step 3 to yield a flood stage that includes the effects of uncertainty in the stage-discharge relation and the estimation of the flood quantiles. If the performance of a proposed project is being simulated, the level of protection may be empirically determined by counting the number of flood stages that are higher than the project capacity and dividing by the number of simulations, provided the number of simulations is sufficiently large. The standard deviation of the standard normal variate is determined from the previously described methods used to determine uncertainty in the stage-discharge relation.

(5) The flood stage obtained in step 4 is converted to the expected flood damage using the expected flood-damage relation. For a particular proposed project, the simulation procedure may end here if the simulated flood stage does not result in flood damage.

(6) A value of a standard normal variate is randomly selected, and it is used to compute a random value of error associated with the flood damage obtained in step 5. This random error is added to the flood damage obtained in step 5 to yield a flood-damage value that includes the effects of all the uncertainties considered. If the flood-damage value is negative, it is set equal to zero. The standard deviation of the standard normal variate is determined by Monte Carlo simulation of the component economic uncertainties affecting the stage-damage relation as previously described.

Steps 1-6 are repeated as necessary until the values of the relevant performance measures (average flood damage, level of protection, probability of positive net-economic benefits) stabilize to consistent values. Typically, 5 000 simulations are used in USACE projects.

The risk-based approach, summarized in steps 1 to 6, has many similarities with the traditional methods particularly in that the basic data and discharge-frequency, stage-discharge and stage-damage relations are the same. The risk-based approach extends the traditional methods to consider uncertainties in the basic data and relations. The major new task in the risk-based approach is to estimate the uncertainty in each of the relations. Approaches to estimate these uncertainties are described in detail by the USACE (1996) and are not trivial. However, the information needed to estimate uncertainty in the basic component variables is often collected in the traditional methods, but not used. For example, confidence limits are often computed in flood-frequency analysis, error information is available for calibrated hydraulic models, and economic evaluations are typically done by studying in detail several representative structures for each land-use category providing a measure of the variability in the economic evaluations. Therefore, an excessive increase in the data analysis relative to traditional methods may not be imposed on engineers and planners through application of this risked-based analysis.

Because steps 1 to 6 are applied to each of the alternative flood-damage-reduction projects, decision makers will obtain a clear picture of the trade-off among level of protection, cost and benefits. Further, with careful communication of the results, the public can be better informed about what to expect from flood-damage-reduction projects, and, thus can make better-informed decisions (USACE, 1996). Finally, with careful communication of the results, decision makers and the public may gain a better understanding of the amount of uncertainty surrounding the decision-making process and the impact such uncertainty may have on the selection of the "optimal" outcome.

8.4.2 The Inondabilité method

The Inondabilité method was developed by researchers at CEMAGREF in Lyon, France (Gilard *et al.*, 1994; Gilard, 1996). The essence of this method is to: (1) develop flood-hazard maps and maps of acceptable risk in commensurate units; (2) identify land uses with low acceptable risk located in high-hazard areas and land uses with high acceptable risk located in low-hazard areas; and (3) propose changes in land-use zoning such that activities with high acceptable risks are moved to or planned for high-hazard areas and, conversely, activities with low acceptable risks are moved to or planned for low-hazard areas. These maps are developed for entire river basins as per recent French laws (Gilard, 1996).

Gilard (1996) reasoned that the level of acceptable risk is related to the sensitivity of land use to flooding and is dependent only on the type of land use and the social perception of hazard (which can be different from one area to another, even for the same land use, and can change with time), independent of the potentially damaging natural phenomenon. For example, the same village has the same acceptable risk whether it is located in the flood plain or on top of a hill. The difference in the risk for these two villages results from the hazard, i.e. the probability of occurrence flooding, which is obviously different for the two locations. Conversely, hazard primarily depends on the flow regime of the river, which is relatively independent of the land use in the flood plain. Land-use changes in the flood plain and within the basin can result in shifts in the stage-probability and stage-discharge relations, but as a first approximation for land-use zoning the assumption of independence between hazard and land use in the flood plain may be applied. After changes in land use in the flood plain are proposed, the hydraulic analysis of hazard can be repeated to ensure the new land-use distribution is appropriate. Therefore, acceptable risk and hazard may be evaluated separately, converted into commensurate units and compared for risk evaluation.

