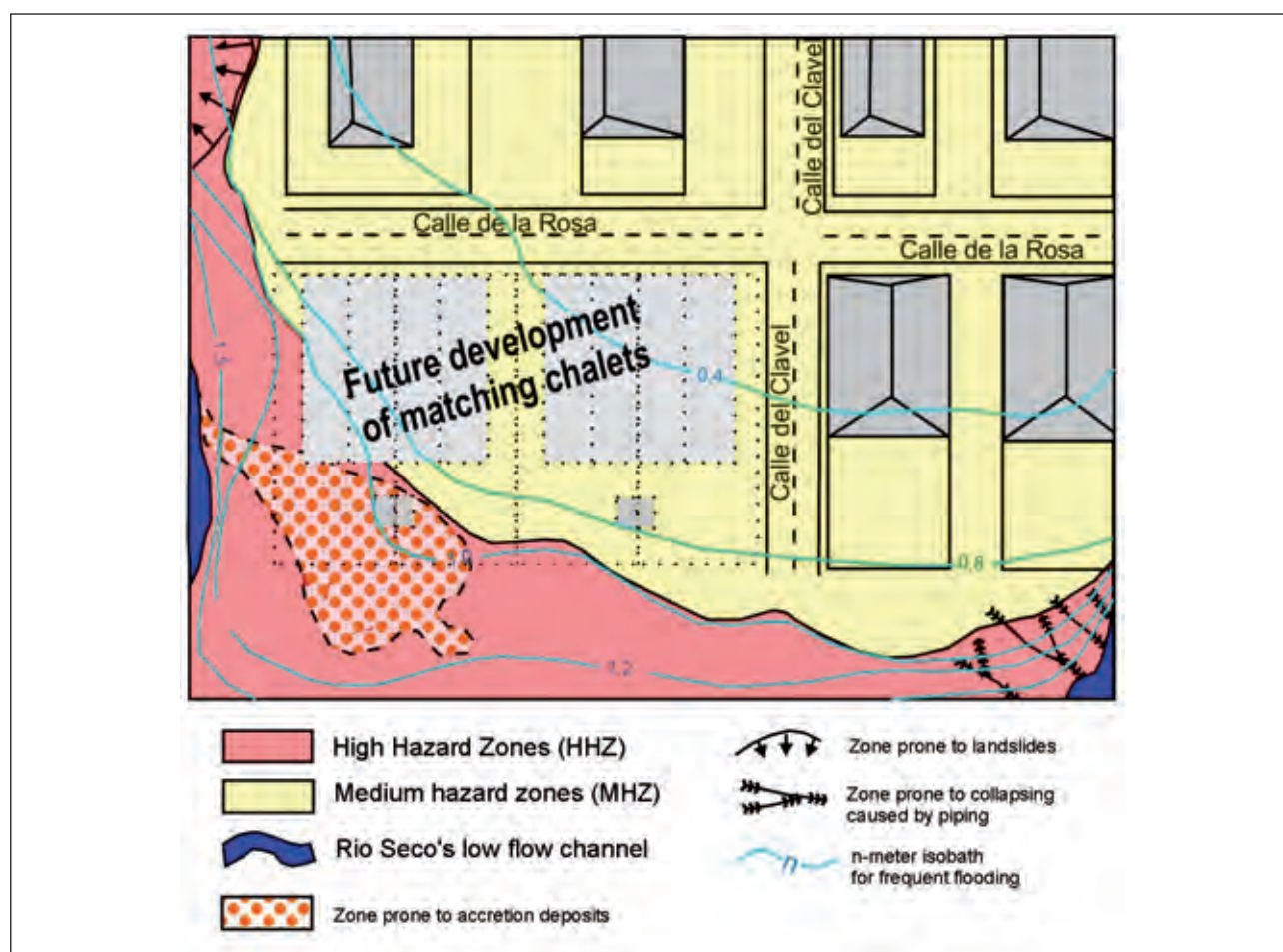


Figure 70. Integrated flood hazard map for the district of Villanueva de Riaseco. Adapted from Díez and Pujadas (2002).

abandoned meander branches, bars, terracettes) and or marks on natural elements (dendrogeomorphological signs, lines left by floating materials, etc. When the geomorphological criteria are not sufficiently clear, they are complemented with historical information (documents, surveys) and/or hydrologic-hydraulic information (area prone to flooding by a flood with a 100-year return period). As would be the case for the river bed, the dynamics-evolutionary variations of this area will be taken into consideration, as well as significant changes in the catchment basin (soil use, regulations, variation in feeding regime) which may have changed or are able to change the zoning. It is recommended that detailed studies be carried out in this area using hydrologic-hydraulic models which represent flow simulation in two-dimensional hypotheses, placing great emphasis on the plain's detailed topography and the bathymetry of the channel(s).

- In *detrital or alluvial fans*, any part of the alluvial fan's surface not included in the HHZ is included as part of the MHZ.
  - Also included in the MHZ is the centre part of *aclinal* (slopes inferior to 1%) or *endorheic* land sections. These situations will require a detailed study of the probable maximum precipitation and its accumulation on the territory (accumulated flow maps using DEMs and GIS tools), in addition to water table variations.
- **Low Hazard Zones (LHZ, yellow)**, corresponding to the section of the territory in which only there are only extraordinary floods with low frequencies (equal to return periods of 500 years or more) and very low depths



**Figure 71.** Idealized example of a flood hazard map for a project, partial plan or detailed special plan, with proposed zoning, combining elements from the derivative map (zoning) and partial maps (bathymetry and associated geological phenomena). Corresponds to a sector of the Soto de Rioseco housing development in the Villanueva de Rioseco district (see Figure 70).

and velocities and which do not present a danger to the population. This would be the equivalent of the low hazard zone of the European Floods Directive and, approximately, the exceptional flood zone of the SNCZI (see modification to the RDPH), and the Basic Directive of Civil Protection Planning (MJL, 1995).

- In *rivers and alluvial streams*, geomorphology is also a main delimitation criterion, including the geomorphological unit or element occupying the entire valley bottom, whether the floodplain or the bottom benches of thalwegs and lower terraces. This would be the equivalent of the extent of flood-prone areas as laid down in the Water Law Act. Moreover, geomorphological information can be complemented with historical, botanical and hydrologic-hydraulic information. Also taken into account is the possible existence of forms and deposits which do not match the current dynamics of the river flow, such as large floodplains which correspond to the flow's former feeding regimes and which have not been subsequently modified by other identifiable fluvial processes. In such cases, the current situation will be adjusted while adequately justifying the adjustment from the point of view of dynamics and evolution.
- In *detrital or fluvial fans*, the areas between fans are included in the LHZ as a precaution against possible abrupt changes due to mitigation or lateral avulsion, or obstruction of the feeder canal at the apex.
- Low-slope areas (<2%) are also part of the LHZ.

### 3.2.3. ELEMENTS RELATED TO INTERACTION WITH OTHER GEOLOGICAL HAZARDS

Notable importance shall be given to the interaction between the floods and other geological dangers, both those triggered by the flood and those which may cause it or exacerbate it.

In the first case, there must be an analysis of the possible induction of piping due to the process of moistening or sapping of the base of the slopes near the flooded zone. Also to be studied is the probability of the occurrence of piping phenomena resulting from leaching due to subsurface flows, once the water in the flooded area has subsided and the channel returns to in-bank storage levels. Another case of interest could be the induction of swelling in expansive saline soils or soils with special clays. Lastly, the flooding-related acceleration of the erosion process of fertile soils will also be studied.

As regards the second case, the possible occurrence of natural damming as a result of landslides will be studied, for instance tongues and outflows from rockfalls and landslides which may dam up the river current flow. Added to this is the formation of barriers due to the accumulation of plant remains (trunks and branches) of biotic origin (beaver dams) or abiotic origin (accumulations caused by avalanches and lateral currents from debris). Each of these damming formations can break up and worsen the effects of the flood wave.

### 3.2.4. LIMITATIONS IN THE USE OF HAZARD ZONES

The different usage groups and territory settlement types can be related to the different hazard zones described in the previous section either with total compatibility, incorporating a series of limitations or restrictions (requiring more detailed studies), or by being totally prohibited, according to the cross relationships shown in Table 11.

## 3.3. Representing the information

### 3.3.1. SCALES: SELECTION CRITERIA

The scales must correspond to those determined in the decision-making document for which the flood hazard maps are made.

The future application and use of the mapping will determine which scale of detail is most appropriate.

**Table 11.** Degree of suitability of the broad activity groups of territorial occupancy or land uses in the different hazard zones established on the maps: S, perfectly suitable without restrictions; R, settlement restrictions (detailed studies are required); P, non-suitable and prohibited. Adapted and synthesized version of Francés (2005), CGRM (2007) and Llorente-Isidro et al. (2007).

TYPES OF LAND USE OR TERRITORY SETTLEMENT ACTIVITY		HAZARD ZONES		
		High hazard	Medium hazard	Low hazard
Natural and seminatural areas		S	S	S
Agriculture and cattle	Extensive	R	S	S
	Intensive	P	R	S
Leisure and recreation	Parks and gardens	R	R	S
	Tourism campgrounds	P	P	R
Industrial	Extractive (mining)	P	R	S
	Storage of inerts	P	R	S
	Transformation	P	R	R
	Energy	P	P	R
	Dangerous substances	P	P	P
Urban (residential)	Isolated buildings	P	R	R
	Low density	P	P	R
	High density	P	P	P
	Nerve centres	P	P	P
Linear and sporadic infrastructures		P	R	S

Three broad scopes of application can be defined for flood hazard maps: Land-use planning, civil protection and insurance (private companies and, in Spain's case, the *Consorcio de Compensación de Seguros* [Insurance Compensation Consortium]).

In addition to the maps' intended use, in all three fields, scale plays an exceedingly central role in determining other vital aspects: the ability to use certain analysis and representation methods, and which elements can be included and represented. Therefore, within the range of scales, an attempt must be made to choose the one of most value (greatest detail) so as to increase precision and pave the way to a greater number of methodological possibilities and elements that can be represented.

Figure 72 shows the relationship between scale and representation, the scopes and fields of application, the hazard analysis methods, and the elements to represent on the maps.

In the case of town planning under the Spanish Land Law, there are certain planning figures which vary from one Autonomous Region to another but which can be summed up as follows:

- Special detailed maps and partial maps of urban areas, produced with scales ranging from  $\geq 1:1,000$  to  $1:10,000$ .
- (General) town planning maps of an urban settlement, with intervals ranging from  $1:2,000$  to  $1:10,000$ .
- Municipal (or parochial) maps at  $1:5,000$  to  $1:10,000$ .





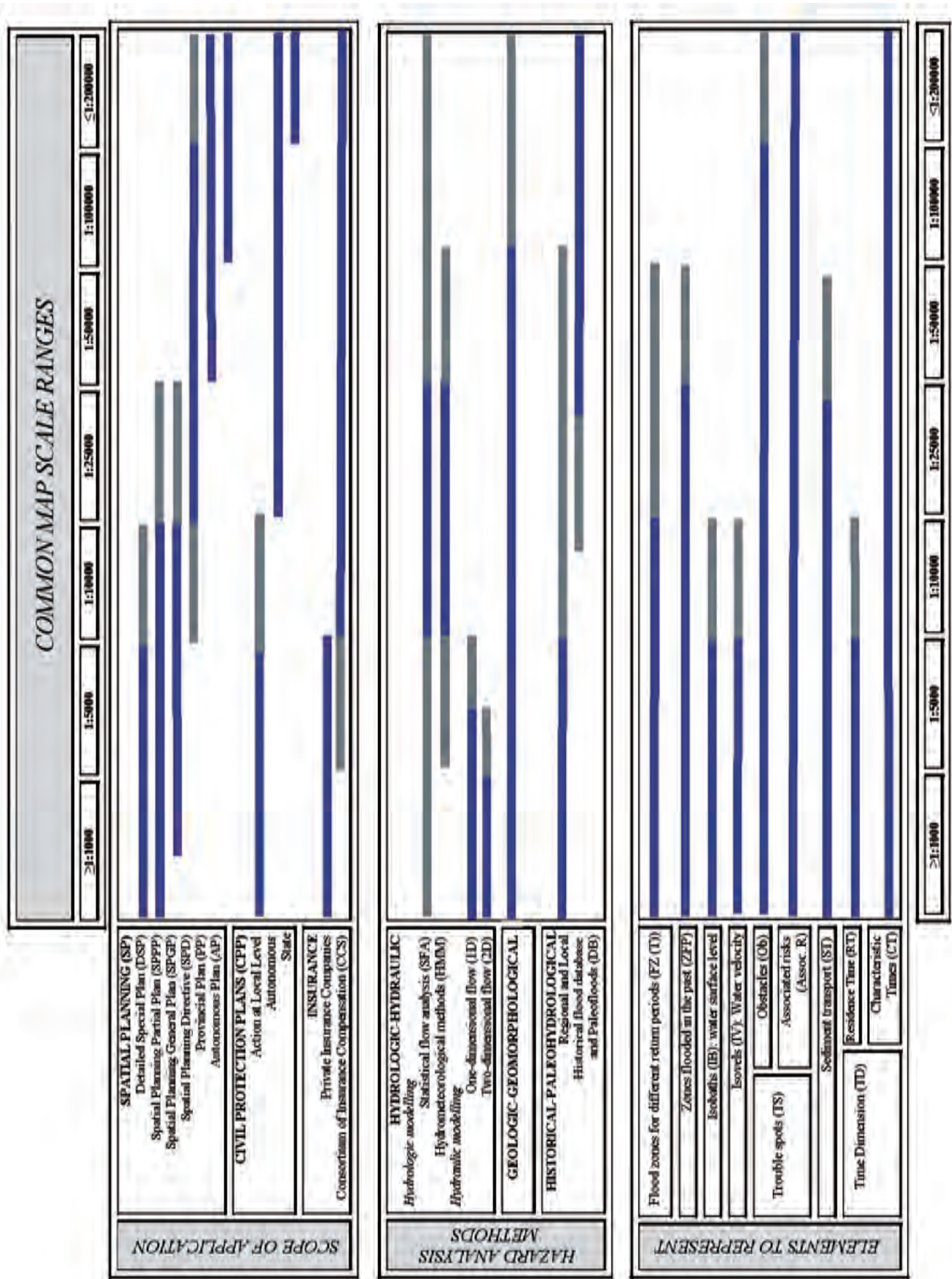


Figure 72. Relationship between scale and representation on flood hazard maps with scopes of application (top), methods of hazard analysis (middle), and the elements to represent (bottom). The purple bars represent the recommended range and the grey bars the permitted range in Spain.



- Supra-municipal maps (communities, town councils or sub-regions [*comarcas*]), from 1:10,000 to 1:25,000.
- Provincial or island plans, with scales of 1:25,000 to 1:100,000.
- Autonomous plans, ranging from 1:100,000 to 1:400,000.
- National plans at 1:400,000 or less.

For Civil Protection Planning on Flood Risk plans created under the Basic Directive, the working spatial ranges are:

- Local, at scales greater than 1:1,000 to 1:25,000.
- Autonomous Region, for which the range of scales may vary from 1:25,000 to 1:200,000.
- State-level, with index mapping at scales of  $\leq 1:200,000$ .

As for the private insurance companies domain, such as reinsurance and the scope of the Insurance Compensation Consortium<sup>52</sup>, the interval of scales is very wide: from individual projects, at scales of 1:500, to regional projects, from 1:1,000 to  $\leq 1:200,000$ .

Whether or not certain elements can be represented on the map will depend on the map's ultimate purpose and, above all, the scale of work and representation.

Section 3.2 contains a classification system of the different types of commonly-represented elements, and Figure 72 shows the most frequent scale ranges for representing these elements. Most of them are represented at scales of 1:1,000 to 1:25,000, although others, such as obstacles, trouble spots, associated dangers and characteristic times may be defined using greater ranges. The legend in Figure 75 shows the elements' symbology, distinguishing between the elements based on the method used to analyse them, to include them in synthesis maps. Even if they can be represented, it is not always useful to do so. Figure 73 shows the elements that should be represented in flood mapping, according to the scope of application.

In all cases, the flood-prone area should be represented for several return periods, except in state-level plans in which the boundaries between the flood-prone areas cannot be differentiated, as well as the trouble spots, be they obstacles or associated risks (landslides, piping, erosion, expansive clays, etc.).

Delimiting isobaths and isovels is limited to detailed studies, such as special detailed maps or civil protection maps for local use.

Characteristic times are fundamental in the domain of civil protection, for which it is necessary to identify the response time in the event of a flood. Bathymetry is also fundamental for delimiting evacuation zones where the water table does not reach levels high enough to prevent evacuation.

In the case of insurance, the elevation reached by the water table is also crucial since, as explained in earlier sections, the table effect (0.8 m) is what indicates the limit beyond which the greatest economic losses occur.

### 3.3.2. REPRESENTATION SYSTEMS AND METHODS

As regards the system and method of representing the elements, it is desirable to consider their nature when trying to decide on what type of mapping element to use (polygon, line, point, grid squares area, grid square-pixel) and the symbology to use (shaded, hatched, dotted, continuous, discontinuous, proportional).

It seems only logical, therefore, for the representation of flood-prone areas to use completely filled polygons. For transported sediment load, you could superimpose a line or weave, whereas other elements, such as bathymetry, permit the use of discrete DBMs (isobaths) or continuous DBMs (matrix or vector). In each case it will be necessary to choose whichever element best represents the information and which is easiest to combine with the other elements to represent without clogging the map or covering each other up (Figure 74).

<sup>52</sup> Consorcio de Compensación de Seguros.



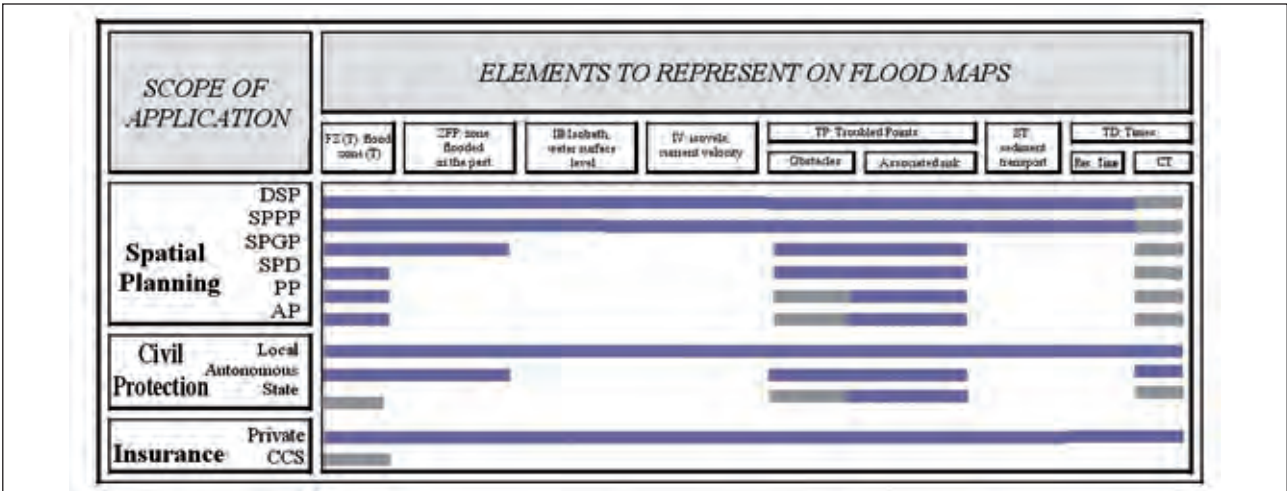


Figure 73. Elements which can be represented on flood hazard maps based on their application (see meaning of abbreviations and leg-end of bars in Figure 72).

Another way to incorporate information in the represented elements is to employ continuity in the type of line used for zone or area boundaries (polygons) to indicate the method or criteria behind their delimitation: continuous line for boundaries established with two or more criteria or methods integrated and calibrated with one another; discontinuous line for boundaries established exclusively using hydrologic-hydraulic criteria; dashed-dotted line for boundaries established exclusively using geological-geomorphological criteria; and a dotted line for boundaries based on historical criteria.

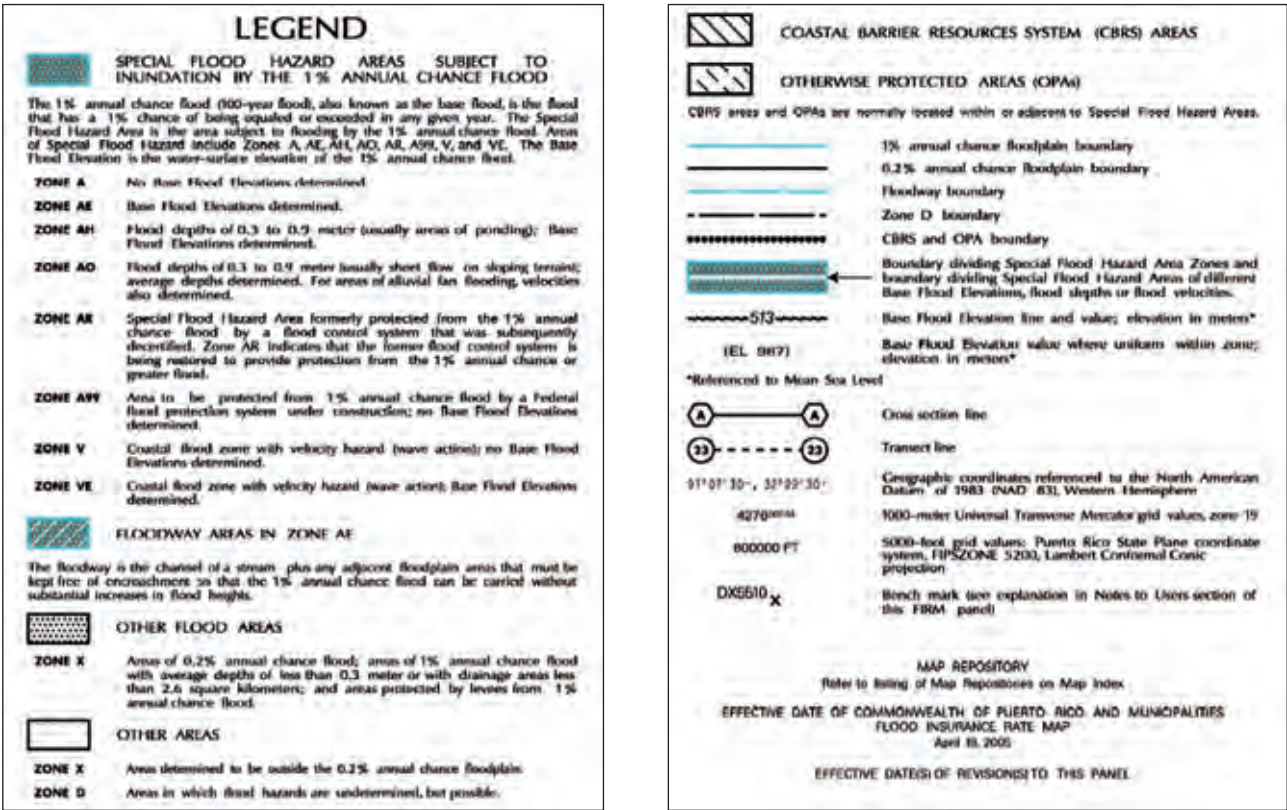


Figure 74. Legend of FEMA's NIFP maps (Godesky, 2006).



The elements' colours should be the natural or common colour of the element being represented; purplish blue for anything related to water (flood-prone areas, isobaths, isovels); yellow or orange for elements related to transported sediment load or sedimentation; red for obstacles to circulation, whether natural (vegetation, rocky outcrops), or anthropogenic (narrowings, channelization, bridges); sepia or brown for human elements (buildings, communication routes, etc.); or historical elements. In case of doubt, always opt to use the standardized colours on basic official Spanish maps (when mapping Spanish territory, for example).

Figure 75 contains a suggested integrated, simplified legend of the elements which can be represented on flood hazard maps, as well as the method for doing so. They have been divided into two categories: those which should appear on partial or sectorial hazard maps, and those which appear in integrated or derivative hazard zoning maps.

As for so-called flood risk maps, the only elements that should be represented are the potential losses, whether in terms of human life (units of persons/year) or material or materials and services (units of Euros/year), on continuous maps or using isopleths, separating social risk from economic risk.

### **3.4. Format of the published map, report and complementary information**

#### **3.4.1. FORMAT OF THE PUBLISHED MAP**

Publishable maps can be divided into two groups: standardized products, that is, adjusted to standardized design characteristics, and specific products adapted to user preferences and to the products' specific purpose (see Figure 72). Furthermore, with respect to the elements they contain, the maps can be divided as follows: partial or sectorial, with solely hydrologic-hydraulic elements, geologic-geomorphologic and/or historical elements; integrated or synthesised maps, with hazard zoning based on one or more of these criteria; or, finally, mixed maps, which combine characteristic of the two previous types (sectorial and integrated).

#### **STANDARDISED MAPS**

Standardised maps are those which are adjusted to standard characteristics or characteristics dictated by some technical guide, regulation or recommendation by a public body with recognized or de facto authority in the relevant domain. In Spain, the principle and most prevalent characteristic of these maps is that they are represented within the Official Geodetic Reference System of Spain (*Sistema Geodésico de Referencia Oficial de España*) in accordance with Royal Decree 1071/2007 of 27 July (BOE no. 207 of 29/8/2007), that is, the ETRS89 (European Terrestrial Reference System 1989) for the Iberian Peninsula, Balearic Islands, Ceuta and Melilla, and REGCAN95 for the Canary Islands, although the ED50 system can still be used until 2015 (International Hayford Ellipsoid of 1924; European Datum, in Potsdam, Germany, of 1950; and the Greenwich meridian as the origin of measurements of longitude). As stipulated by RD 1071/2007 of 27 July, the projection to be used for scales greater than 1/500,000 is the Universal Transverse Mercator (UTM) coordinate system, while for scales less than that the Lambert conformal conic projection (LCC) must be used.

As regards the layout of the contents on standardized maps, the following major elements must be present: main window, legend, box, location and maps, diagrams, and auxiliary elements (Figure 76).

Moreover, the following references should appear in the upper part of the map's main window: the title "geological risk maps" in the upper left corner, the name of the map (for example, "integrated hazard map") centred above the main window and, in the upper right corner, the name of the catchment basin to which the studied reach belongs (one or more), the name of the main reach studied (*idem*), and the river kilometre points

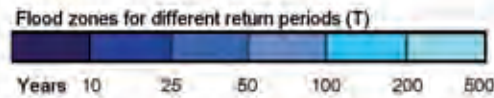




## PARCIAL OR SECTORIAL FLOOD HAZARD MAPS

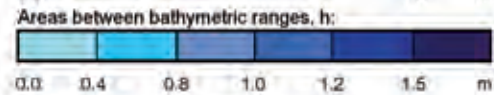
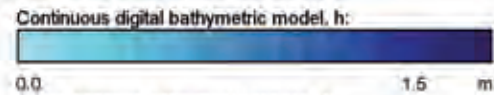
### Hydrologic-hydraulic elements:

#### Flood hazard:



Boundary of flood-hazard area with  $n$  m³/s flow

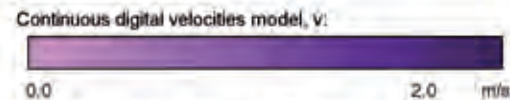
#### Bathymetry:



n-meter isobath

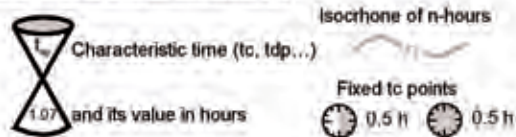
Floodway

#### Water velocity:



n m/s isotach or isovel

#### Characteristic Times:

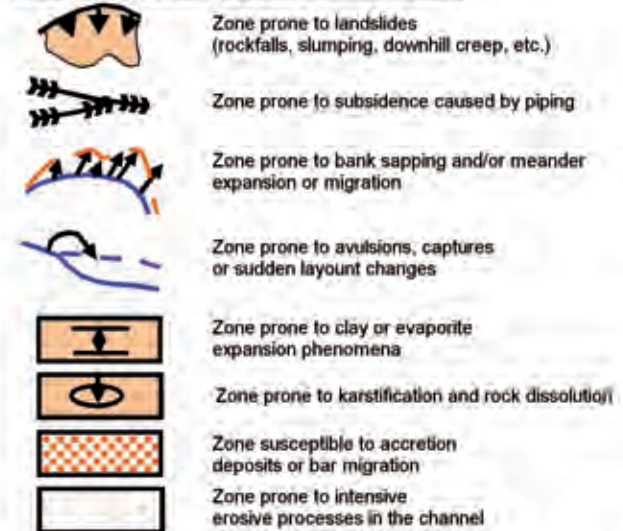


### Geologic-geomorphological elements:

#### Sediment transport:



#### Related geological phenomena:

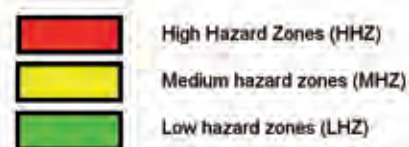
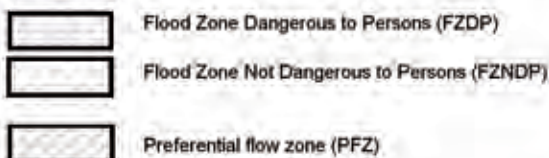


#### Historical elements:



## INTEGRATED OR DERIVATIVE FLOOD HAZARD MAPS

### Zones:



### Boundary between zones:

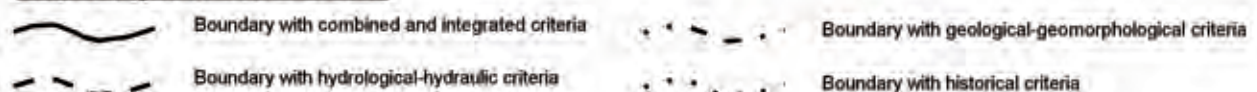


Figure 75. Proposed integrated legend for partial and derivative flood hazard maps.

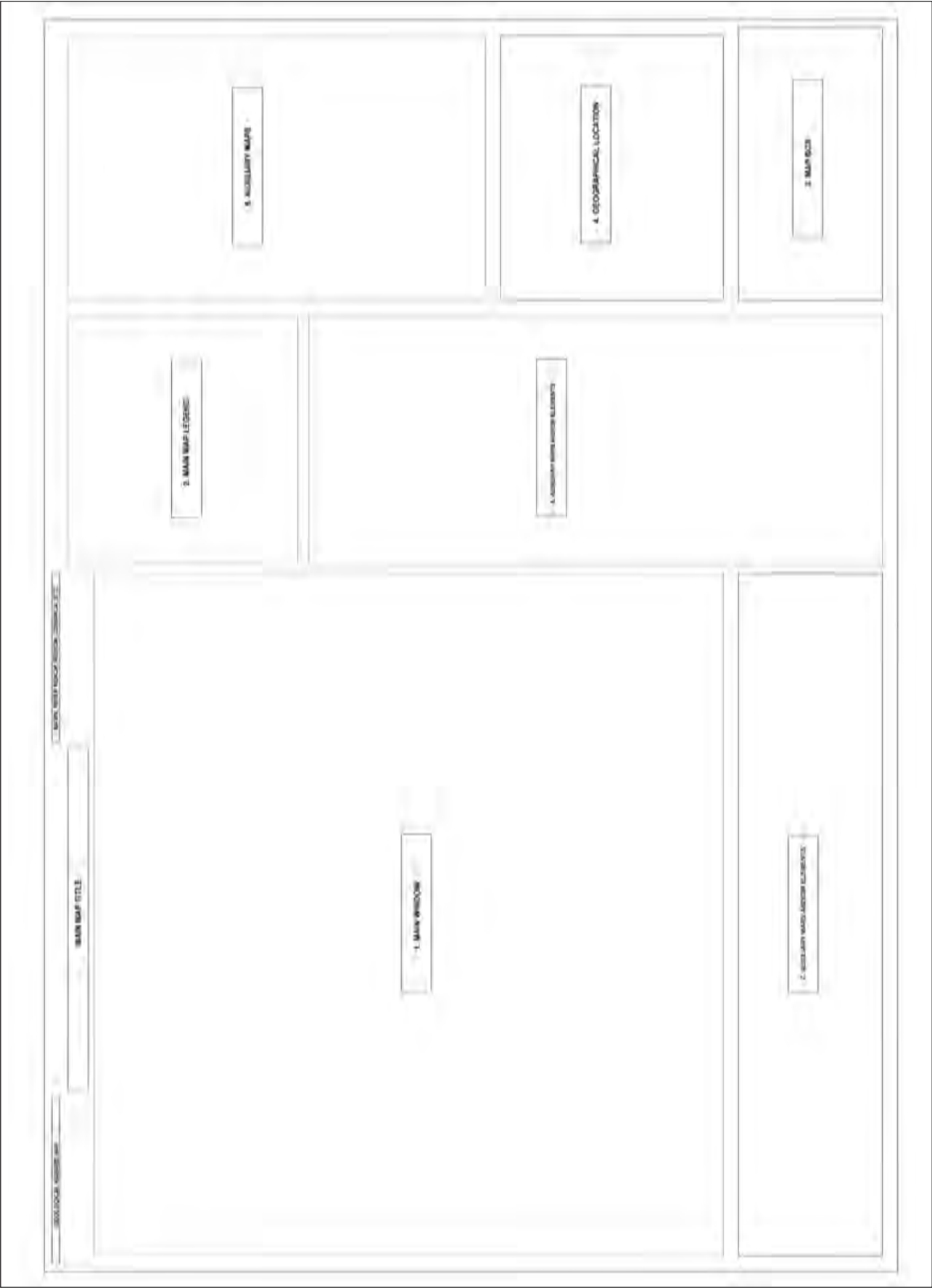


Figure 76. Proposed master template for the layout of elements on a standardized printed map.



(RKP) which define the reach (one or more). These RKPs are calculated through automated GIS-based procedures based on the IGN's (Spain's National Geographic Institute) official BCN25, using "RKP 0.00 km" to indicate the source of the river in question.

Figure 77 shows an example of a small-scale map produced for a civil protection study, for which the auxiliary elements are: other hazard maps from which hazard was drawn; maps of other associated geological dangers; regional  $P_0$  map; and map of mean annual precipitation values for the Iberian peninsula. A brief explanatory text is also included.

For large-scale maps, as shown in Figure 78 (and in the template in Figure 79), some auxiliary elements which could be included are: longitudinal and transversal profiles, images of singular spots, among others. Moreover, to contextualize the area of study, a diagram of the  $P_0$  for the catchment basin, a regional geomorphological map, and a climatic map are included.

#### *Main window (1)*

On flood hazard maps, the **main window** occupies most of the page, while leaving space for elements to the right (map legend, legend of conventional symbols, diagrams, etc.) and below (auxiliary information, complementary graphical information, etc.).

In this main window, the geographical information conveyed by this type of mapping is represented, while the following elements should be common to all maps: planimetry and flood hazard elements.

*Planimetry elements:* the core information must contain all of the official mapping system elements used for each case, complemented wherever necessary for analysis with other information compiled for the same purpose, such as detailed topographical surveys, information related to structures or elements which could potentially obstruct the flow, bathymetries, or altimetric information sources or of other types. If the official system is less detailed than what is required for the compulsory studies, the information used to carry out the analyses shall prevail. This information should always contain references and links consistent with the official system and must be represented in accordance with RD 1071/2007 of 27 July. The symbology of planimetry elements must be adjusted to the corresponding official system, except for the colours of all of the elements, which will be reduced to grey scale, and hydrographic layers, which can remain in their original colours. To complement the data, it is recommended that a highly smoothed grey scale Digital Shading Model be used as a background to facilitate the reading of enclosed elements. The DSM will be a derivative of the Digital Elevation Model used for the analysis, completed, if necessary, by however much enclosed information is deemed necessary to cover the entire main window. The DSM is to be carried out with a light source that has an azimuth of around  $315^\circ$  and an altitude of around  $45^\circ$ , without shadow projection. If the number of elements on the map leads to congestion (for example, when the scale of representation is lower than the scale of the map used), the appropriate filtering must be applied to make it as easy as possible to interpret the map, while always keeping toponymy elements indicating large population centres or landmarks (main thoroughfares, etc.) which act as references.

*Flood hazard elements:* these elements are the key feature of these types of maps, which, in accordance with the method used to produce them, the scale of representation and the intended use, will contain the elements described in the previous sections.

As a suggestion, and for standard scale ranges, the main window of mixed standardized official maps could contain the hazard elements shown in Table 13.

The main window will be framed following the templates of the BCN25 and 50 cartographic databases, that is, with an outer graticule space with intervals in accordance with the scale and an inner line with indications from



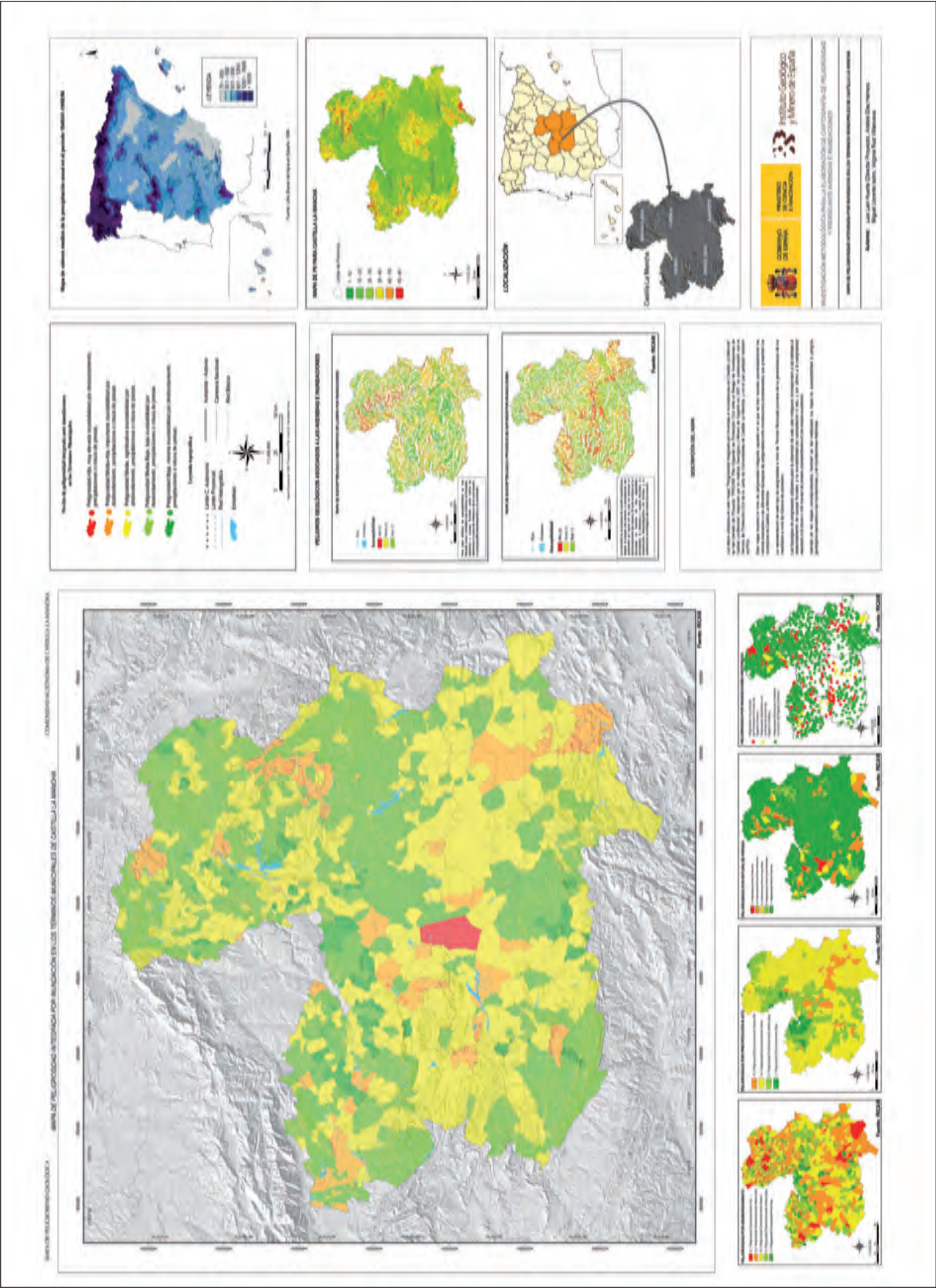


Figure 77. Sample layout of elements on a printed small-scale map.