The hazard level is imposed by the physical conditions and climate of the watershed (hydrology and hydraulics). The conditions resulting in hazard can be modified somewhat by hydraulic works, but basin-wide risk mitigation is best achieved by modifying the land use particularly within the flood plain thereby increasing the acceptable risk for the land use in the flood plain. The acceptable risk must be expressed in suitable units for deciding which land uses should be changed in order to reduce risk. In the USACE (1996) risk-based analysis for flood-damage-reduction studies (section 8.4.1), acceptable risk is determined by minimizing the expected economic damages that are calculated by integration of economic damages with the flood probability (hazard). This approach was rejected by French researchers because of the problems of considering the probability of each damaging event and the indirect damages. In the Inondabilité method, the acceptable risk is determined by negotiating allowable characteristics of flooding, such as duration and frequency or duration, depth, and frequency for each type of land use. Negotiations include all parties in charge of management of a portion of the river system, even including each riverine landowner, if necessary. These allowable flood characteristics are converted to an equivalent flood frequency or level of protection that can be compared with the flood hazard determined from flood-frequency analysis and hydraulic routing that are done as described in the following paragraphs.

The transformation of the allowable flood characteristics into an equivalent flood frequency is accomplished using locally calibrated, regional flood discharge (Q)-duration-frequency (QdF) curves The flood regimes of most French and European rivers are described by three regional models and two local parameters: the 10-year instantaneous maximum flow for a particular site and the characteristic duration of the catchment (Gilard, 1996). The characteristic duration of the catchment (D) is the width of the hydrograph at a discharge equal to one half of the peak discharge. The value of D may be determined from gauge records, or from empirical equations relating D with the catchment's physical characteristics (Galea and Prudhomme, 1994). QdF curves have been derived for three regions in France, and the QdF curves span flood flows of 1-s to 30-day duration and return periods from 0.5 to 1 000 years for watersheds less than 2 000 km^2.

Transformation of an allowable duration and frequency of flooding into an acceptable risk in units equivalent to those used in flood-hazard analysis using the QdF curves is illustrated in Figure 8.5. In this case, a flood duration of a little less than one day is allowed, on average, once in 100 years for the type of land use under consideration. The equivalent instantaneous peak discharge has a frequency (TOP = return period, T, of protection) between 10 and 50 years (say 20 years). This means that if the type of land use under consideration is flooded more often than once, on average, in 20 years (probability of flooding > 0.05), an unacceptably high probability of floods with a duration slightly less than one day results.

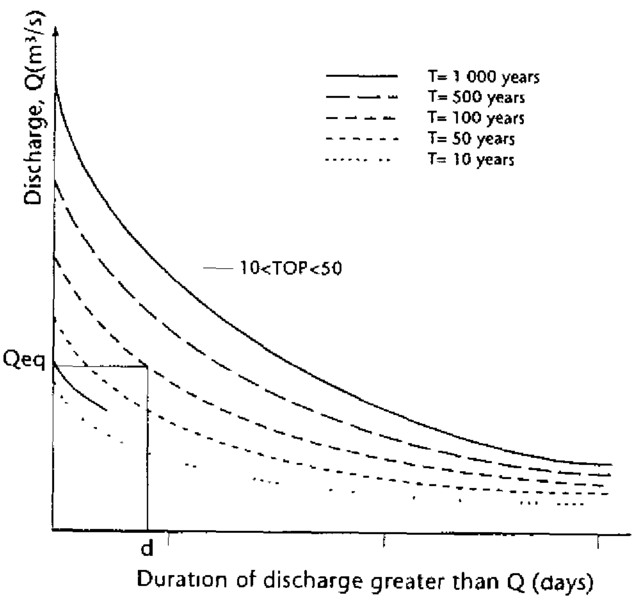

Figure 8.5 — Determination of equivalent frequency (return period, T) of protection (TOP) given societally acceptable duration and frequency of flooding applying locally calibrated discharge (Q)-duration-frequency (QdF) model (after Gilard et al*., 1994)*

Specified values of an acceptable depth (p_{obj}), duration (d_{obj}) and frequency (T_{obj}) of flooding also can be transformed into an equivalent level of protection as shown in Figure 8.6. In general, the combination of allowable flood conditions ($p=p_{obj}$, $d=d_{obj}$, $T=T_{obj}$) is transformed to an equivalent condition where ($p=0$, $d=0$, $T=TOP$) as follows (Gendreau, 1998).

(*a*) The elevation of the level of protection is $z_{obj} = z_0 + p_{obj}$, where z_0 is the elevation of the parcel of land under consideration.

(*b*) Using the local stage-discharge-rating curve, and equivalent discharge, Q_{obj}, is determined for z_{obj}.