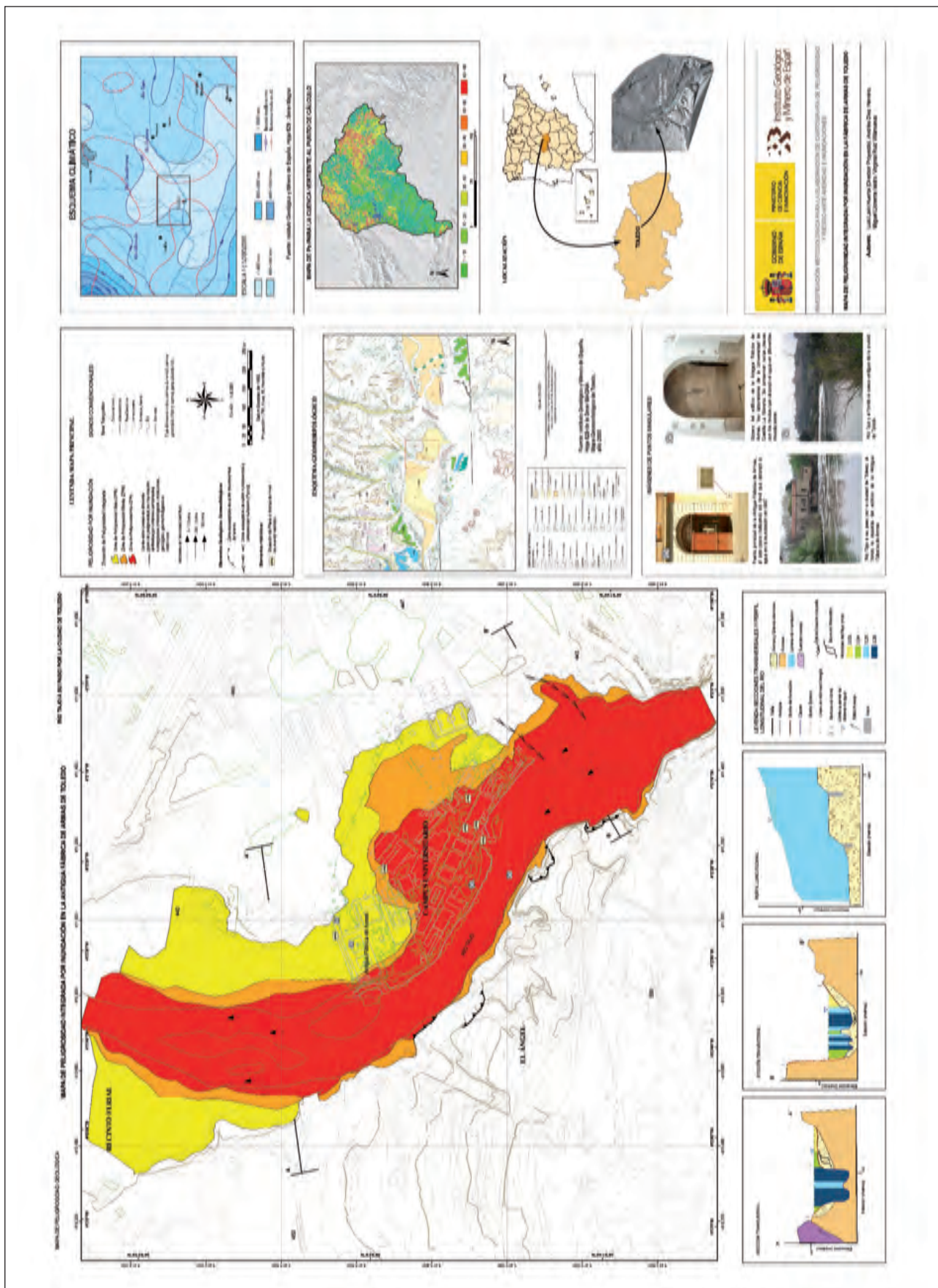


Figure 78. Sample layout of elements on a printed large-scale map.

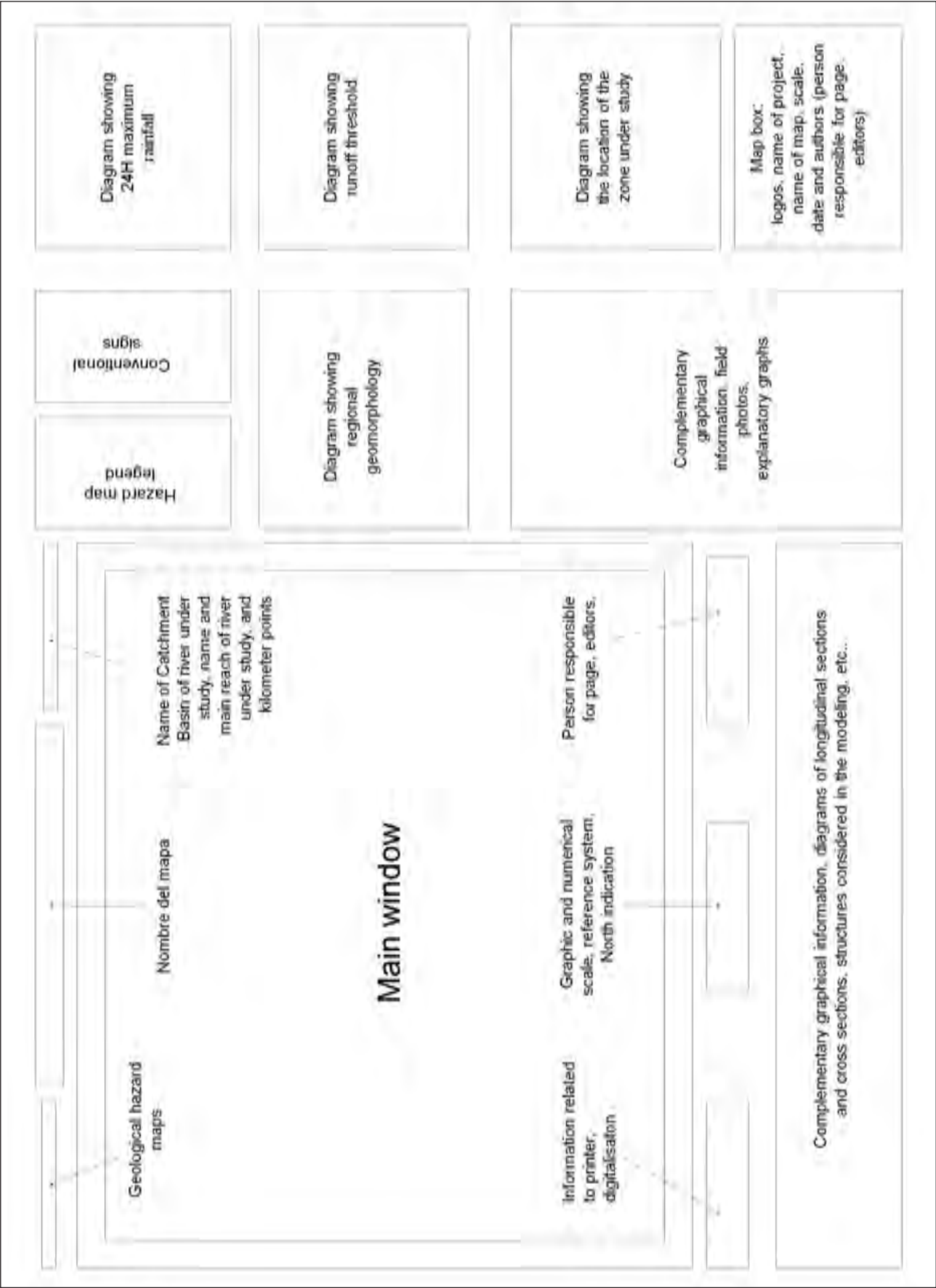


Figure 79. Typical make-up of a large-scale map.



**Table 13.** Components in the main window of a standardized, printed flood hazard map for the range of representation scales. The letters indicate the position of the information layer in order of superimposition, from background (A) to foreground (D).

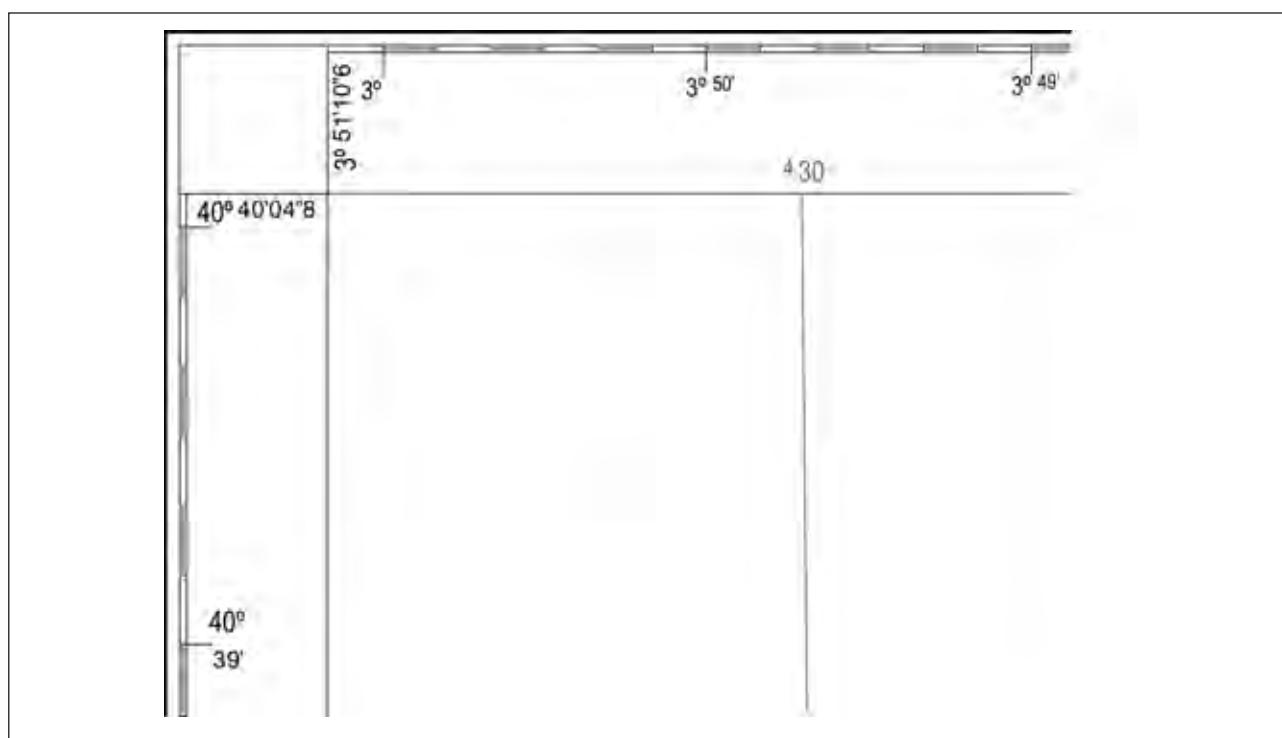
MAPS			Information layer	ORDER OF REPRESENTATION E 1:500 to 1:25,000
Partial or sectorial hazard maps	Hydrological and hydraulic elements	Flood risk	Flood zones for T	A, B
			Flood zone boundary Q	B, C
		Bathymetry	Bathymetric digital model	A
			Bathymetric ranges	A
			Isobaths	C
			Major storm runoff	B
			Single depth point	D
			Stream velocity	Digital velocity model
		Tachometric ranges		A, B
		Isovels		B, C
		Velocity vectors*		D
		Characteristic times	Characteristic time and value	D
			Isochrones	C, D
			Points of fixed time	D
	Geological- geomorphological elements	Sediment load	Ranges of sediment load	B, C
		Related geological phenomena	Landslides	C
			Piping	C, D
			Undercutting by extension	C, D
			Avulsion or entrainment	C, D
			Expansiveness	B, C
			Karstification	B, C
			Accretion	B, C
			Erosion	B, C
	Historical elements	Flood zone boundary	C	
		Elevation reference mark or plaque	D	
		Trouble spot	D	
		Location with information	D	
Integrated or derived hazard maps			FZDP/FZNDP	A
			Integrated hazard zones	A
			Boundaries between zones	B,C

\* The “velocity vector” item is a point represented as a vector whose direction and modulus are part of the element’s attributes.

the UTM graticule (at intervals in accordance with the scale). Only the lines of the UTM graticule may extend into the inside of the main window (Figure 80).

### Legend (2)

In the **legends**, elements from the hazard theme layers of each case will be represented, along with the conventional signs of the planimetry used, in accordance with the adaptation done for this type of mapping. In the same space reserved for the legend, but as an element clearly differentiated and set apart from the legend, there



**Figure 80.** Detailed example of map grid (based on the IGN's BCN25).

will be the graphic and numerical scale, the coordinates system, and the indication of North – all in reference to the main window.

### *Box (3)*

The map box is the space reserved for the map's most immediate information and – together with the location diagram located above it – acts as the map's presentation cover, if it is folded (18x28 cm folds). This box (Figures 77 and 78) shall include, from top to bottom and left to right, the logos of the institutions participating in the map's creation and publication, the number of the project it is being prepared for, the map number, the publishing date, and the authors, starting with the person in charge of the page or the project guarantor and the team which reports directly to them.

### *Location (4)*

The location diagram of the area of study shall contain a polygon vector map of the Iberian peninsula at a scale of 1:4,000,000 with the provincial divisions of Spain (filled with colour) and border boundaries, as well as the boundaries of the main catchment basins (polygons with lines and no filling), and one or two areas amplified successively in order to show the context of the main window (Figures 77 and 78). This diagram will be represented with a smoothed DSM which gives an idea of the relief of the main window.

### *Auxiliary maps, diagrams and elements (5, 6, and 7)*

The final map composition is usually accompanied by other elements (in addition to the corresponding legends, coordinates, scales and orientation) which help to understand the production process, interpret the map or add additional information (Pujadas *et al.*, 1997). For this purpose, there are three areas on the sheet reserved for



complementary regional information. Following are examples of the features represented in them: partial or sectorial maps which contribute information to the main map, such as complementary maps (geological, geomorphological, surficial formations, precipitation, climatic, etc.); cross sections or longitudinal profiles, representation of existing structures, regional diagrams, morphometric studies, field images of landmarks, tables and graphs with data used in the analysis and/or results thereof, explanations or brief descriptions of the map, and the methods used to produce the map.

The information included here will depend on the map type, its use and the scale of representation (Figures 77 and 78; Table 14).

The precipitation diagram will show the maximum precipitation in 24 hours expressed in millimetres for the least favourable case considered in the analyses and which encompasses the catchment basin at the river kilometre points RKP(s) downstream from the studied reach (one or more) and, at a minimum, the immediate boundaries of the basin, or up to the complete covering of the diagram's quadrant. The graphic expression of precipitation shall be done at a scale of five intervals represented by a range of blues, increasing in intensity, as the precipitation value increases. On this diagram, an unfilled polygon will indicate the catchment basin, the main hydrographic elements contained in the basin, and the downstream hydrographic elements which fit. Furthermore, there should be a few elements which help identify the location of the area represented, such as the area's largest population centre(s) or main thoroughfares.

Elements included in the runoff threshold theme layer are the same as those in the precipitation diagram (catch-

**Table 14.** Auxiliary elements to include on the printed, standardized flood hazard map, representation scale in accordance with the representation scale. Green: recommended; yellow, recommended in some cases; orange, not recommended.

AUXILIARY ELEMENTS	SCALE				
	1:5,000	1:10,000	1:50,000	1:200,000	1:1,000,000
Boxes with explanatory text at hazardous locations					
Diagram of maximum 24-hour rainfall with average annual values, etc.					
Runoff threshold diagram					
Diagrams or plans of structures (bridges, obstacles, etc.)					
Regional diagrams (district, region, Autonomous Community, mainland, island, etc.)					
Explanations or brief descriptions					
Field images of landmarks					
Geomorphological and surface formation maps					
Partial or sectorial maps of geological-geomorphological elements					
Partial or sectorial maps of hydrological-hydraulic elements					
Partial or sectorial maps of historical elements					
Cross-sectional or longitudinal profiles					
Tables and graphs with data used in the analyses and results thereof					

ment basin at downstream RKP, population centre, hydrography). The runoff threshold layer is represented re-classified in eight classes delimited by quantiles in a progressive spectrum of colours: brown, yellow, red, blue. The geomorphological and surficial formations diagram will be done in agreement with the corresponding guide (Martín-Serrano *et al.*, 2004-2008) and must cover an extent which is greater than the studied reach and which makes it possible to contextualise the studied area and determine the position of the main geomorphological units directly or indirectly related to the studied reach.

### **3.4.2. REPORT AND COMPLEMENTARY INFORMATION**

Every map must be accompanied by its corresponding written report, which must contain all of the information needed to understand and interpret it properly. Therefore, the report must summarise the techniques, methods and criteria used to produce the map so that anyone with the adequate knowledge and means could reproduce the map production process to obtain an identical end result. For this reason, the report should be exhaustive and complete, including raw information (calculations, partial maps, field notes and data sheets, etc.), as well as detailed results (conclusions, final values).

Depending on the method(s) used in analyzing the flood hazard and the map representation techniques, the report may contain various documents. Nevertheless, a list of the report's minimum elements can be assembled here:

1. Introduction and justification
2. Map objectives
3. Mapped area
  - 3.1. Geographical location
  - 3.2. Geological and geomorphological framework
  - 3.3. Hydrological and hydrogeological context
  - 3.4. Edaphology
  - 3.5. Flora and Fauna
  - 3.6. Soil use and socio-economic activity
4. Hazard analysis methods
5. Hazard representation methods
6. Results: the flood hazard map
7. Discussion about the map's uncertainties
8. Conclusions
9. Bibliographical references

#### **ANNEXES:**

- A. Cartographic annex
- B. Photographic annex
- C. Document annex
- D. Computer annex (files)

At a minimum, the following should be included in the cartographic annex to the report, using as a basis the document entitled "Contents and procedure of flood hazard studies pursuant to the Land-use Planning Ordinance of the Coastal Region of Murcia" (CGRM, 2007):

- Map showing, at a suitable scale, the positioning of the area studied
- Map showing, at a suitable scale, the hidrogeomorphology of the area studied
- Map showing, at a suitable scale, the water basin of the area studied

It would also be worth adding:



- Area photographs (vertical or orthophoto) of the area studied
- Map of values or ranges of the P0 parameter for the catchment basin
- Map of the maximum precipitation values in 24 hours for a given return period
- Lithologic map of the catchment basin at the mapped reach, with the units reclassified in accordance with the hydrologic behaviour potential of their soils (see section 2.2.4)

## ***3.5. Digital representation of the information***

### **3.5.1. ORGANIZATION OF THE INFORMATION**

Digital information generated during the process of preparing flood hazard maps must be properly organized and stored depending on the data logic model to facilitate the access, use, reproduction, and distribution of the data.

The organization is defined as the conceptual description of the information (map elements, graphs, statistics, compiled documents, etc.) in accordance with certain logic classification criteria and is achieved through a file storage structure, a standard for digital representation and special documentation descriptive of the data and related aspects.

To organize digital information it is necessary to define the nature of each element from an automatic mapping point of view, by determining first hand if they are coordinate coverage (comprised of pixels) or vector coverage (comprised of points, lines and polygons, or text, although preferably it will involve dynamic or pseudo-dynamic labelling). The type of digital coding that specifies elements in the legend for flash flood and inundation hazard maps (Figure 75) is represented in Table 15.

The design of the logic model must aim for the highest levels of integration between the information for flash flood and inundation hazard maps, both between itself (different partial or sector maps, and integrated maps) and with the rest of related maps (basic and thematic). This level of integration would be completed with semantic integration in which the elements are linked to a glossary or unified vocabulary. All while following the organization and philosophy for Spatial Data Infrastructures (SDIs), and all requirements derived from the Directive of the European Community establishing an Infrastructure for Spatial Information (INSPIRE). To accomplish this, two tasks must be carried out: digital coding of the elements of the maps and structuring of the digital information.

This data logic design involves establishing a hierarchical conceptual organization within the **discipline of mapping** elements, encompassing the various **concepts** reflected (through their name and origin), their **classes** (through their relations and dependencies), and the **attributes** of each class. For the case in question, flash flood and inundation hazard maps have several concepts to be represented, nearly as many for layers as for coverage (Table 15) for those that establish their contents and relations by means of inventory files (Table 16).

The data model must be completed with a dictionary or glossary of terms and vocabulary, an organizational structure for storing digital information (Figure 81) and a metadata file for each layer, cover, or information storage record.

All this digital information organization work on a logic model will considerably facilitate the implementation in informatics systems as geographic information systems and georeferenced databases.

### **3.5.2. STRUCTURE**

The purpose is to create a single storage repository for all information, data, and documentation for the project, including initial information such as the information generated during analyses and development of the project, final results, and descriptive and final documentation. It is achieved in files classified with criteria related mainly to the typology and meaning of the information, disciplines or themes addressed and required data formats.

**Table 15.** Types of digital layers found on flood hazard maps, along with the elements each layer contains. The cover type refers to M, Matrix and V, Vector; the element types are: Po, Polygon; L, Line; Pt, Point; Pi, Pixel.

MAPS			LAYER OR COVERAGE	Geometry	ELEMENT TYPE
Partial or sectorial hazard maps	Hydrological and hydraulic elements	Flood risk	Flood zones for T	V	Po
			Flood zone boundary Q	V	L, Po
		Bathymetry	Bathymetric digital model	M	Pi
			Bathymetric ranges	V	Po
			Isobath	V	L, Po
			Major storm runoff	V	Po
			Single depth point	V	Pt
			Stream velocity	Digital velocity model	M
		Tachometric ranges		V	Po
		Isovels		V	L, Po
		Velocity vectors*		V	Pt
		Characteristic times	Characteristic time and value	V	Pt
			Isochrones	V	L, Po
			Points of fixed time	V	Pt
	Geological-geomorphological elements	Sediment load	Ranges of sediment load	V	Po
		Related geological phenomena	Landslides	V	Po, L
			Piping	V	L, Pt
			Undercutting by extension	V	L, Pt
			Avulsion or entrainment	V	L, Pt
			Expansiveness	V	Po
			Karstification	V	Po
			Accretion	V	Po
		Erosion	V	Po	
	Historical elements	Flood zone boundary		V	L, Po
		Elevation reference mark or plate		V	Pt
		Troubled spot		V	Pt
		Location with information		V	Pt
Integrated or derived hazard maps			FZDP/FZNDP	V	Po
			Integrated hazard zones	V	Po
			Boundaries between zones	V	L

\* The “velocity vector” item is a point represented as a vector and whose direction and modulus are part of the element’s attributes.

\*\* FZDP: Flood Zone Dangerous to Persons; FZNDP: Flood Zone NOT Dangerous to Persons.

A path is also sought for global access which would allow any user from any PC to reproduce the maps created with GIS technology. This enables direct implementation of data on any computer in such a way that makes its direct and automatic reproduction possible.

Generally, the following levels of organization should be established in the structure:

- All Project information and digital data are stored at the First Level. It physically corresponds to a directory



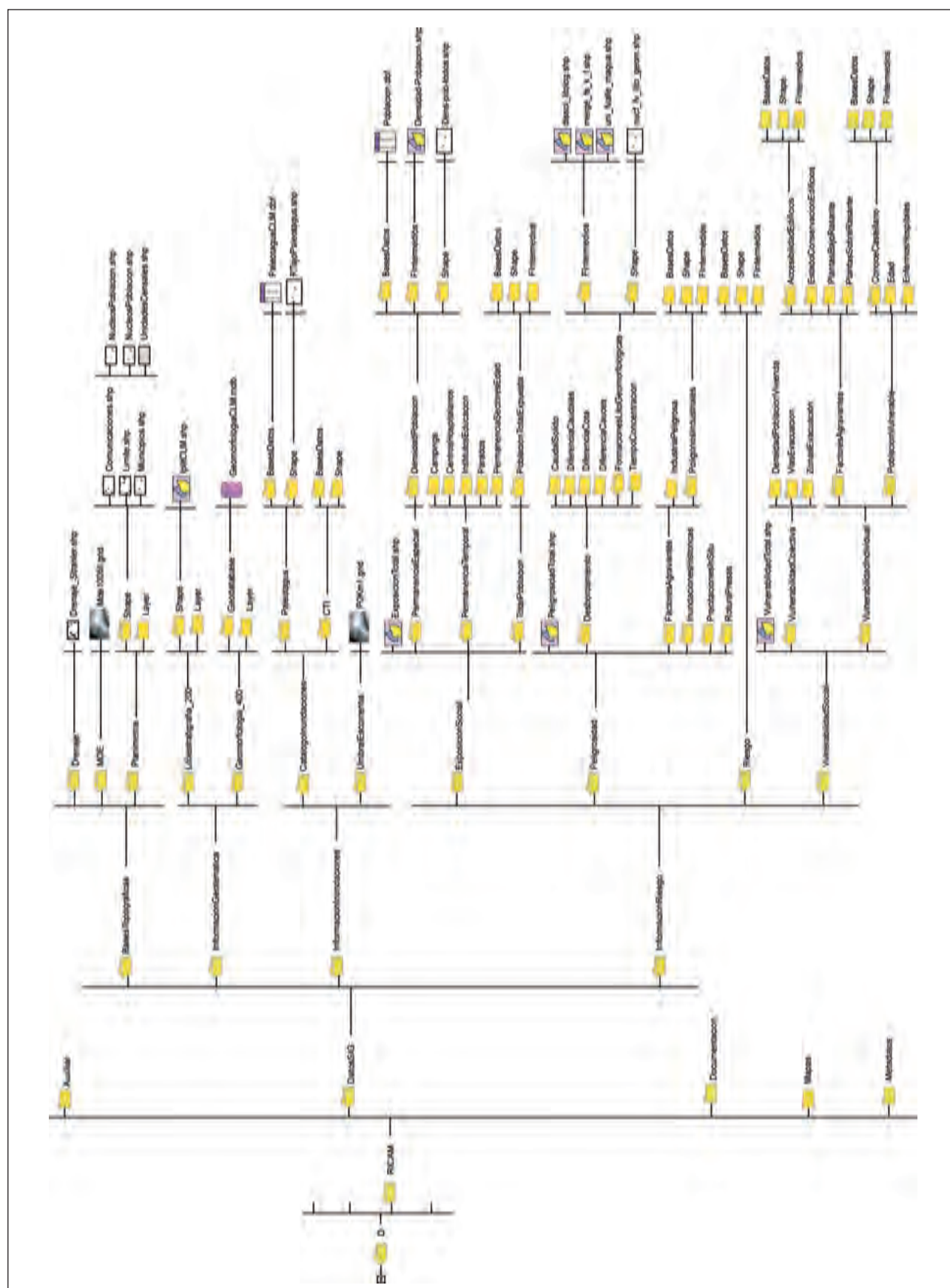


**Table 16.** Example of a file summarizing the contents of a flood hazard map so they can be subsequently organized in a logical data model. Adapted from the sheet proposed by the IGME Geoscientific Mapping Work Group (Pérez-Cerdán, com. pers.).

<b>DISCIPLINE</b>		
Name: FLOOD HAZARD MAPS		
<b>Mapping</b>		
Name: FLOOD HAZARD MAP 1:10,000		
	<b>CONCEPT</b>	
	Name: Integrated hazard zones	
	Origin: Combined analyses through various hydrological-hydraulic, historical and geological-geomorphological methods. Work in the field, laboratory, and office	
	<b>CLASS</b>	
	Name: Map unit	
	Relations: Other geological bases: hydrogeology, geomorphology	
	Dependencies: Parcels from a geomorphological map (surface formations) and from zone maps of danger to persons	
	<b>PROPERTIES</b>	
	Name: Hazard level	
	Name: Representation	
	<b>CLASS</b>	
	Name: Map contact	
	Relations: Other geological bases: hydrogeology, geomorphology	
	Dependencies: Parcels from a geomorphological map (surface formations) and from zone maps of danger to persons	
	<b>PROPERTIES</b>	
	Name: Type of contact	
	Name: Certainty (method by which the contact was obtained)	
	Name: Representation	

with an abbreviated and descriptive name of the map, limited to three words without spaces, and the initial letter of each word is capitalized. To prevent conflicts in reading the information, tildes, diaeresis, apostrophes, and any other diacritical mark not part of the English alphabet (a-z;A-Z, without ñ, ç, parentheses, etc.) or number (0-9) are not used.

- The Second Level contains information structured in five subdirectories which are: Auxiliary, GIS Data, Documentation, Maps and Metadata, which are distinguished by the content of the information that they store.
  - Auxiliary: Stores all information that, unless it is base information for the development of the map or map results, is pertinent to be saved or required to create the maps. For example: Styles, Figures, Logos, Reference Maps and Multimedia Material.
  - GIS data: Contains all spatial data and associated databases, classified first by theme and scale, if specified, and secondly, by data formats in which they are presented, for example: Shapefile, ArcINFO coverage, layers, databases (XLS, ACCESS, etc.) and other documents such as DOC or PDF. The themes are:
- Topographic bases contain topographic information compiled and used for the hazard analysis.
- Geothematic information groups spatial information, direct or indirect, that geologically characterizes the analysis zone and has been used to calculate the flood hazard analysis.
- Hazard information stores information relative to the factors considered for the calculation of the flood hazard.



**Figure 81.** Tree diagram of the folders, subfolders and files, with the information about the data model used to store the flood hazard maps in the framework of the RICAM project (Díez et al., 2008).



- *Documentation: includes all document information relating to the map. For example: Summary sheet, Memory, Other Information and Triptych.*
- *Maps: Stores map products ready for printing and distribution. As in the previous case, they will be organized around theme and format.*

### 3.5.3. STANDARDIZATION

The purpose of standardization is to create a common technical language for the entire project. To this end, basic aspects and organizational and operational fundamentals are addressed for digital mapping products. It will enable the identification of both the contents of the information stored in the records and the internal structure of tables that provide the minimum information required to make it possible to consult the GIS.

The standardization criteria that are to be observed are the following:

- The specification of a clear and legible nomenclature that identifies the elements represented.
- The unique coding of the graphic elements.
- The creation of descriptive tables of the elements represented.
- The generation of an appropriate and unique symbol system.
- The establishment of formats for the distribution and use of the project information.

*Nomenclature* should follow some basic standards for the naming of all the directories and subdirectories that make up the storage structure. In this way, all information records, both the directories that classify the information and data and the different layers that represent them will be retrieved through an abbreviated name indicative of its contents, with a maximum of three words without spaces and initial capital letters. Likewise, to prevent conflicts in reading the information the tildes and accents shall not be used. The names may be of considerable length in many cases, provided that the intent is to be as descriptive as possible of the specific content.

These names may be modified, by adding an underscore and a number where the scale of information represented is specified.

It should be pointed out that this convention will not be applied to information compiled for the execution of the project or existing information. In which case, the original nomenclature is to be retained. Examples are geology, geomorphology and topographic bases.

The *coding* aims to identify unequivocally each graphic element represented in flood hazard maps. To this end, in the spatial table a field named "ID" shall be included that contains an identification number of the elements. Element coding also involves the inclusion of the fields.

- <SYMBOL>, alphanumeric field used for the symbolization of elements.
- <STYLE>, alphanumeric field where the style used shall be specified in the symbolization of elements.

At the same time a table external to the spatial table shall be created where a field <DESCRIPTION> shall be included and any other fields needed to describe the graphic element, its properties and ranges. This table shall be cross-referenced to the spatial table through the identifier.

For existing information and information compiled for the execution of the project, the coding that it had shall be observed.

Regarding the *symbolology* of the flood hazard information, an Arc-GIS style file shall be created where the elements to be symbolized shall be defined in colour, raster, line and point symbolology. From each digital map this

style symbolization shall be applied using the “Match” function. In this way, to maintain the organization of the information and to help their reproduction from any work station it shall be standard that this file is saved in the “Auxiliary” directory in the data structure under a directory named “Symbology”.

Regarding the symbology of auxiliary elements such as geology, geomorphology, topographic bases and others bases, representation that they have of origin shall always be maintained whenever possible.

### **3.5.4. SOFTWARE FILE FORMATS**

#### **VECTOR SOFTWARE FILE FORMATS**

**ArcINFO coverage:** ArcINFO coverage is a vector format for storing spatial information using an arc-node topology that includes INFO tables for attributes of the features included. Coverage consists of a series of files in a folder named after the coverage. Additionally, coverage needs an INFO folder in the same path as the INFO folder with the same name, in which files with classification information are stored. This INFO folder is the most basic unit of spatial information for a GIS environment using the ArcGIS programme by ESRI, although its use and software is oriented toward the ArcINFO version by command line in the corresponding console, it is being used less frequently.

**Shapefile:** The ESRI Shapefile format is a de facto vector standard, very basic to GIS analysis as far as its features and capabilities are concerned, rendering it extremely versatile but with considerable limitations compared to other formats. A Shapefile alone can store only one type of geometry (point, line, or polygon) but is an editable format using virtually any GIS tool currently available, or otherwise, can be imported or exported by several tools to or from different GIS programmes. Information stored in this format is divided into a minimum of three files with the following extensions: .shp (contains the geometry), .shx (contains the index of the features), and .dbf (dBASE IV format that contains the attributes of the objects), but there may be several other extensions, all under the same prefix (that comprises the name of the Shapefile). Among the optional files two are particularly important: .prj contains the coordinate reference system, and .shp.xml contains metadata. Although Shapefiles do not store annotations or use dynamic labels, they may still be of great interest. A Shapefile can store geometry shaped by XYZ nodes, but final mapping deals with 2D (XY) Shapefiles and Z is an explicit attribute. Due to its great ease of use, for both the relatively simple organization of these types of formats, it is the preferred format for vector elements.

There are other vector formats of value to GIS environments, but whether due to their less widespread use than Shapefiles, or due to the fact that they are dedicated mainly to other uses (distribution), this handbook will not address them further.

#### **COORDINATE SOFTWARE FILE FORMATS**

**ESRI Grid:** The ESRI grid coordinate format is the other de facto standard due to its extensive use in multiple platforms and environments. This ESRI Grid format has a binary format (ESRI Grid), an INFO (ArcINFO Grid) format, and an ASCII (ESRI ASCII Grid) format. With the exception of the ASCII format, their organization in folders and files is very similar to the ArcINFO Coverage with its info folder and the folder that names the grid (with strict naming conventions regarding nomenclature). On the other hand, in ASCII format the grid is comprised of a header that contains information on the number of columns and rows, the position of the reference cell, cell size (square), no data value, and then lists the values corresponding to each one in the cells. From a software point of view, the binary format is the most popular, while the ASCII format is the preferred format to ensure compatibility used for the exchange of information in other environments. For flash flood and inundation hazard maps, the ESRI binary grid format is preferred for representing and storing information on velocities and depths, or derived elements from numerical analysis with continuous results (MDBs, MDVs, etc.).





Other coordinate formats are: TIFF or GeoTIFF, IMG, MrSID, BMP, PNG, used primarily for remote sensing applications, with TIFF being the preferred uncompressed format in this case.

#### OTHER SOFTWARE FILE FORMATS

**Spreadsheets:** Several spreadsheet tools are available on the market that are frequently used for software complementary to other tools for flash flood and inundation hazard analysis. They are used particularly to perform analysis of series of precipitation, complex evaluation of tabulated data and other data. However, for compatibility reasons among the most widely used platforms, Microsoft Excel, the office software application, is recommended.

**Other databases:** As with spreadsheets, there are many relational database systems and for the same reasons as with spreadsheets, Microsoft Access is recommended. This database management system performs operations, queries, reports, etc. between complex tables, and interfaces with other applications that use VBA (rest of Microsoft Office applications, ArcGIS, etc.). Both of these also enable, among other things, the creation of macros, interconnection with high-level database environments (for example with SQL Server) through linkage and support of reading individual file systems (such as FoxBASE and other similar applications) through linkage and data import.

#### 3.5.5. DISTRIBUTION FORMATS

**Layers:** .lyr files are ArcGIS records that contain information on the presentation of data contained in other elements (Shapefiles, coverage, grids, etc.), such as symbols, colours, visualization scale parameters, relationships with other tables, etc.

**MXD:** .mxd files are the same as layers, ArcGIS files for use in the ArcMap module. As with layers, they contained all information required for symbolization and visualization of elements contained in other layers, and unlike layers, .mxd contain information on the composition of the map sheet, in other words, the position of the different elements symbolized in relation to the sheet which may be printed (legends, scale bars, auxiliary elements). Like layers, in mxd files information that is visualized is not stored, unless some image is incorporated that is not geographical information (embedding a logo, for example). In an mxd file, different areal graphics have a capacity that allows several geographic zones, texts, titles, images, etcetera, to be represented in such a way that allows the creation of mapping for their edition and reproduction. In each graphic window the coordinates and projection system are stored corresponding to the information symbolized.

**PMF (Published Map File):** Graphic file prepared with an ArcPublisher extension from ArcMap whose representation is a map. It is comprised of a series of points that allow the information to be reconstructed depending on the visualization criteria and query previously established. These files are generated from mxd as they do not include the information that they represent. The visualization of pmf files is done through ArcReader, free-ware that allows the reproduction of pmf files and queries on the information that they include. But unlike mxd files, it is not possible to modify the contents of the file.

**PDF (Portable Document File):** Format for storing text and graphics (coordinate and vector) viewable with Adobe Acrobat. Information contained in the file alone is only a faithful digital rendition of any element comprised for printing on paper, that is to say, in the case it contains a map, all attributes of the geographic information are lost and the coordinates become relative to the sheet on which it will be printed. This format is the most popular for information exchange that is to be referenced graphically or as non-digital support after it is printed, or as a master copy of samples that are sent for printing.

**JPG:** Coordinate format for storing images which retains their quality without the large file size. There are various levels of compression and logically more compression means less quality for an image. Another format sim-

ilar to JPG is PNG, which unlike JPG does not compress the image and therefore provides better potential for quality, enabling the file size to be reduced even more if the colour spectrum used is not very wide. Other coordinate formats are those mentioned earlier (TIFF, MrSID, etc.), which can be more suitable for distributing information in high quality.

*DOC*: Native format of Microsoft Word application, a word processor created by Microsoft, and currently integrated in the Microsoft Office suite. Due to the widespread use of Microsoft Word, this format has become a de facto standard in which texts can be transferred with or without formatting, images, tables, etc. This format is very suitable for editing of memo- and report-type documents, etc.

### **3.5.6. GEOSCIENTIFIC LANGUAGE**

Geoscientific language is the means of expression and transmission of Geoscientific Knowledge in a general and concrete fashion of the knowledge transmitted through flood hazard maps. It is done through the precise and clear description of all elements in these maps and related information. It was developed to provide data and information for different users (governments, businesses, investigational centres, the general public) by means of a standardized and consistent linguistic structure and with a specific terminology that is clear, concise and descriptive.

This enables users not only to access digital map information and associated databases but also enables access to complete descriptive schema for each element represented.

The principal issues that Geoscientific Language should cover are:

- The specification of a Data Model through the formal definition of the Concepts, Classes, Use-Cases, and Features represented in a logical data model.
- The specification of a standardized Geoscientific Vocabulary that describes, classifies, and interprets geoscientific elements and features represented in the model.

The languages are developed through vocabularies and dictionaries that contain the main terms used in flood hazard maps, as needed for describing these maps.

### **METADATA**

The use of metadata, understood as “data specified from the information produced adding value to the information”, will enable the documentation of data in a way that serves to support those who use the information available to the project, allowing them to identify and understand what the data represent.

Geospatial metadata inform users about existing data by describing: the spatial reference system, quality, distribution, format, safety restrictions or frequency of updates, in such a way that describes a set of geographical data for the: “what, when, where, whose, and how” of the data generated.

The information described in metadata can be very diverse, enabling it to be adapted to concrete specifications for each institution. In the concrete case of flood hazard maps, metadata are to follow the model based on the Spanish Core Metadata<sup>53</sup>.

Independently from project objectives, the management of metadata delivered with the proper systems will enable specific searches to be done for the identification of which data are available and where we can find them.

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<sup>53</sup> *Núcleo Español de Metadatos (NEM).*



### **3.6. Updating and maintaining flood hazard maps**

Owing to the fact that flood hazard maps are geothematic, they require continuous updating and maintenance, since the subject being represented, i.e. the hazard from flash floods and inundations, varies over time at human scale.

The changes and variations introduced in the hazard, and therefore in its representation in maps, have three possible sources or origins:

- 1) **The advancement of knowledge and methods of analysis and representation;** within a few years after the development of one of these maps, the methods and techniques used in the analysis and representation (Sections 2 and 3 of this Handbook) may undergo improvements, with the incorporation of new tools, criteria and techniques. An example is the advancement in informatics in the implementation of hydraulic models resulting in representative flood zones.
- 2) **The appearance, discovery or compilation of new sources of data or more data for hazard analysis;** the simple passing of time allows more data to be collected from systematic gauging record and precipitation which enable the improvement of statistical analysis and hydrometeorological models. Also access to more detailed and precise topographies for hydraulic modelling and more historical or palaeohydrological data can be discovered which improve and complete statistical analysis.
- 3) **Changes and trends in determining and trigger variables for inundations;** phenomena such as modifications in the occupation and uses of soil alter the terrain response during the precipitation-runoff process, based on which flood hazard is modified. Other circumstances from climate change, such as variations in the precipitation regime, also cause the hazard value to change, and with it the maps (Anadón *et al.*, 2008).