(*c*) Using the local QdF curves, the return period $T(Q_{obj},d_{obj})$ can be estimated.

(*d*) Using the discharge corresponding to an elevation of z_0, $Q(p=0)$, at a constant return period, the equivalent duration $d(p=0)$ for no water depth can be estimated. That is, $T(Q_{obj},d_{obj}) = T(Q(p=0),d(p=0))$.

(*e*) The equivalent discharge for T_{obj} is estimated as $Q_{eq} = Q(T_{obj},d(p=0))$.

(*f*) The equivalent return period for the desired level of protection then is determined as $TOP = T(Q_{eq},d=0)$.

Methods to consider allowable flood duration, depth, velocity and frequency are currently under development.

If allowable frequencies, durations and/or depths of flooding can be defined for each type of land use throughout the river basin by negotiation, then the equivalent frequency of protection (TOP) may be determined for each area in the flood plain. CEMAGREF has also developed preliminary standards for acceptable flooding levels for different types of land use in France and these are listed in Table 8.1 A map delineating areas with specific acceptable risk levels expressed in terms of TOP in years is then drawn as shown in Figure 8.7.

The hazard level for various locations throughout the river basin also is determined using the QdF curves. A consistent definition of flood hazard throughout the river basin is obtained by using the QdF curves to define mono-frequency synthetic hydrographs (Galea and Prudhomme, 1994) for selected frequencies at key locations throughout the river basin (Gilard, 1996). The mono-frequency synthetic hydrograph is determined from the QdF curve as follows. The peak discharge is the maximum instantaneous value from the QdF curve, and the duration during which specified smaller discharges are exceeded is then determined from the QdF curve. This duration is proportioned in time, as appropriate, on either side of the peak discharge to yield a hydrograph that has the appropriate discharge and duration for the selected

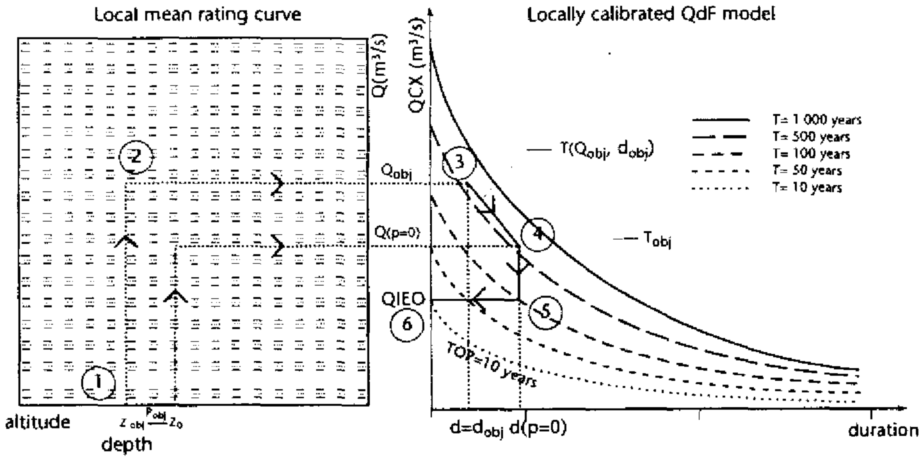

Figure 8.6 — Determination of equivalent frequency (return period, T) of protection (TOP) given societally acceptable depth, duration and frequency of flooding applying locally calibrated discharge (Q)-duration-frequency (QdF) model (after Gilard, 1996)

frequency. Thus, the mono-frequency synthetic hydrograph does not represent actual hydrographs, but rather is an envelope curve. The hydrographs for selected frequencies are used as input to dynamic-wave flood routing models that are applied to determine the exact location of inundation for all areas along the river and tributaries for the specific frequency of occurrence of the flood. A composite map of the flooded areas for various return periods is then drawn as shown in Figure 8.8.

The hazard and acceptable risk maps are then overlaid and a colour code (shown in grey-scale in this report) is used to identify protected and underprotected areas on the resulting river-basin risk map. Three types of areas are delineated as follows.

(1) The hazard level, expressed as a return period, is undefined (larger than the simulated maximum return period). That is, the area is outside of the flood plain of the simulated maximum flood and, because the frequency of protection for this area is finite, the area is protected. These areas are marked in yellow.

(2) The hazard level is larger than the acceptable risk, expressed as a return period. That is, the probability of hazard is less than the equivalent frequency of protection required for the land use under consideration. Therefore, the area is subject to flooding but not at unacceptable levels for that land use. These areas are marked in green.