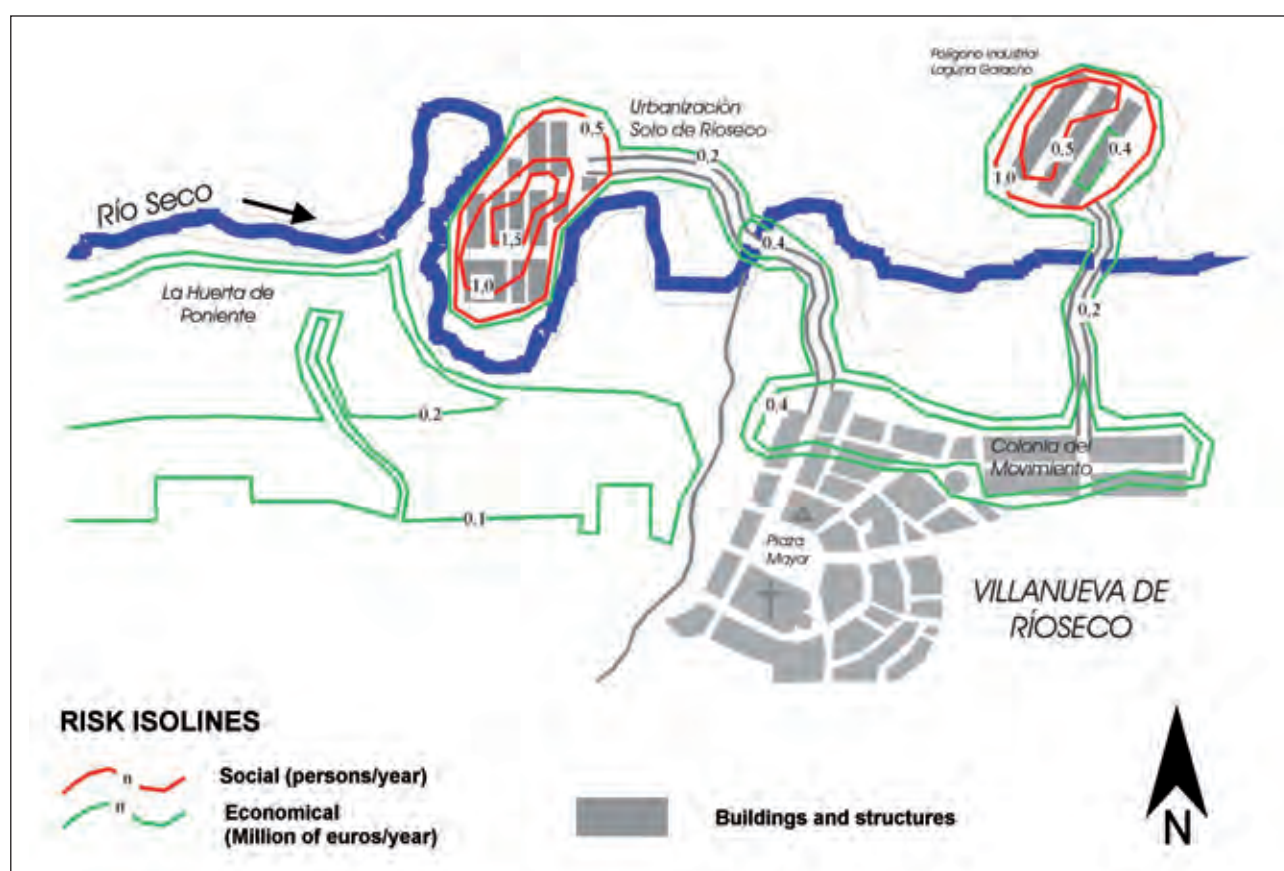
The effects of these sources of variation on hazard and its mapping are not linear, since they can produce changes in them without having a perceptible effect on the result, while a minimum change in any of the variables can precipitate sudden changes (catastrophes) in a characteristic threshold effect on the system. Additionally, simultaneous or consecutive changes in the different sources do not always yield the same resulting hazard, since sometimes they counterbalance and sometimes they enhance the hazard and cause feedback.

For this reason it is not easy to establish values of change, for example, in the use of soils that would serve as a limit to determine the need to update or redo the map. Any simplification in this sense could be counterproductive. Of course, temporary criteria could be established on the recommended timeframes to update maps, as a function of scale and finality of the map, since both variables encompass many of the aforementioned effects and changes. In this way, the flash flood and inundation hazard maps in Spain at a scale of 1:1,000,000 established solely from historic flood catalogue, would specify updates only every 15-20 years, since these days, new inundations that are incorporated into the analysis (with dozens of thousands of historical records), do not vary the results significantly. On the other hand, flash flood and inundation hazard maps for a special detailed urban plan at a scale of 1:500, created using hydrometeorological and hydraulic methods, should be updated every 3-5 years, since the dynamics themselves of urbanization will be the determining factor of change in the hazard.

Therefore, any proposal to prepare these maps is not complete if it is not accompanied by a schedule detailed and evaluated for updating and maintenance, including the timeframes and processes to do it.

### **3.7. From hazard maps to risk maps**

The creation of flood risk maps begins with the socioeconomic analysis and assessments of risk, approached punctually at the parcel or building scale (see methodology in De Mora and Díez, 2008), to later interpolate the values until continuous distributions are obtained from them or isoline maps (Figure 82).



**Figure 82.** Idealized example of a municipal flood risk map for Villanueva de Riaseco. Adapted from Díez and Pujadas (2002).

As it would occur with hazards, a specific flood risk zone could be made, by separating on one side the social risk and on the other side, the economic risk, since legally different treatments are required, due to the protection of human life being more prescriptive for public administrations according to the Spanish Constitution of 1978.

For the social risk, class boundaries are established with criteria used by different international organizations for the categorization of an event such as a disaster or catastrophe (10 death victims) and based on media impacts (100 affected):

- Low social risk zone (yellow): less than or equal to 1 person dead, or less than 10 injured or affected (displaced) annually.
- Medium social risk zone (orange): between 2 and 10 persons dead, or between 11 and 100 injured or affected (displaced), annually.
- High social risk zone (red): greater than or equal to 11 persons dead, or more than 101 injured or affected (displaced) annually.

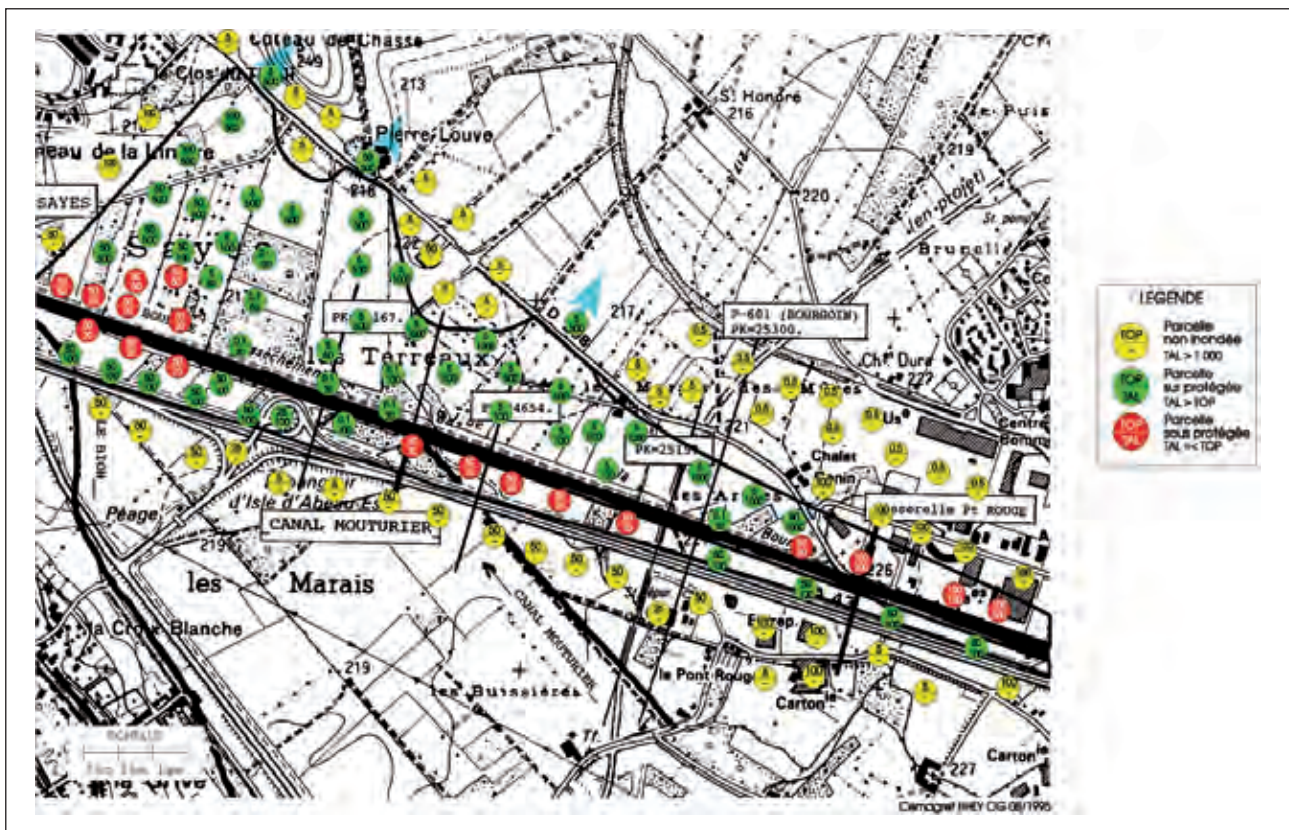
For economic risk, classes that can be established should not be absolute, in other words, from the total number of losses expected, but relative, as long as this number assumes a percentage more or less elevated over insured property or the total of assets of the community. This proposal links risk maps to the concept of resilience, established at the Kobe conference. The classes would be:

- Low economic risk zone (yellow): annual damages predicted between 50 and 100% of insured assets and services.



- Medium economic risk zone (orange): annual damages predicted between 50 and 75% of total assets and services.
- High economic risk zone (red): annual damages predicted between 75 and 100% of total assets and services (complete destruction).

Actually, a much more interesting analysis with its consequent map would be not only social and economic risk maps, but also the difference in both cases between the preoperational situation (before the scheduled urban project or action) and the post-operational (after the execution of the urban project or action). This way, the socioeconomic impact could be evaluated from this action on the risk status and its acceptability studied with a cost-benefit analysis. This proposal links to the final risk maps developed in France using the “flood risk method” (Obelin, 1990; Paquier, 2006) in which the level of exposure and vulnerability are compared, parcel by parcel, with or without preventive actions, so as to extrapolate conclusions on prioritizing measures (Figure 83).



*Figure 83. Example of a risk map obtained using the flood susceptibility method (Paquier, 2006).*



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# ANNEXES

## ***A. Information sources for hazard analysis in Spain***

### MAPS AND PHOTOGRAPHS

#### *Basic maps*

- *Topographic (paper or digital analogue)*: National Geographic Institute (IGN) and Spanish Military Survey (CGE) for scales less than 1:25,000 and 1:10,000, respectively; mapping institutes and agencies of Autonomous Regions, county councils, city councils, and town councils, for more detailed scales.
- *Digital elevation models*: IGN (MDT25, 25x25 m) and CGE (Spanish digital military map, 100x100 m); Aerial Orthophotography National Plan (PNOA), Shuttle Radar Topography Mission (SRTM) ([www2.jpl.nasa.gov/srtm/](http://www2.jpl.nasa.gov/srtm/)), mapping institutes and services of Autonomous Regions, for more detailed scales (up to 5x5 m), and Light Detection and Ranging (LIDAR) (Hydrographic Confederations), 1x1 m.
- *Historical maps*: IGN map collection and CGE map archive, map bases from institutions such as the former National Institute for Nature Conservation (ICONA) and Hydrographic Confederations...

#### *Thematic maps*

- *Geological, geomorphological, and hydrogeological maps*: Geological Survey of Spain (IGME) (Geologic National Map [MAGNA] and GEO-DATA Explorer [GEODE] 1:50,000 and 1:25,000) and geological institutions and agencies of Autonomous Regions.
- *Soil science and soil textures*: Spanish National Research Council (CSIC) and agricultural institutions and agencies of Autonomous Regions, county councils, and city councils.
- *Vegetation and crops*: Crop and yield maps (Spanish former Ministry of Agriculture, Fisheries and Food [MAPA]), Spanish forestry map 1:50,000 (Spanish former Ministry for the Environment [former MMA]), and agricultural and environmental ministries and agencies of Autonomous Regions, county councils, and city councils.

- *Soil use*: Land Cover and Use Information System of Spain (SIOSE); IGN and Autonomous Regions.
- *Maximum daily rainfall maps*: Averages and coefficients of variation (CV) (General Directorate for Roads [DGC], 1999); intensity-duration-frequency (IDF) curves (MAXIN-AQUALIS, Sala and Carrero, 2005 and 2006; Muñoz Martínez, 2002).
- *Runoff threshold map* ( $P_0$ ) of Spain (1x1 km): Centre of Studies and Experimentation of Public Works (CEDEX) (Ferrer, 2003).
- *Maximum peak discharge maps of Spanish streams*: General Directorate for Water (former MMA) and CEDEX (Jiménez, 2007).
- *Flood zone map*: Spanish National System for Flood Zone Mapping (SNCZI), on [www.marm.es](http://www.marm.es), water section, flood prevention (also on [www.mma.es/snczi/](http://www.mma.es/snczi/)).
- *Cadastral map and data*: Cadastral Web Services (Spanish Ministry of Economy and Finance).

#### *Satellite photographs and images*

- *Vertical aerial photographs for stereo vision*: IGN (national flights of 1984 and 2000), CGE (national flights of 1946-47 and 1955-56), other state institutions (National Institute for Agricultural Reform and Development [IRYDA], ICONA...), and mapping institutes and agencies of Autonomous Regions, county councils, and city councils.
- *Orthophotographic and orthophoto maps*: Farming Land Geographical Information System (SIGPAC) (former MAPA and Autonomous Regions), PNOA (IGN and Autonomous Regions), Google Maps, Google Earth ([www.google.com](http://www.google.com)), Yahoo Maps ([maps.yahoo.com](http://maps.yahoo.com)), NASA World Wind ([worldwind.arc.nasa.gov](http://worldwind.arc.nasa.gov)), and mapping institutes and agencies of Autonomous Regions, county councils, and city councils.
- *Oblique aerial photographs*: Private firms (Paisajes Españoles), former CGE, and mapping institutes and agencies of Autonomous Regions, county councils, and city councils.
- *Satellite images*: Landsat (Earth Observation Satellite Company [EOSAT]), Envisat, SPOT, ASTER, IKONOS, QuickBird, WorldView...

### ALPHANUMERIC DATA

#### *Hydrological data*

- *Precipitation data*: State Agency for Meteorology (National Institute of Meteorology of Spain [INM], 1998 and 2003), automatic hydrological information systems (SAIH) of Hydrographic Confederations, DGC (1999), and autonomous meteorological institutions and agencies.
- *Reservoir gauging and levels*: Hydrographic Confederations (official network of capacity stations [ROEA] and SAIH), hydroelectric and management companies for reservoirs, irrigation regions, CEDEX (HIDRO database), water boards, and institutes, agencies and ministries of water management in Autonomous Regions.
- *Water point inventories*: General Directorate for Water (DGA) and IGME.
- *Piezometric levels*: Hydrographic Confederations and IGME.
- *Historical floods*: Technical Commission for Flood Emergencies (CTEI, 1985); Spanish National Catalogue of Historical Floods (CNIH), General Directorate for Civil Protection and Emergencies (DGPCE) (Pascual and Bustamante, 2008); surveys, reference marks or plates, newspaper library, historical archives, local histories and chronicles, ICONA and Guardia Civil reports...
- *Palaeofloods*: Publications in Documentation on Floods and their Risks in Spain (DIRE) (<http://www.riada.es>)
- *Manning's roughness coefficient*:
  - Tables for Manning's N values, with images compiled by the US Geological Survey (USGS): <http://www.rcamnl.wr.usgs.gov/sws/fieldmethods/Indirects/nvalues/>
  - Complete guide also developed by the USGS, more extensive and also with images, values for natural channels and floodplains: <http://www.fhwa.dot.gov/bridge/wsp2339.pdf>





- Compilation of values for natural channels, canals and conduits, extracted from several authors.  
[http://www.fsl.orst.edu/geowater/FX3/help/8\\_Hydraulic\\_Reference/Mannings\\_n\\_Tables.htm](http://www.fsl.orst.edu/geowater/FX3/help/8_Hydraulic_Reference/Mannings_n_Tables.htm)

#### *Socioeconomic data*

- *Census Data*: National Statistics Institute (INE) and Autonomous Regions.
- *Municipal register*: civic primary municipalities.
- *Insured assets and losses*: Insurance Compensation Consortium (Spanish Ministry of Economy and Finance) and Government Sub-delegations and Delegations.
- *Geographic toponymy and nomenclature*: IGN and INE.

#### FIELD DATA ACQUISITION

- Geomorphological characterization (detailed landforms associated with flooding).
- Position of historical reference marks and levels.
- Analysis of palaeohydrological deposits and dendrogeomorphological evidence.
- Morphometric measures: Detail and bathymetric topography.
- Roughness analysis.
- Check of gauging stations and rain gauge stations.
- Field photographs.
- Surveys and interviews of the population.



## **B. Applicable legislation**

### 1. EUROPEAN LEGISLATION

Of the scarce European legislation on flood risk mapping, of particular note is the recently adopted 'EU Floods Directive' (Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks", *Official Journal of the European Union* L 288, 6.11.2007, p. 27–34). It contains multiple references to the utility and necessity of preparing flood risk maps (Article 13), and minimum requirements and deadlines are established for preparing them for each of the Member States' river basin districts (Chapter III).

There are also mentions of flood-related issues in other European legislation, as well as international conventions and treaties (Water Framework Directive, transboundary river treaties, etc.), although these are always in reference to their management and not mapping their associated hazards and risks.

### 2. GOVERNMENT LEGISLATION

#### GOVERNMENT WATER MANAGEMENT LEGISLATION

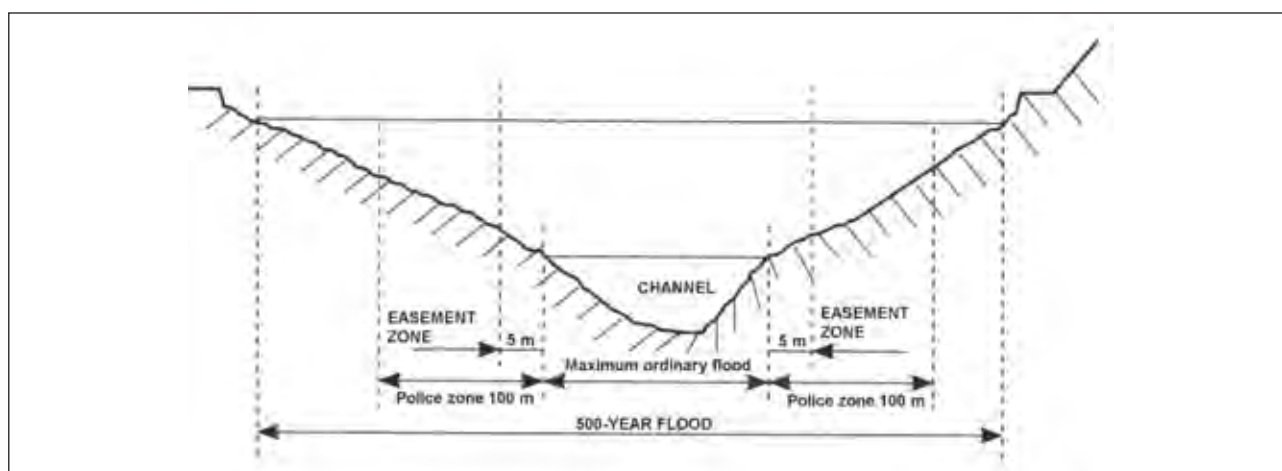
##### *The Spanish Water Act*

The Spanish Water Act (Act 29/1985), the Regulations on Hydraulic Public Domain (RDPH, Royal Decree 849/1986 and its modification in Royal Decree 9/2008) and the Revised Text of the Spanish Water Act (Legislative Royal Decree 1/2001), define flood-prone zones and zone and restrict use of shores in certain areas, such as the natural channel or riverbed (public hydraulic domain) and easement and police zones (boundaries).

Flood-prone zones (Article 11 of the Spanish Water Act and Article 14.3 of the RDPH) are delimited by the theoretical levels waters would reach during floods with a statistical return period of 500 years, unless the Ministry of the Environment and Rural and Marine Affairs, upon proposal by the river basin authority, determines in specific proceedings the demarcation most suited to the river's behaviour. The Revised Text says in its Article 11.2 that river basin authorities shall send to the Administrations responsible for land-use planning and town planning a copy of available flood-related data and studies to be accounted for in land planning and, in particular, land use authorizations issued in flood-prone areas. Furthermore, the following section (11.3) stipulates that the Spanish government, by Royal Decree, shall be entitled to set whatever limits on the use of flood-prone zones it deems necessary to guarantee the safety of persons and property. The modification to the RDPH adds that, for the purposes of delimiting flood-prone zones, consideration will be given to "geomorphological, hydrological, and hydraulic studies, in addition to studies of historical floods and historical documents or evidence related thereto". Within the flood-prone zones, distinction is made between the preferential flow zone, which envelops the intensive drainage waterway, and the zone dangerous to persons (Article 9.2 of the modification to the RDPH).