(3) The hazard level is smaller than the acceptable risk. That is, the probability of hazard is greater that the equivalent frequency of protection required for the land under consideration. Therefore, the area is subject to more frequent flooding than is acceptable for that land use, which is considered underprotected. These areas are marked in red.

An example risk map is shown in Figure 8.9. The goal of flood management then is to alter land use throughout the basin or add hydraulic-protection works at key locations such that the red areas (areas with unacceptable flooding) become green areas (areas with acceptable flooding). If hydraulic-protection works are implemented for areas with low acceptable risk, the hazard analysis must be redone to ensure that hazards have not been transferred from one area to another.

Table 8.1 — Preliminary standards for selection of acceptable duration, depth and frequency of flooding for different land uses in France (after Desbos, 1995)

Land use	*Season*	*Maximal acceptable duration*	*Maximal acceptable water depth*	*Maximal acceptable return period*
Market gardening	Spring	Instantaneous to 1 day		5 years
Horticulture	Summer/Autumn	1 to 3 days		5 years
Vineyard	Summer	Instantaneous		10 years
	Autumn	Instantaneous		10 years
	Winter	1 month		5 years
Forest, wood		1 week to 1 month		1 year
Home:				
Cellar		Instantaneous	–2 to 0 m	10 years
Ground Floor		Instantaneous	0 to 50 cm	100 years
First Floor		Instantaneous	1 m	1 000 years
Industry		Instantaneous	30 to 60 cm	1 to 100 years
Campsite	Spring/Summer	Instantaneous	50 cm	10 years
Sports ground		1 day		1 year

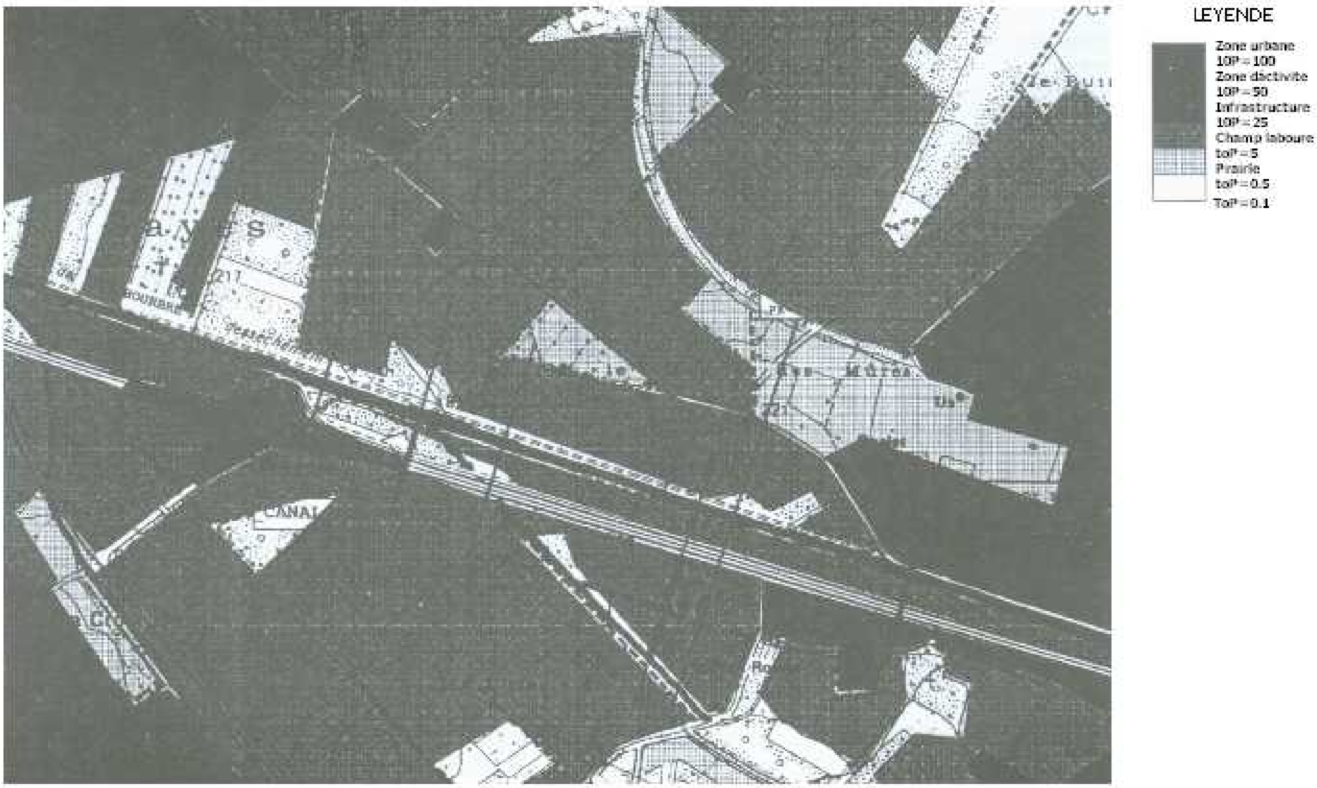

Figure 8.7 — Example acceptable risk map derived with the Inondabilité method. Acceptable risk is expressed in terms of the equivalent frequency (return period, T) of protection (TOP) in years (after Gilard, 1996)

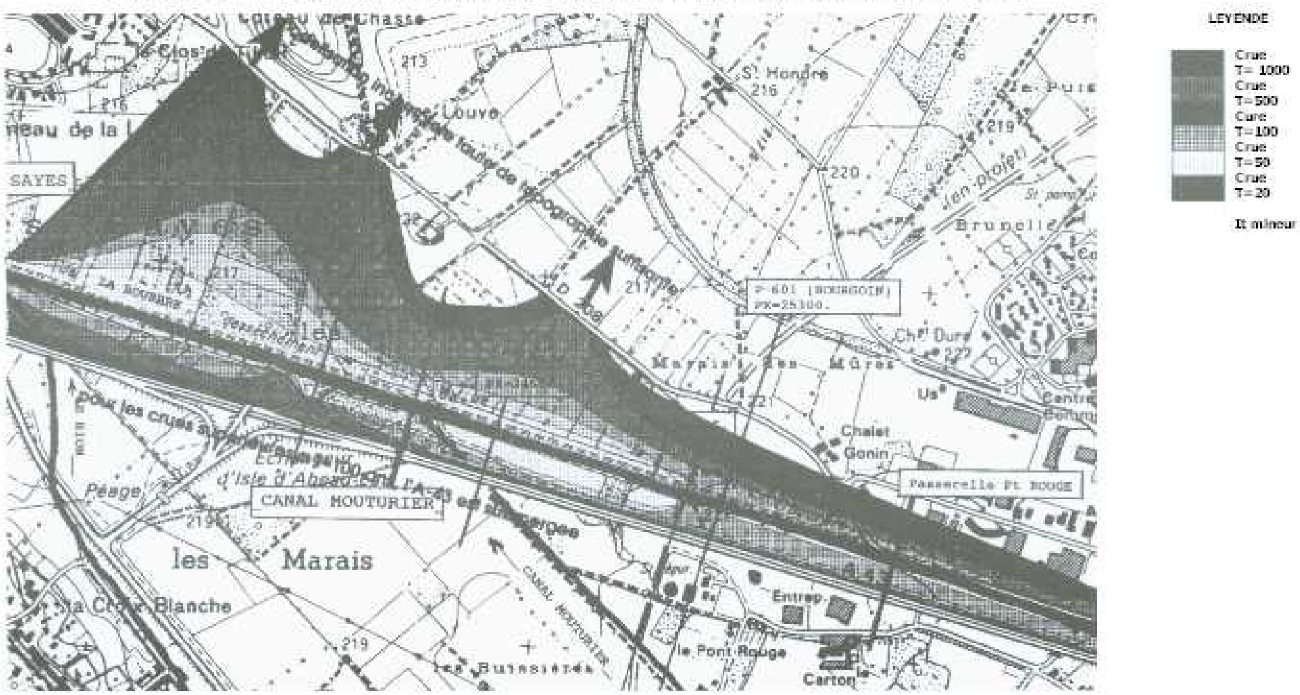

Figure 8.8 — Example hazard map for use in the Inondabilité method (after Gilard, 1996)

Implementation of the Inondabilité method can be lengthy because of the necessary negotiations among the affected communities and landowners (Gilard and Givone, 1993). However, the Inondabilité method has been successfully applied in several river basins in France ranging in area from 20 to 1 000 km^2 (Gilard, 1996).