The natural channel or riverbed is the terrain covered by waters in maximum ordinary floods (Article 4 of the Spanish Water Act). This zone is public and any other use contrary to its natural evolution is therefore prohibited. The modifications to the RDPH add: "the use of this terrain shall be determined taking into account its geomorphological and ecological characteristics and in accordance with existing hydrological, hydraulic, photographic and cartographic information, in addition to available historical information".

Any river current possesses strips of territory on both sides of the channel which are subjected to usage restrictions: the riversides or banks. Taking this channel delimitation defined by the Law as a basis, strips of metric dimension are established along both banks: easement zones (5m) and police zones (100m). The uses on both require the prior authorization of the corresponding river basin authority, and activities are very restricted (Articles 7 and 9 of the Regulations and their modification).



**Figura 84.** Zoning of the channel and banks according the Spanish Water Act (MMA, 2000).

### Hydrological plans

The Revised Text of the Water Act stipulates in Article 42.1, heading n', among the contents of the hydrological river basin plans, that is compulsory to include the criteria in studies, actions and construction works to prevent and avoid damages due to floods, flash floods and other hydraulic phenomena. In Article 2 of the 10/2001 Act of the National River Basin Plan establishes complementary standards for the protection of waters in the public domain and activities in flood-prone areas, such as promoting agreements between the Ministry of the Environment and Rural and Marine Affairs and the autonomous and local administrations in view of eliminating buildings and other installations on waters in the public domain and flood-prone areas which may pose a serious risk to persons and properties in these areas as well as efforts to protect the areas (section 28.3).

## GOVERNMENT LEGISLATION ON LAND USE

### *The former "Land-use Law"*

The so-called Land Law (Royal Decree-Legislative 1/1992 of 26 June, Revised Text of the Land-use Law and Town Planning), as well as its predecessor from 1976, establishes planning as the basis of urban development. This land-use planning is broken down into different classes of town planning (Article 65), such as the National Development Plan, General Municipal Plans, and Territorial Outline Plan for Coordination drawn up in the Autonomous Regions. All of them are structured in a pyramid fashion, since each plan must comply with decisions of the one immediately before it.

As regards municipal activity, the General Municipal Land use Plans are an integral, original instrument which is operated and coordinated at the municipal or supramunicipal (*comarca*) level. They are regulated in Articles 70 and 71 of the Act (word-for-word reproduction of Articles 10.1 and 11 of the Land law of 1976. Their objectives and contents include the classification of land in view of establishing the appropriate legal regime. Other urban figures which can be utilized are the Complementary and Subsidiary Regulations on Planning<sup>54</sup> (Articles 73-75), Urban Action Programmes, Partial Plans, Detailed Studies, and Special Plans. In many Spanish municipalities, the absence of general land-use plans is compensated by Subsidiary Planning Regulations<sup>55</sup>, applied at the municipal level, the main objective of which is to classify the land as: urban, can be urbanised, and cannot be urbanised.

<sup>54</sup> *Normas Complementarias y Subsidiarias del Planeamiento.*

<sup>55</sup> *Normas Subsidiarias de Planeamiento.*



Indeed, classifying municipal land into areas of urban land, land that can be urbanised (or, as the case may warrant, for urbanisation), and land that cannot be urbanized (or their equivalents in the Autonomous Regions), is the best instrument for reducing exposure to elements at risk (persons and properties). The classification is based on Title I of the Law (Town-Planning Regulation on Land Ownership<sup>56</sup>), in particular, Articles 9 and 12. There are two ways in which these classifications can contribute to the prevention of hydrological risks.

1. Protecting the land from the urban development process and establishing protective measures (land which cannot be urbanized).
2. Defining the structure, uses, intensities and types of urban development (land which can be urbanized), or regulating the uses and necessary renovations and reforms (urban land).

The first point rules out the urbanization of certain areas of the district “due to their exceptional value related to agricultural, forests or cattle raising, the possibilities to exploit their natural resources, their landscape, historical, or cultural value, or in view of protecting the fauna, flora or ecological equilibrium thereupon” (Article 12). 12). For this reason it requires decisions (Article 71.3d), such as the establishment of measures and conditions for the conservation and protection of natural elements (soil, flora, fauna or landscape) and recommendations of buildings and locations. It is an effective risk prevention measure insofar as it prevents the establishment of at-risk elements and thus reducing exposure.

The second aspect, the legal nature of the planning instruments, confers administrative powers for deciding the sites of production and residential centres in a way which fosters the best distribution of the population (Article 3.2 b). The same takes place with population density, percentage of occupation, volume, type, number of storeys, class and purpose of buildings, etc. (Art. 3.2 e). These technical decisions may complement one another by means of Detailed Studies, essentially for placing restrictions on size (Article 91). 91). This measure can be effective when it comes to the vulnerability of at-risk elements through distributions and designs suitable for mitigating damages: roads orientated with the flow of the current, buildings with hydrodynamic storeys, absence of basements and depressions, etc.



**Figure 85.** Clipping of a news item published in El País newspaper which offers a clear example of the contradictions arising from the application of the revised text of the Land Law of 1992 and its predecessor of 1976. It reads as follows:

“Local complaints of construction on channel. A judge blames a stream for ‘invading’ construction site. Luis Estaban, El Boalo. Local residents in the Matalpino district of the El Boalo municipal area were taken aback after losing a legal battle they had launched against a development company which had started to erect a block of 27 flats on the banks of a stream. For the residents, what was particularly surprising were the terms used in the verdict issued by substitute judge Esmeralda Casado Portilla at Court number 2 in Colmenar Viejo. “The judge gives to understand that the river invaded the construction project, and not the contrary,” affirmed the residents.”

<sup>56</sup> *Régimen urbanístico de la propiedad del suelo.*

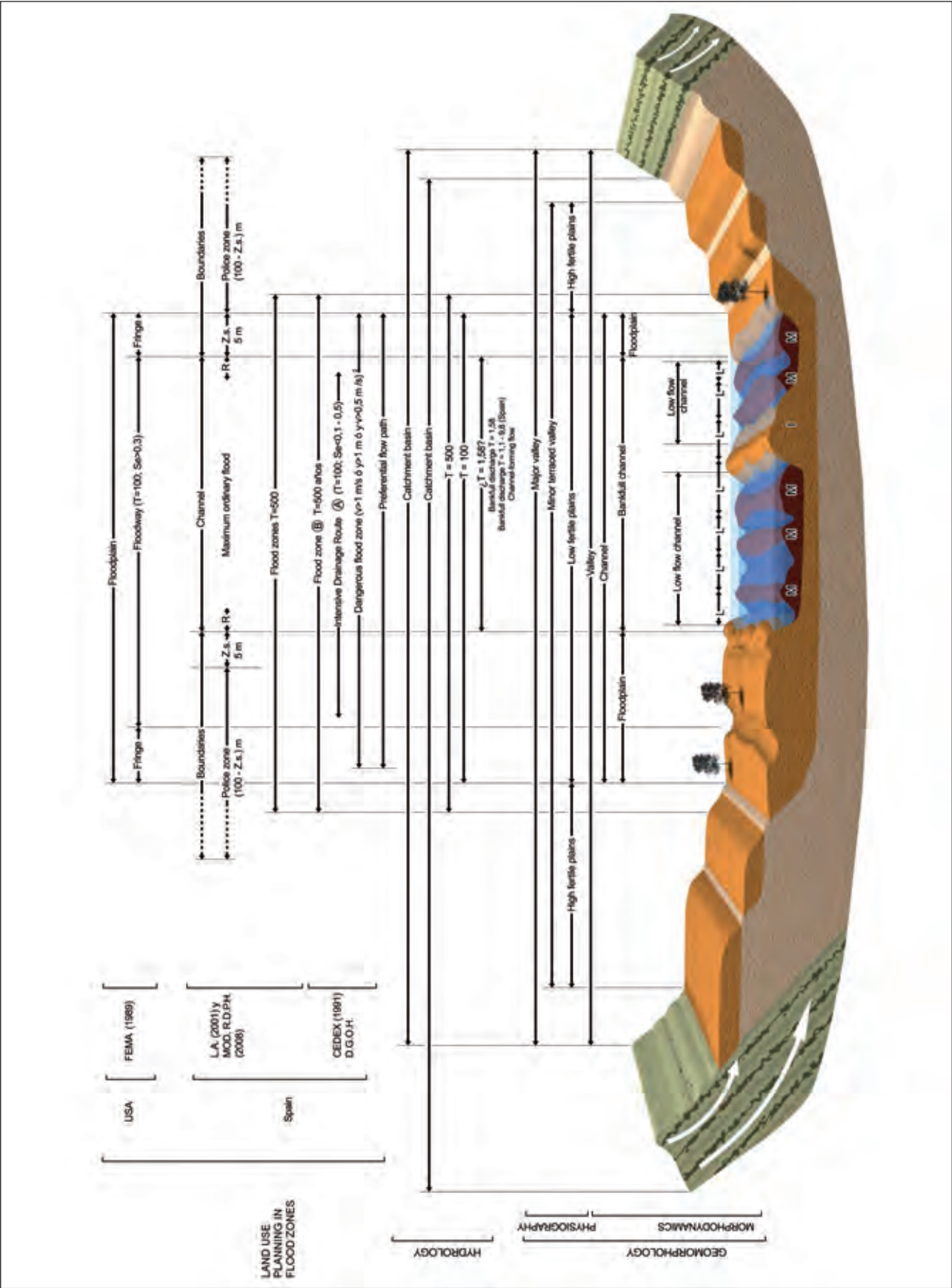


Figure 86. Different zones and ordinance criteria for a flood-prone area along a multi-channel alluvial river. Modified version of Díez and Pedraza (1996).



As a result of the 20 March 1997 sentence by the Spanish constitutional court declaring unconstitutional and null and void a large portion of the articles of the Land Law (Law 8/90 and RDL 1/92) in the face of resources controlled by various regional executives, an important legal void was created. The sentence declared unconstitutional 200 of the 310 articles of the Revised Text, including many of the aforementioned planning regulators (Articles 11, 12, 70, 71, 72, etc.). In Castilla y León alone, this sentence affected the town halls of Soria, Palencia and Valladolid, which had adapted their master plans to that Law, and over 2,235 municipalities with less than 25,000 in habitants.

All of the Autonomous Regions have assumed in the framework of Article 148.1.3 C.E. exclusive powers in land-use planning, town planning and housing development. Therefore, by the power of the Constitution and the Autonomous Statutes, competency in matters related to town planning and housing development lies with the Autonomous Regions. Strictly speaking, this does not mean that the State has been disposed of its jurisdiction in this area, particularly with matters relating to so-called “urban ownership” and the basic conditions which guarantee the equality of all Spanish citizens in exercising their rights.

### *Law on Land Use and Valuation*

On 13 April 1998, the new Law 6/1998 on land use and appraisal was passed and sanctioned. Set forth in five acts, its articles were published in Official State Gazette number 89 of Tuesday 14 April (pages 12296-12304). This Law repeals most of Royal Legislative Decree 1/1992 of 26 June (for which the revised text of the Land and Urban Planning Law was passed), and the first three articles of the Law 7/1997 of 14 April, on Land and Professional Associations Liberalisation Measures.

Just as the Law's Explanatory Statement says, the aim is to achieve greater flexibility in the use of land, eliminating factors of rigidity and facilitating the increase in the availability of land. This will make any land not included in the urban development process, and for which no reasons are found to protect it, susceptible to development. The latter must be in accordance with territorial and sector planning and legislation because of its environmental, landscape, historical, archaeological, scientific, or cultural value, or the richness of its forest, cattle raising, etc., or because it is proven to be unsuitable for urban development.

With respect to the consideration of natural risks, they are only referred to for the purpose of declaring land as non-suitable for development in Article 9, which reads:

#### Article 9. Land not suitable for development.

For the purposes of this Law, land to which the following circumstances apply shall be considered non suitable for development:

1<sup>st</sup>. Which must be so classified for being subject to some special protection regime which does not permit its transformation in accordance with territorial planning or sector legislation owing to its landscape, historical, archaeological, scientific, environmental or cultural value, **or due to natural risks attested to in area planning**, or for its being subject to limitations or easement for the protection of the public domain.

2<sup>nd</sup>. The general planning considers it necessary for the aforementioned instances of ‘value’: agricultural, forest, cattle, or for its natural riches, in addition to whatever other types of land considered non-suitable for urban development.

As can be observed, for the first time in governmental legislation on land use, possible usage restrictions due to natural risks are being considered. However, the subsequent nuances make the measure ineffectual, since no area risk planning has been drawn up yet (progress is only being made on the initial phases of the National Flood Risk Prevention Plan)

### *Natural risks in the new Land Law*

Currently, a new Land Law is in force (Law 8/2007 of 28 May on Land Use; Official State Gazette No. 128 of 29 May 2007), which contains a few relevant references on natural risks in general, and floods in particular: Article 12. Basic land situations.

2. Rural land [...] is land protected by territorial and town planning from being transformed through urban development; said land must include, at a minimum, lands... with natural or technological risks, including **flooding** or other grave accidents, and any others provided for by land-use or town planning legislation.

Article 15. Assessment and monitoring of the sustainability of urban development.

2. The report on the environmental sustainability of the urban planning and activity instruments must include a map of natural risks of the area under study for development.

### 3. LEGISLATION IN THE AUTONOMOUS REGIONS ON LAND MANAGEMENT, TOWN PLANNING AND LAND-USE PLANNING

The new autonomous regulations on land use and spatial planning are to play an important role, complementing and accelerating the processes of declaring zones in the Autonomous Regions which present obvious natural risks in a preliminary area planning phase at the municipal level. Take, for example, the regulations passed by a few of the Autonomous Regions:

- ***Law 9/1994 of 29 September on the use of land in rural Cantabria***

Article 2. Land not suitable for development.

[...] land suitable for development, which cannot be built upon due to risks, including those lands located on excessive slope areas, **flood-prone areas**, places in which there is a risk of rockfalls of any type and the areas affected by said rockfalls, insufficient geotechnical characteristics...

- ***Law 5/1999 of 08 April on Town Planning in Castilla y León***

Article 15. Rural Land (Section e).

"Land threatened by natural or technological risks which make it unsuitable of urban development, such as **flooding**, erosion, sinking [...]"

- ***Decree 94/2005 of 20 October, through which the Sub-regional Land-use Planning Directives of Segovia and Surrounding Area are applied***

#### CHAPTER III

#### Directives on Landscape Management and Risk Prevention

#### Article 33. Protection of plains and **flood-prone areas**

[...] Town planning must preferably classify [plains] as rural land with natural or special protection, and in all cases of land which is part of an easement along natural channels, where any construction, installation, fence, or any other erection would obstruct the flow of waters is prohibited [...]

[...] flood-prone areas delimited in accordance with water legislation shall also be classified, for the purposes of town planning, as rural land with natural or special protection.

[...] Areas prone to flooding due to insufficient drainage or conditions of endoreism shall also be classified preferably as rural with natural or special protection, and if they affect urban land, measures must be established to limit their rising.

[...] The buildings and installations already existing in flood-prone areas must be declared non-compliant with town planning.

Among the various plans and regulations in the Autonomies is PATRICOVA plan in the Autonomous Community of Valencia, a true land use action plan in the face of flood risks (Francés, 1997; GV, 2002). There are also Autonomous Community regulations on the content and procedures of flood hazard studies, such as the terri-





torial plans of the Region of Murcia (Francés, 2005; CGRM, 2007). There are codes governing the handling of risks (including flood-related) in the legislation of the Andalusian Autonomous Community (Pita, 1999).

An exhaustive collection of Autonomous Community legislation on spatial planning which covers natural risks, particularly flood-related, can be found in the summary works by Díez (1997, 2001-2003), Olcina (2002, 2006 and 2007) and in some chapters of the collective work Services and Loans Cooperatives [CCS] (2000).

#### 4. OTHER RELEVANT REGULATIONS

##### *Environmental legislation*

There are many other legal concepts which affect planning in varying degrees and on different scales. The only ones worth mentioning are the national and Autonomous laws on natural reserves and/or nature conservation, since they sometimes impose usage restrictions on large areas of the territory which are classified as protected natural reserves (National Parks, Regional Parks, Natural Parks, Natural Reserves, Natural Monuments, etc.): these usage restrictions are often reflected in the elaboration of Usage and Management Master Plans or the establishment of protected areas for areas which cover one or more municipalities. Likewise, legislation on delimiting and protecting livestock trails (cattle routes, lines, paths, etc.) permits the establishment of public domains in cases where they pass through flood-prone areas.

An example of applicable environmental legislation intended to prevent flood risk is Law 2/2002 on Environmental Impact Assessment of the Community of Madrid, which stipulates:

Article 28. Environmental Impact Study (Content j).

“Identification, characterization and valuation of the generation of direct or indirect risks; land-slides, subsidence, **flooding**, erosion, fire [...] of the project or activity.”

##### *Civil Protection legislation*

Section 6 of the Basic Regulation on Civil Protection (Royal Decree 407/1992 of 24 April) and the Resolution which enacts the Basic Directive (MJJ, 1995) specify the character of Special Plans for the Civil Protection Plans elaborated, passed and officially approved in accordance with the provisions under the Directive. Likewise, it recalls that “they shall be taken in to account by authorized bodies in spatial planning and land-use planning process”.

##### *Sectorial legislation on Public Works*

Development and Public Works legislation contains standardized procedures and methodologies which are useful for the analysis flood hazards, as is the case of the successive Instructions on highway surface draining which, in their different versions (5.2-IC in Decree 14 May of 1990) and with the variants of the modified rational method they propose, make it possible to estimate the flows generated in small and medium-size basins.

##### *Sectorial legislation on Tourism*

There is also sectorial legislation on Tourism pertaining to flood prevention, such as Decree 125/2004 of 11 May by the Government of Aragon, which enacts the Regulation on Open-Air Tourist Accommodation, which presents a precise list of zones in which it is prohibited to set up touristic campgrounds in accordance with sectorial regulations. As a requirement for the authorization of such campgrounds, it proposes a methodology for conducting an analysis of flood, fire and other risks. Among other articles and annexes, Article 15 stipulates:

Other zones posing risks to persons and properties

1. In general, campgrounds may not be located on land where there may be an unacceptable risk, natural or artificial, to the life of persons or to properties.

#### ANNEX I. METHODOLOGY FOR THE ANALYSIS AND ASSESSMENT OF RISKS

1. Analysis and assessment of flood risk at the campground location

A) Direct procedure: historical evidence + hostile area

B) Simplified procedure: flood hazard study

C) General procedure: technical study + zoning of campground's uses



## C. Computer tools and programs

In the technical process of developing flood hazard maps, there are two key phases in which computer tools and applications can be used.

### 1) FLOOD HAZARD ANALYSIS

Flood hazard analysis involves simple programs to facilitate the application of equations and algorithms (statistical analysis of extremes, the rational method...), or of complex programs for digital modelling of processes (rainfall-runoff, open channel flow...). A compilation of these programs and commercial brands can be found in Díez-Herrero (2002c), Francés (2005) and the Governing Council of the Region of Murcia (CGRM) (2007), or by referring to the listing of applications that include endorsement and approval of mapping production agencies at an international level (e.g., FEMA: [http://www.fema.gov/plan/prevent/fhm/fm\\_soft.shtm](http://www.fema.gov/plan/prevent/fhm/fm_soft.shtm)).

For derivation, and for various aspects of hazard analysis, some of the most widely used computer programs, packages, and applications are (see details in the alphabetical listing):

- \* **Statistical analysis for discharges:** LEYES, CHAC, FRESH, AFINS, MAX, HEC-WRC, HEC-FFA, STATS, REGFRQ, MLRP, HEC-SSP, PEAK FQ, MICRO\_FRS and CFA.
- \* **Computerized data sources of maximum rainfall, its parameters (intensity) and analysis:** MAX-PLUWIN, MAXIN-AQUALIS and IDF curves; for statistical analysis, CHAC and ANALEST.
- \* **Morphometric analysis of fluvial catchments with hydrological applications:** ArcHydro and HEC-GeoHMS.
- \* **Hydrological modelling of flood discharges** (simulation of the rainfall-runoff process):
  - Lumped and pseudodistributed models:
    - Equations for the rational method: CHAC, TEMEZv2 and CAUCE.
    - Unit hydrograph: HEC-HMS, MAXAVE, HBV, LISFLOOD, TOPKAPI, TR-20/55, WMS, MIKE-11 UHM, PondPack, ISIS...
  - Distributed models: TETIS, MIKE-SHE, SHETRAN, CASC2D, AFFDEF, DINOSOP, SSVAT...
- \* **Hydraulic modelling of discharge circulation in open channel flows:**
  - Uniform and steady flow equations (Manning): Cauce
  - One-dimensional models: HEC-RAS, MIKE-11, WSPRO, FLDWAV, ISIS, DAMBRK, QUICK 2, SWMSS...
  - Two-dimensional and quasi-two-dimensional models: MIKE-21, Guad 2D, Telemac, Plana, FLOW-2D, Sobek, Riverine, TufLOW, River 2D, Tabs, ALGOR, Flow3D, SMS, LISFLOOD-FP, UCL, DHM, FESWMS 2DH...
  - Two-phase models or with moving beds: DELTA, MOSEC, HEC-6, 4.0 HEC-RAS version, SEDIMOD, SED 2D...
- \* **Combined hydrological-hydraulic modelling:** MIKE-11 Flood Watch, EFFORTS, RIVER CAD...

Other compilations can be found at:

<http://www.miliarium.com/Paginas/Soft/SoftwareHidrologiaHidraulica.asp>

<http://www.bossintl.com/html/products.html>

There are comparative analyses of the different programs, such as that done by Woodhead (2006) and Andrés and Garrote (2007), by comparing the most common two-dimensional hydraulic models.

### 2) CARTOGRAPHIC REPRESENTATION OF HAZARD PARAMETERS

In this respect, the use of GIS is fundamental; in recent years modules and extensions have been developed to be combined with the modelling programs cited, such as HEC-GeoHMS ( $\text{HEC-HMS} \cap \text{ArcGIS}$ ), HEC-GeoRAS ( $\text{HEC-RAS} \cap \text{ArcGIS}$ ) and GISPLANA ( $\text{Plana} \cap \text{GRASS}$ ); by allowing hazard maps or their parameters to be developed (flood prone regions, bathymetry, velocities...) in a semiautomated fashion. A compilation of the numerous fields for the application of GISs in these flood analyses can be found in Díez-Herrero (2002c) and Llorente *et al.* (2008a).

*Brief description of the applications and programs (in alphabetical order)*

**AFFDEF:** Spatially distributed hydrological model developed by the Dept. of Engineering of the University of Bologna and the Hydraulic Engineering Institute of Stuttgart by Montanari and Moretti.

<http://www.costruzioni-idrauliche.ing.unibo.it/people/alberto/pub.html>

<http://www.costruzioni-idrauliche.ing.unibo.it/people/alberto/affdef/affdef.doc>

**AFINS:** A program for frequency analysis of hydraulic extremes (discharge or rainfall), at a point and using systematic information (measure without any type of statistical censoring) and/or not systematic (with statistical censoring). *AFINS* was developed under *IDL* and can be executed using *IDL Virtual Machine 6.1*. This tool is distributed at no charge by RSI (Research System, Inc., <http://www.rsinc.com>) that allows programs built under *IDL 6.1* to be executed without a license. Hydraulic and Hydrological Research Group, *Universidad Politécnica de Valencia* (UPV).

<http://lluvia.dihma.upv.es/software.php?language=en>

**ANALEST:** Hydraulic and Hydrological Research Group (UPV).

<http://lluvia.dihma.upv.es/>

**AQUALIS:** (Muñoz Martínez, 2002) This application enables the computation of maximum daily rainfall values in catchment basins. It was developed as an extension to GIS *ArcView* and uses the *MAXPLU* application.

<http://www.geocities.com/infoaqualis/descarga.htm>.

**ARC-HYDRO:** Developed by the Water Resources Consortium and coordinated by the Center for Research in Water Resources of the University of Texas in Austin. It is a data model that integrates spatial and hydrological information through an *ArcGIS* environment of the Environmental Systems Research Institute, (ESRI). Freeware.

<http://support.esri.com/index.cfm?fa=downloads.dataModels.filteredGateway&dmid=15>

**CASC2D:** This model combines distributed hydrological analysis and two-dimensional hydraulic simulation. Developed by the University of Connecticut in 1995.

<http://gcmd.nasa.gov/records/CASC2D.html>.

**CAUCE:** IGME. Application programmed for the MS-DOS operating system.

**CAUDAL:** IGME. Application programmed for the MS-DOS operating system.

**CHAC:** Hydrometeorological Calculation of Runoff and Rises from CEDEX: Application developed in Visual Basic for MS Windows with calculation subroutines in Fortran 77. Easy to use through its graphical interface. Freeware. Download pre-alpha03 version program and manual: <http://hercules.cedex.es/Chac/>

**IDF CURVES:** (INM, 2003). Based on 67 observations with a precipitation hyetograph from at least 15 years of data, the series of annual maximum precipitation intensities for each year of the observations selected over different time intervals of accumulation from 5 minutes to 72 hours, for the purpose of covering the largest range of time scales possible. To compute the IDF curves the series for annual maximum intensity values were set to the SQRT function, obtaining maximum intensities expected for different return periods for each duration of the episode.

<http://www.aemet.es/es/portada> (new web page of the State Meteorological Agency)

**DAMBRK:** One-dimensional hydraulic modelling software developed by USACE. [http://www.bossintl.com/html/dambrk\\_overview.html](http://www.bossintl.com/html/dambrk_overview.html).

**EFFORTS:** Environmental Technologies & Products.

**FESWMS 2DH:** A modular computer application for 2D modelling of surface water based on a numeric model of finite difference grids.

<http://water.usgs.gov/software/FESWMS-2DH/>





**FLDWAY:** Application for one-dimensional hydraulic modelling of unsteady flows (National Oceanic and Atmospheric Administration [NOAA]). An application of the model can be found at:  
<http://kfkf.baw.de/conferences/ICHE/2002-Warsaw/ARTICLES/PDF/119C1.pdf>

**FLOW 3D:** Calculation of steady flow grids in a three-dimensional system using the finite element method. Distributed by GGU Software.  
<http://www.ggu-software.com/software/ggu-geohydraulic-analysis/geohydraulic-analysis.html>

**FLOW-2D:** Calculation of steady flow grids in a two-dimensional horizontal, vertical and axis-symmetrical system using the finite element method. Distributed by GGU Software.  
<http://www.ggu-software.com/software/ggu-geohydraulic-analysis/geohydraulic-analysis.html>

**FRESH** (*Frequency Estimation in Hydrology*): Program developed by T.B.M.J Ouarda, Y. Handi and B. Bobée (University of Quebec; Ouarda *et al.*, 2004) for Windows on a *Matlab* 5.3 platform. Article Reference:  
[http://www.ccma.csic.es/dpts/suelos/hidro/images/chapter\\_32\\_phefra.pdf](http://www.ccma.csic.es/dpts/suelos/hidro/images/chapter_32_phefra.pdf)

**GISPLANA:** A hydraulic model for simulating elevations and flows in channels and margins of floodplains. These floodplains are discretized into cells and the types of hydraulic connections are defined between them. The computer application was developed by CEDEX and integrates the PLANA model, developed by J. Cuena and his research team, and connection to a GIS for the pre-processing and post-processing of information. Initially it was connected to the GIS GRASS model and currently is connected to GIS of ESRI through an interface programmed for ArcView. The purpose of this model is the hydraulic simulation of two-dimensional unsteady flows in floodplains, and is integrated into GIS.  
<http://hercules.cedex.es/Hidrologia/pub/proyectos/gisplana.htm>

**GUAD 2D:** A two-dimensional simulation model designed by INCLAM for the analysis of flood waves caused by rainfall or by gradual or spontaneous destruction of dams and retaining walls for large reservoirs of water.  
[http://www.inclam.com/en/\\_INCLAMSOFT/is\\_hidraulica.php](http://www.inclam.com/en/_INCLAMSOFT/is_hidraulica.php)

**HEC-6:** A one-dimensional model developed by USACE for the analysis of the interaction between sediment and water flow. <http://www.hec.usace.army.mil/software/legacysoftware/hec6/hec6.htm>

**HEC-FFA:** This application follows the instructions in Water Resources Council Guidelines for Determining Flood Flow Frequency, Bulletin 17B: <http://www.fema.gov/library/viewRecord.do?id=2360> of March 1982; it was designed for calculating flood frequency curves in those catchment basins with a data series of at least 10 years that guarantees statistical analysis. Download the software and manuals from:  
<http://www.bossintl.com/products/download/item/HEC-FFA.html>

**HEC-GeoHMS:** A software package that functions as an extension to the ESRI's *ArcGIS* environment for developing hydrological models with HEC-HMS. Analyzing digital terrain information, HEC-GeoHMS yields data such as drainage paths and watershed boundaries.  
<http://www.hec.usace.army.mil/software/hec-geohms/>

**HEC-GeoRAS:** An extension for the *ArcGIS* environment for pre- and post-processing of geospatial data in the HEC-RAS hydraulic model.

**HEC-HMS:** Developed by the Hydrologic Engineering Center (HEC) of USACE. This software calculates the hydrograph produced by a catchment when precipitation data are available.  
<http://www.hec.usace.army.mil/software/hec-hms/>

**HEC-RAS:** Freeware developed by USACE that uses a one-dimensional model to calculate hydraulic parameters of floods.  
<http://www.hec.usace.army.mil/software/hec-ras/>

**HEC-SSP:** This application combines the capabilities of statistical analysis of HEC-FFA, STATS, REGFRQ and

**MLRP.** It performs flood flow frequency analysis based on the Guidelines for Determining Flood Flow Frequency, Bulletin 17B.

<http://www.hec.usace.army.mil/software/hec-ssp/>

**HEC-WRC (USACE):** This application performs frequency analysis for annual maximum flood values according to the Water Resources Council Guidelines for Determining Flood Flow Frequency, Bulletin 17B. It was developed using Fortran language for use in IBM/PC with MS-DOS systems 2.1 or higher and a minimum of 156K memory.

<http://www.fema.gov/library/viewRecord.do?id=2360>

**IHAV7:** Software program for estimating hydrologic alteration indicators.

<http://www.nature.org/initiatives/freshwater/conservationtools/art17004.html>

**ISIS:** Software developed by Wallingford for hydrologic analysis; it also includes modules for computing water quality (Quality Module) and sediment transport (Sediment Module).

<http://www.wallingfordsoftware.com/products/isis/>

**LISFLOOD-FP:** This model was developed for simulating floods in large European catchment basins, taking into account such parameters as soil use, precipitation, and climate change.

<http://source.ggy.bris.ac.uk/wiki/Lisflood>

**MAX:** Developed by Jerry R. Stedinger (Stedinger *et al.*, 1988; Cornell University, School of Civil and Environmental Engineering). It integrates data from palaeohydrology in flood frequency analysis, using a maximum likelihood algorithm.

[http://www.cee.cornell.edu/index.php/people/?ktf=website/person/faculty\\_research\\_detail/research\\_id=1676/id=188](http://www.cee.cornell.edu/index.php/people/?ktf=website/person/faculty_research_detail/research_id=1676/id=188)

**MAXAVE:** A program for calculating flood hydrographs in small catchment basins, developed by the Council of Alicante, Department for the Water Cycle.

<http://bibliot.udl.es/cgi-bin/vtls.web.gateway?authority=0807-96380&conf=080000>

**MAXIN:** Estimation of maximum rainfall intensity for certain durations and return periods in the Peninsula of Spain. Developed by the *Universidad Politécnica de Madrid, Escuela Universitaria de Ingeniería Técnica Forestal (EUIT)*, University Dept. of Hydraulics and Hydrology (Salas and Carrero, 2005 and 2006). A computer application developed based on GIS for computing annual maximum intensities.

[http://138.100.95.131/hidraulica/MAXIN\\_v2/MAXIN/APLICACION/principal.html](http://138.100.95.131/hidraulica/MAXIN_v2/MAXIN/APLICACION/principal.html)

**MAXPLUWIN:** Developed by the Technical Office of the General Directorate for Roads of the Ministry of Public Works and the Center for Hydrographic Studies (CEH) of CEDEX in 1999. This operation method provides a value for the maximum daily rainfall in the Peninsula, for the purpose of serving as a foundation for computing flows by compensating for the absence of gauged data.

[http://epsh.unizar.es/~serreta/documentos/maximas\\_Lluvias.pdf](http://epsh.unizar.es/~serreta/documentos/maximas_Lluvias.pdf)

**MIKE 11:** Developed by the Danish Institute of Hydraulics (DHI), MIKE 11 is a surface water modelling system. It consists of a software package for one-dimensional modelling, using Saint Venant equations. It includes a set of modules for analyzing advection-dispersion, ecology and water quality, sediment transport, flood prediction, real-time operations, dam breach modelling, etc.

<http://www.dhi.es/Software/RecursosHídricos/MIKE11.aspx>

**MIKE 21:** A two-dimensional DHI software. A version exists for rectangular grids and another one for flexible grids, MIKE 21 FM. MIKE 21 FM.

<http://www.dhi.es/Software/Marino/MIKE21.aspx>

**MIKE FLOOD:** An integrated tool for flood analysis developed by DHI. It combines one-dimensional MIKE 11 model with the two-dimensional MIKE 21 model, for the analysis of floodplains.

<http://www.dhi.es/Software/RecursosHídricos/MIKEFLOOD.aspx>



**MIKE SHE:** Developed by DHI, this software program is a modelling system for hydrological cycles at all phases. Not only is it a three-dimensional, numerical groundwater model but also includes numerical models for over-land flows, unsaturated flows, evapotranspiration, etc.  
<http://www.dhi.es/Software/RecursosHídricos/MIKESHE.aspx>

**MLRP** (Multiple Linear Regression Program): A linear regression analysis tool.  
<http://www.hec.usace.army.mil/software/hec-ssp/>

**PLANA:** A hydraulic model for simulating elevations and flows in channels and floodplain margins developed by J. Cuenca and his research team (CEDEX).  
<http://hercules.cedex.es/Hidrologia/pub/proyectos/gisplana.htm>

**PONDPACK:** Hydrologic analysis software developed by Bentley.  
<http://www.bentley.com/en-US/Products/PondPack/>

**QUICK 2:** Software developed by FEMA for the study and analysis of flood risk dedicated to the local office's use in the application of the National Flood Insurance Program.  
[http://www.fema.gov/plan/prevent/fhm/dl\\_qck22.shtm](http://www.fema.gov/plan/prevent/fhm/dl_qck22.shtm)

**REGFRQ** (Regional Frequency Computation): This application performs regional frequency analysis.  
<http://www.hec.usace.army.mil/software/hec-ssp/>

**RIVER 2D:** A finite difference hydrodynamic model applied to the two-dimensional modelling of open channel flows, developed by the University of Alberta. Freeware.  
<http://www.river2d.ualberta.ca/>

**RIVER CAD:** Software supported by HEC-RAS that incorporates structures such as culverts, outlets, dikes, bridges in the model for calculating the flood zone.  
[http://www.bossintl.com/html/rivercad\\_overview.html](http://www.bossintl.com/html/rivercad_overview.html)

**SEDIMOD:** A one-dimensional hydraulic calculation model.

**SED 2D:** A two-dimensional finite element model for computing sediment transport, developed by USGS.  
[http://smig.usgs.gov/cgi-bin/SMIC/model\\_home\\_pages/model\\_home?selection=sed2d](http://smig.usgs.gov/cgi-bin/SMIC/model_home_pages/model_home?selection=sed2d)

**SHETRAN** (European Hydrologic System): A physically based, spatially distributed, coupled surface/subsurface model. Developed by the University of New Castle (UK), Dept. of Civil Engineering.  
<http://www.ncl.ac.uk/>  
<http://www.epa.gov/nrmrl/pubs/600r05149/600r05149shetran.pdf>

**SMS** (Surface Water Modelling System): A 2D and 3D hydrodynamic model with three modules: a 2D based on finite elements, another 2D on finite differences, and a 3D on finite elements. It contains two phases: pre- and post-processing for modelling surface water. Software that models data such as surface water elevations and flow velocities for steady and unsteady flows. Developed by EMS-I: <http://www.ems-i.com/>

**SOBEK:** Software used for one-dimensional and two-dimensional hydraulic flood modelling, developed by Delft. <http://delftsoftware.wldelft.nl/>

**SSVAT** (Snow- Soil- Vegetation Atmosphere Transfer): Distributed analysis model for characterizing catchment basins. Some articles on the applications for this model can be found in:  
<http://www.eecs.umich.edu/RADLAB/html/techreports/RL1015.pdf>  
[http://www.easternsnow.org/proceedings/2006/chung\\_and\\_england.pdf](http://www.easternsnow.org/proceedings/2006/chung_and_england.pdf)  
<http://www.hydrol-earth-syst-sci.net/7/920/2003/hess-7-920-2003.pdf>

**SSIIM-CFD:** A 3D hydraulic model.

**STATS** (Statistical Analysis of Time Series Data): Performs frequency analysis.  
<http://www.hec.usace.army.mil/software/hec-ssp/>

**TABS:** A two-dimensional hydraulic modelling system developed by USACE. Previous version, FastTABS.  
<http://www.ce.utexas.edu/prof/maidment/gishydro/ferdi/research/ccbflow/ccbflow.html>  
<http://tabs.lsu.edu/Phase%20I%20report%20feb7.pdf>  
<http://search.informit.com.au/documentSummary;dn=495096086514797;res=IELENG>

**TELEMAC:** A comprehensive system for hydraulic modelling of open channel flows. It also includes pre- and post-processing tools as well as modules for two- and three-dimensional models. Developed by Jean Michel Hervouet. <http://www.telemacsystem.com/gb/default.html>

**TEMEZ V2:** Hydraulic and Hydrological Research Group, UPV: <http://lluvia.dihma.upv.es/software/temezv2b.xls>

**TETIS:** UPV Hydraulic and Hydrological Research Group, <http://lluvia.dihma.upv.es/>. Freeware. The TETIS model was developed at the Institute for Water and Environmental Engineering (IIAMA) and is a conceptual distributed model. This model calculates runoff using the kinematic wave approach (simplification of the Saint Venant's principle), taking into account geomorphological characteristics of the catchment to route the flow along the channel (geomorphological kinematic wave). See Section 2.1.1.

**TOPKAPI:** A distributed hydrologic model developed by Liu and Todini in 2002 (University of Bologna). This model transforms precipitation and temperature data in runoff. An article on the bases of the model and applications can be found at:  
<http://www.hydrol-earth-syst-sci.net/9/347/2005/hess-9-347-2005.pdf>

**TR-20/55:** A tool for generating hydrographs developed in Fortran by the US Department of Agriculture. The versions for Windows are WINTR-20 and WINTR-55. WINTR-55 uses the bases of WINTR-20 to improve hydrological calculations.  
[http://www.wsi.nrcs.usda.gov/products/W2Q/H&H/Tools\\_Models/WinTR20.html](http://www.wsi.nrcs.usda.gov/products/W2Q/H&H/Tools_Models/WinTR20.html)  
[http://www.wsi.nrcs.usda.gov/products/W2Q/H&H/Tools\\_Models/WinTR55.html](http://www.wsi.nrcs.usda.gov/products/W2Q/H&H/Tools_Models/WinTR55.html)

**TRISULA:** A 3D hydraulic model.

**TUFLOW:** A tool for flood modelling and tide simulation. Developed by the finite difference method, uses one- and two-dimensional flow equations. Distributed by the Scientific Software Group.  
[http://www.scientificsoftwaregroup.com/pages/product\\_info.php?products\\_id=204](http://www.scientificsoftwaregroup.com/pages/product_info.php?products_id=204)

**WMS:** The Watershed Modelling System is a hydraulic and hydrologic modelling system, compatible with other HEC-RAS and HEC-HMS programs. Developed in the GIS environment, which facilitates mapping of the model results. This software package has functions such as: Automatic delimiting of catchment basins, stream network, and extracting cross-sections. Developed by EMS-I: <http://www.ems-i.com/>

**WSPRO:** An application of a one-dimensional gradually varied model. Developed and distributed by USGS.  
<http://water.usgs.gov/software/WSPRO/>





## ***D. Directory – Flood Risk in Spain***

In simplified terms, the directory of organizations, centres, and working groups that address in Spain each aspect of flood risk mentioned in previous sections may be organized schematically for the General State Administration (AGE) in:

- **Flash flood and inundation hazard mapping and analysis:**
  - Geological Survey of Spain (Ministry of Science and Innovation): <http://www.igme.es>
  - Centre for Hydrographic Studies (CEH), CEDEX (Ministry of Development): <http://hercules.cedex.es>
  - The Spanish Hydrographic Confederations and the General Directorate for Water (Ministry of Rural, Marine and Natural Environment): <http://www.mma.es>
- **Flood prediction measures:**
  - Spanish State Meteorological Agency (Ministry of Rural, Marine and Natural Environment): <http://www.aemet.es>
  - The Spanish Hydrographic Confederations and the General Directorate for Water (Ministry of Rural, Marine and Natural Environment)
- **Flood protection measures:**
  - The Spanish Hydrographic Confederations and the General Directorate for Water (Ministry of Rural, Marine and Natural Environment): <http://www.mma.es>
  - General Directorate for City Planning and Soil Policy (Ministry of Housing): <http://www.mviv.es>
  - Spanish General Directorate for Nature Conservation (Ministry of Rural, Marine and Natural Environment)
- **Flood mitigation measures:**
  - General Directorate for Civil Protection and Emergencies (Ministry of the Interior): <http://www.proteccioncivil.org/>
  - Consortium of Insurance Compensation (Ministry of Economy and Finance): <http://www.consorseguros.es/>

### PUBLICATIONS ON FLOODS

A plethora of publications exist on flood risk analysis and protection in Spain, which are found throughout national and international magazines, book chapters, conference proceedings and meetings, etc. Most of this bibliography is available on the Spanish Information System on Water Resources (Hispagua) of CEDEX and the Spanish Ministry of the Environment, and Rural and Marine Affairs (<http://hispagua.cedex.es>). Over the past year, through an IGME initiative within the framework of the PRIGEO Plan, a listing of most of the organizations in this bibliography has been compiled under the name of DIRE (a compendium of flood and flood risk literature on Spain), which is available on the Internet (<http://www.riada.es>). The latest update of this listing contains over 500 bibliographic references, and a future listing will be georeferenced and linked to a GIS.

### FLOOD-RELATED LINKS OF INTEREST

#### *General*

- Spanish Information System on Water Resources, CEDEX (Ministry of Development) <http://hispagua.cedex.es/>
- Spanish National System for Flood Zone Mapping (SNCZI), Ministry of Rural, Marine and Natural Environment: [http://www.mma.es/portal/secciones/acm/aguas\\_continent\\_zonas\\_asoc/prevencion\\_inundaciones/cartografia\\_inundables/](http://www.mma.es/portal/secciones/acm/aguas_continent_zonas_asoc/prevencion_inundaciones/cartografia_inundables/)
- Flash floods, rapid rises and flood risks. Page in Spanish: <http://www.riada.es>
- Congress on Flood Hazard Maps (INUNMAP 2006): <http://www.inundacion.es>

- Hydraulic and Hydrological Research Group, Department of Hydraulic Engineering and Environment (UPV): <http://lluvia.dihma.upv.es/software.php?language=en>
- Hydraulics and Hydrology Educational Unit, Technical School of Forestry Engineering (EUIT Forestal)<sup>57</sup> (*Universidad Politécnica de Madrid*): <http://www.forestales.upm.es/Unidad.aspx?id=5>

#### *Spanish Hydrographic Confederations and Water Resources Agencies*

- Andalusian Water Agency: <http://www.agenciaandaluzadelagua.com/>
- Catalan Water Agency: [http://acanet.gencat.cat/redireccionament/web\\_en.htm](http://acanet.gencat.cat/redireccionament/web_en.htm)
- Duero Hydrographic Confederation: <http://www.chduero.es/>
- Ebro Hydrographic Confederation: <http://www.chebro.es/>
- Guadalquivir Hydrographic Confederation: <http://www.chguadalquivir.es/>
- Guadiana Hydrographic Confederation: <http://www.chguadiana.es/>
- Tajo Hydrographic Confederation: <http://www.chtajo.es/>
- Júcar Hydrographic Confederation: <http://www.chj.es/>
- Northern Basin Council <http://www.chnorte.es/>
- Segura Hydrographic Confederation: <http://www.chsegura.es/>

#### *Other links of interest*

- Special Web page on floods - European Commission: [http://ec.europa.eu/environment/civil/floods\\_2006.htm](http://ec.europa.eu/environment/civil/floods_2006.htm)
- EU Policy on Flood risk management: [http://ec.europa.eu/environment/water/flood\\_risk/](http://ec.europa.eu/environment/water/flood_risk/)
- European Flood Alert System – EFAS: <http://efas.jrc.ec.europa.eu/>
- Federal Emergency Management Agency of the United States: <http://www.fema.gov/>
- International Centre for Water Hazard and Risk Management (ICHARM): <http://www.icharm.pwri.go.jp/>
- Atlas der Hochwassergefährdung Sachsen – Überschwemmungskarte: [http://www.umwelt.sachsen.de/de/wu/umwelt/lfug/lfug-internet/infosysteme/arcims/website/ghk\\_i/viewer-.htm](http://www.umwelt.sachsen.de/de/wu/umwelt/lfug/lfug-internet/infosysteme/arcims/website/ghk_i/viewer-.htm)
- Grenzüberschreitenden Atlas der Überschwemmungsgebiete im Einzugsgebiet der Mosel: [http://www.gefahrenatlas-mosel.de/mapserver\\_gefahrenatlas/](http://www.gefahrenatlas-mosel.de/mapserver_gefahrenatlas/)
- Atlas on the risk of flooding and potential damage due to extreme floods of the Rhine: <http://www.iksr.de/index.php?id=295>
- Global Active Archive of Large Flood Events: <http://www.dartmouth.edu/~floods/Archives/>
- Flood Hazard Research Centre (FHRC) (UK): <http://www.fhrc.mdx.ac.uk/>
- National Flood Forum (UK): <http://www.floodforum.org.uk/>
- International Flood Network: <http://www.internationalfloodnetwork.org/>
- Hydrologic Engineering Center, (HEC) (USACE): <http://www.hec.usace.army.mil/>
- EM-DAT, Emergency Events Database: <http://www.emdat.be/>

<sup>57</sup> Unidad Docente de Hidráulica e Hidrología.



## E. Glossary

**Aquifer recharge**, a process through which the water enters the groundwater storage of the aquifer. The recharge area is the zone that enables the water to be supplied to the aquifer.

**Base flow** is the portion of water derived from groundwater storage or from wedge storage and finally reaches the stream.

**Bench or bank escarpment** is a geomorphological sub-feature or facet consistent of a small escarpment of decimetric- to metric-sized, longitudinal irregular landform that extends along the channel margins formed by the erosive action of the stream during low flow. It is usually easily recognizable in straight reaches of streams and outer banks of meanders with a worn profile and even replaced by other sub-features in the outer margins of meanders.

**Channel** is a geomorphological feature of various sizes (from cm to km), with an elongated configuration and irregular concave (depression) cross-section, around which low flows of a stream circulate, since it contains the natural canal(s) or thread(s) of streams. It is delimited by various geomorphological sub-features or facets, such as benches or bank escarpments, natural groins or dikes, side or meander bars, etc. According to the Law of Water, a channel, or its Hydraulic Public Domain (DPH) equivalent, is the zone covered by the ordinary high water profile (MCO), established by hydrological criteria. The recent modification to the DPH regulation incorporates other criteria (historical, geomorphological, ecological...) in its delimitation.

**Evaporation** is a process through which water transforms from a liquid state to a vapour through the transfer of heat energy. For water resources planning, this process must be considered in detail, however, for the analysis of flood events it can be excluded due to its short duration.

**Flash flood** refers to a discharge from upstream that “comes toward” the position of the observer. Many flash floods, especially those that occur in torrential zones, are not rising stages, since the increase in the flow produced is sudden, abrupt, and even violent. These flash floods, instantaneous and sudden, are more characteristic of small torrential catchments in mountains (coulees and riviulets) and the Mediterranean coastline (gullies and ravines).

**Flood:** According to *Webster's Third New International Dictionary, Unabridged*, **flood**, or inundate (Latin *inundare* ‘flood’, from *unda* ‘a wave’), is “a rising and spreading of water over land not usually submerged”. The Spanish Basic Directive of Civil Protection Planning on Flood Risk (MJI, 1995) defines a flood as the temporary submersion of normally dry lands as a result of an unusual and more or less sudden flow of a quantity of water which exceeds that which is normal in a given zone. The Federal Emergency Management Agency (FEMA) in the United States further quantifies the surface subject to flooding in order to consider it a flood: “A general and temporary condition of partial or complete inundation of two or more acres of normally dry land area or of two or more properties”, that is, an excess of water (or mud) over land that is normally dry. To conclude, the new European Community Directive 2007/60/EC on the assessment and management of flood risks defines flooding as “the temporary covering by water of land not normally covered by water.” (Article 2.1).

**Floodplain** is a geomorphological feature of various scales (from meters to kilometres), with an elongated configuration and planar or gradually sloping cross-sections that occupy the channel margins and is inundated by flood stage flows. Normally, it is located immediately behind the bank escarpments, natural dikes or side bars and is formed by alluvial deposits or recent erosive landforms, nearly always Holocene (last 10,000 years). It is separated from the rest of the valley (lowlands) by terrace steps, sand splays or pendant bars.

**Flood risk** is the potential for loss or injury to persons, material assets or services, such as consequences from submersion of sectors normally dry by inundations associated with a given severity (intensity), spatial-temporal dimension, and frequency or probability of occurrence. The European Flood Directive defines it as the “com-

bination of the probability of a flood event and of the potential adverse consequences for human health, the environment, cultural heritage and economic activity associated with a flood event.” (Article 2.2).

**Groins, levees, natural dikes, or barriers** are geomorphological features of various scales (from centimetres to decimetres) with an elongated profile but discontinuous, and convex cross-sections (semi-circular, trapezoidal, or triangular) that are located in the channel margins. Their formation is associated with the deposition of larger material transported such as sediment load during inundation events. In some situations they are reshaped, built up or substituted by analogous man-made features such as preventive structural defences against floods, which are called artificial dikes.

**Infiltration** is the process of water in liquid form entering soil through the surface. This phenomenon is the most important in a flood event, since the water not infiltrated is the direct runoff that typically comprises the largest percentage of surface runoff, especially in rising stages.

**Interception** is the part of precipitation that is intercepted by surface objects such as vegetation cover or rooftops. Generally, part of this intercepted water never reaches the soil because it adheres to and moistens these objects and ultimately evaporates. Interception can be excluded when flood events are studied. However, when the conservation of the water balance is desired, this process can become important and must be taken into account.

**Isobathic contour** is a line formed by the points of equal depths of a water mass at a given time. In rivers and during floods, they usually are irregular curved lines with sub parallel configurations but very variable. In bodies of confined water (lakes, ponds, etc.), they usually are concentric curves with respect to one another or at various depocentres or points of maximum depth.

**Isotach or isovel** is a line formed by the points of equal instantaneous or mean speed at a given time. In rivers and during floods, they usually are irregular curved lines concentrically configured with respect to the flow axis of the stream.

**Percolation** is the movement of infiltrated water through the openings in soil.

**Rapid rises** are an increase in the size of the river or stream or torrent (rivulet, gully, ravine...), with the consequential overtopping and inundation of the margins. Normally rapid rises are produced during rising periods and/or flash floods, and receive other names, such as winter flooding or water surges.

**Recurrence interval or return period** is the mathematical expectation (approximately the arithmetic mean) of the time period within which an event of a given magnitude (severity) will be equalled or exceeded once on an assumed infinite time series. For example, if it is said that an inundation with a discharge of 3,700 m<sup>3</sup>/s has a recurrence interval of 500 years, that means that the average of the periods between each inundation that equal or exceed this discharge is 500 years, for a sufficiently long time period. The return period is the inverse of the exceedance probability, in other words, a discharge of a 500-year return period is equal to the annual probability of exceedance of  $1/500 = 0.002 = 0.2\%$ .

**Region prone to flooding** is the susceptibility of a region to being covered by water during flood events which are associated with a magnitude (depth) and frequency. This would be the equivalent of flood hazard except not all elements of flood hazard are encompassed in flood risk, such as sediment load transported, stream velocity, associated geological phenomena, etc.

**Rising period** is the gradual and progressive increase in flows resulting in a gradual rise in the water level and/or stream velocity. Nearly all rising stages are also flash floods, since the flows usually originate from upstream, rising periods typically occur in large catchment basins (Ebro, Duero, Tajo, Guadalquivir...).

**Sediment load** is the portion, in volume and weight, of the flow of a stream consisting of solid material, both





inorganic (detrital elements) and organic (decomposed vegetation or animal) matter. Sediment load can be transported as bedload (translation, traction or saltation) suspended in the fluid, or as elements floating.

**Snowmelt** is the process by which the quantity of water is produced by the melting of snow accumulated on the surface.

**Subsurface flow** is the water that was previously infiltrated but does not reach the groundwater storage or aquifer, circulating around the vadose or unsaturated zone, the reason for which it must be considered in surface runoff.

**Surface runoff** is the portion of rainfall that is not intercepted, stored, evaporated, or infiltrated and that flows over land surfaces. Actually, surface runoff, infiltration, and ground moisture are interactive amongst each other, for which reason the appropriate model for each case must be taken into account.

**Surface storage or depression storage** is the water stored in natural depressions in the land surface (puddles) depending on the type of terrain and land use, which leads to evaporation or infiltration into the ground.

**Time of concentration** is one of the so-called characteristic times that are established between the flood hydrograph and the hyetograph, referring to the period of time from when an effective water drop or snowflake falls or melts in the farthest point in a catchment basin until it reaches a gauging station. Empirically, it is computed using simple equations that depend on stream length between both points and their longitudinal slope.



## **F. Structure of the Handbook**

### **1. INTRODUCTION AND PURPOSE**

### **2. METHODOLOGIES AND PROCEDURES FOR FLOOD HAZARD ANALYSIS**

*Floods and flood risks*  
*Types and origin of floods*  
*Flood disasters worldwide and in Spain*  
*Flood risks in Spain*  
*The impact of flood events*  
*Maximum probable events and extreme phenomena*  
*Human actions which may increase risks*  
*Flood hazard analysis methods*

#### **2.1. Hydrological-Hydraulic Methods**

##### **2.1.1. HYDROLOGICAL METHODS**

###### **HYDROMETEOROLOGICAL METHODS**

*Rational Method*  
*Unit hydrograph*  
*Probable Maximum Flood (PMF)*  
*Distributed hydrological modelling: the TETIS model*

###### **FLOOD FREQUENCY ANALYSIS**

*Flood frequency analysis using univariate models*  
- Non-parametric methods: graphical resolution  
- Parametric methods: statistical models  
- Distinction of flows corresponding to exceptional floods in univariate models  
*Flood frequency analysis using regional predictive models*

##### **2.1.2. HYDRAULIC METHODS**

###### **ONE-DIMENSIONAL FLOW**

*Steady uniform flow: Manning's equation*  
*Steady gradually varied flow regime*  
*Unsteady flow regime*

###### **TWO-DIMENSIONAL FLOW**

###### **3D MODELS**

###### **TWO-PHASE FLOW AND SEDIMENT TRANSPORT**

#### **2.2. Geological-geomorphological Methods**

##### **2.2.1. GEOMORPHOLOGICAL CONDITIONING FACTORS FOR FLUVIAL FLOODS**

###### **FLUVIAL MORPHOLOGY**

*Catchment areas*  
*Drainage networks*  
*Streams*

###### **RIVER TYPES**

###### **FLUVIAL MORPHODYNAMICS AND MORPHOLOGICAL EVOLUTION**

*Fluvial action during floods*  
*Fluvial landforms associated with floods*

###### **SPATIAL LAYOUT OF FLUVIAL FORMS: THE FLUVIAL SYSTEM AND ITS ZONES**

##### **2.2.2. METHODS AND SOURCES OF DATA FOR GEOMORPHOLOGICAL ANALYSIS AND MAPPING OF FLUVIAL LANDFORMS**

###### **LITERATURE ON METHODS AND PROCESSES IN FLUVIAL GEOMORPHOLOGY**

## FLUVIAL GEOMORPHOLOGICAL MAPPING METHODS AND PROCESSES APPLIED TO FLOOD HAZARDS

*Delimiting of geomorphological elements*

*Assigning hazard levels to geomorphological elements*

### 2.2.3. METHODS FOR ESTIMATING SEDIMENT LOAD TRANSPORTED BY A STREAM

EMPIRICAL METHODS OF EROSION AND SEDIMENT YIELD

QUALITATIVE ESTIMATION METHODS

### 2.2.4. LITHOLOGICAL INFLUENCE ON THE RAINFALL-RUNOFF TRANSFORMATION PROCESS

### 2.2.5. HYDROGEOLOGICAL CRITERIA FOR THE ASSESSMENT OF FLOODS CAUSED BY RISING WATER TABLE

## 2.3. *Historical and palaeohydrological Methods*

### 2.3.1. HISTORICAL METHODS

SEARCHING FOR AND COMPILING HISTORICAL DOCUMENTATION

ANALYSING AND INTERPRETING HISTORICAL INFORMATION

INTEGRATING THE DATA INTO FLOOD FREQUENCY ANALYSES

### 2.3.2. PALAEOHYDROLOGICAL METHODS

METHODS BASED ON FLOW COMPETENCE

METHODS BASED ON PALAEOSTAGE INDICATORS

PALAEOHYDROLOGICAL METHODS AND VARIABILITY INTRODUCED BY GLOBAL CHANGE

## 2.4. *Other methods, techniques and information sources*

### 2.4.1. THE HYDROLOGICAL-HYDRAULIC METHOD BASED ON GEOMORPHOLOGY

DEVELOPING THE CRITERIUM CONCEPTUALLY AND METHODOLOGICALLY

*Bankfull or overflow discharge*

*Peak discharge for different return periods*

*The ratio or relationship between  $Q_b$  and  $Q_r$  values*

### 2.4.2. BOTANICAL TECHNIQUES AND INFORMATION SOURCES

DENDROGEOMORPHOLOGY

LIQUENOMETRY

## 2.5. *Integrating methods, calibration and selection criteria*

### 2.5.1. INTEGRATING AND CALIBRATING THE METHODS

### 2.5.2. SELECTING AND PROPOSING METHODS

### 2.5.3. THE SCALE FACTOR

## 3. FLOOD HAZARD MAPPING METHODOLOGIES

### BACKGROUND STUDY

*International mapping experience references*

*Mapping experience references in Spain*

## 3.1. *Types of flood hazard maps*

## 3.2. *Contents of hazard maps*

### 3.2.1. ELEMENTS TO REPRESENT ON THE MAPS

### 3.2.2. INTEGRATED HAZARD ZONING

### 3.2.3. ELEMENTS RELATED TO INTERACTION WITH OTHER GEOLOGICAL HAZARDS

### 3.2.4. LIMITATIONS IN THE USE OF HAZARD ZONES





### ***3.3. Representing the information***

#### **3.3.1. SCALES: SELECTION CRITERIA**

#### **3.3.2. REPRESENTATION SYSTEMS AND METHODS**

### ***3.4. Format of the published map, report and complementary information***

#### **3.4.1. FORMAT OF THE PUBLISHED MAP**

##### **STANDARDISED MAPS**

*Main window (1)*

*Legend (2)*

*Box (3)*

*Location (4)*

*Auxiliary maps, diagrams and elements (5, 6, and 7)*

#### **3.4.2. REPORT AND COMPLEMENTARY INFORMATION**

### ***3.5. Digital representation of the information***

#### **3.5.1. ORGANIZATION OF THE INFORMATION**

#### **3.5.2. STRUCTURE**

#### **3.5.3. STANDARDIZATION**

#### **3.5.4. SOFTWARE FILE FORMATS**

**VECTOR SOFTWARE FILE FORMATS**

**COORDINATE SOFTWARE FILE FORMATS**

**OTHER SOFTWARE FILE FORMATS**

#### **3.5.5. DISTRIBUTION FORMATS**

#### **3.5.6. GEOSCIENTIFIC LANGUAGE**

**METADATA**

### ***3.6. Updating and maintaining flood hazard maps***

### ***3.7. From hazard maps to risk maps***

## **4. BIBLIOGRAPHY**

## **5. ANNEXES**

### ***A. Information sources for hazard analysis in Spain***

#### **MAPS AND PHOTOGRAPHS**

*Basic map*

*Thematic maps*

*Satellite photographs and images*

#### **ALPHANUMERIC DATA**

*Hydrological data*

*Socioeconomic data*

#### **FIELD DATA ACQUISITION**

### ***B. Applicable legislation***

#### **1. EUROPEAN LEGISLATION**

#### **2. GOVERNMENT LEGISLATION**

GOVERNMENT WATER MANAGEMENT LEGISLATION

*The Spanish Water Act*

*Hydrological plans*

GOVERNMENT LEGISLATION ON LAND USE

- *The former "Land-use Law"*

- *Law on Land Use and Valuation*

- *Natural risks in the new Land Law*

3. LEGISLATION IN THE AUTONOMOUS REGIONS ON LAND MANAGEMENT, TOWN PLANNING AND LAND-USE PLANNING

4. OTHER RELEVANT REGULATIONS

- *Environmental legislation*

- *Civil Protection legislation*

- *Sectorial legislation on Public Works*

- *Sectorial legislation on Tourism*

## ***C. Computer tools and programs***

1) FLOOD HAZARD ANALYSIS

2) CARTOGRAPHIC REPRESENTATION OF HAZARD PARAMETERS

*Brief description of the applications and programs (in alphabetical order)*

## ***D. Directory – Flood Risk in Spain***

PUBLICATIONS ON FLOODS

FLOOD-RELATED LINKS OF INTEREST

*General*

*Spanish Hydrographic Confederations and Water Resources Agencies*

*Other links of interest*

## ***E. Glossary***

## ***F. Structure of the Handbook***





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