8.5 SUMMARY AND CONCLUSIONS

The development of various new methods of probabilistic, economic and structural- and hydraulic-engineering analyses used in the risk-assessment methods described in this chapter is impressive and noteworthy. However, the real potential for mitigation risks from natural hazards

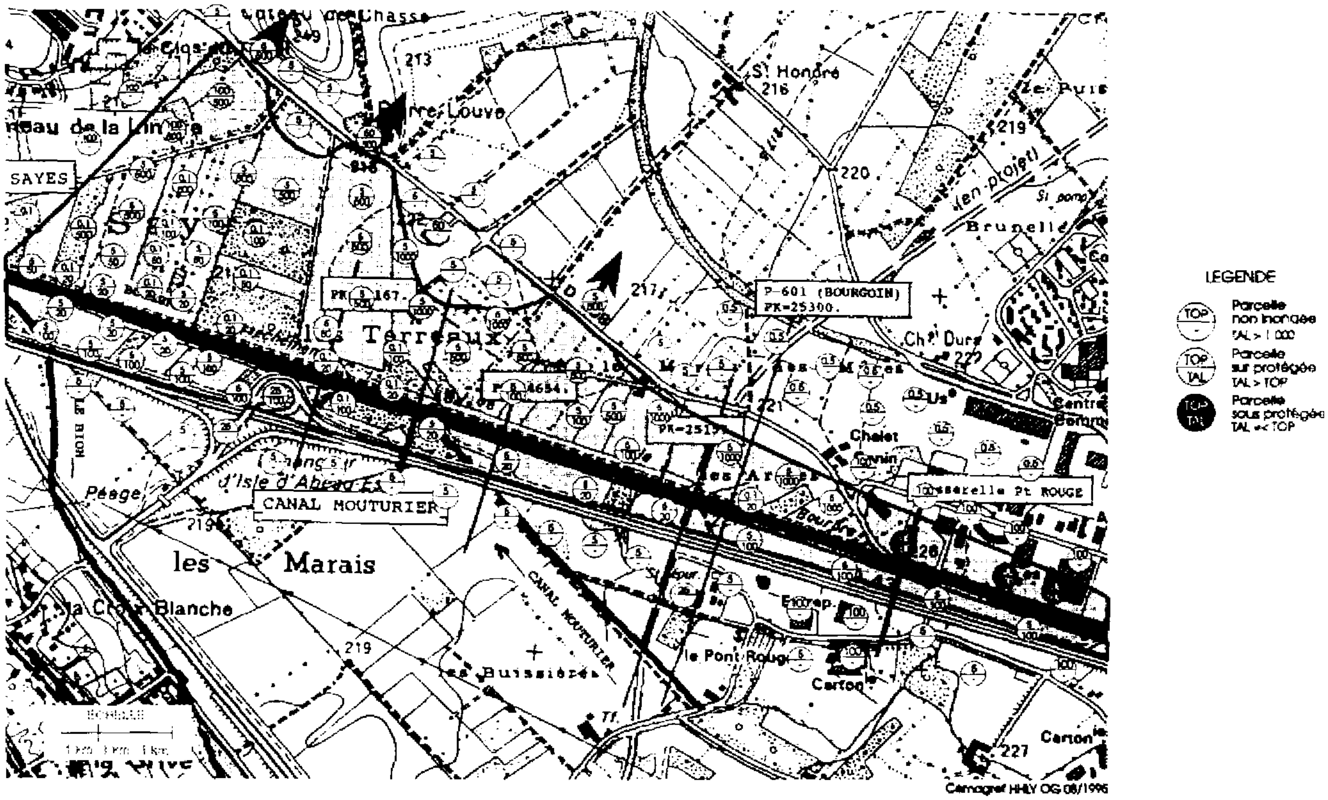

Figure 8.9 – Example flood risk map derived with the Inondabilité method by comparison of the flood vulnerability (Figure 8.7) and flood hazard (Figure 8.8) maps (after Gilard, 1996)

through implementation of the methods described here results from the political will of legislators in France, The Netherlands and the USA to specify actual societally acceptable risks or processes for the establishment of these risks and to charge local governments, engineers and planners to meet appropriate risk criteria. Therefore, advances in the mitigation of risks from natural hazards are dependent on governments to realistically assess societally acceptable risks establish criteria that reflect these risks and mandate their use.

8.6 GLOSSARY OF TERMS

Assessment: A survey of a real or potential disaster to estimate the actual or expected damages and to make recommendations for prevention, preparedness and response.

Astronomical tide: Tide which is caused by the forces of astronomical origin, such as the period gravitational attraction of the sun and moon.

Basin level: Water level on the landward side of a sea defence structure.

Characteristic duration of the catchment: The width of the hydrograph at a discharge equal to one half of the peak discharge.

Damage-frequency relation: The relation between flood damages and flood frequency at a given location along a stream.

Discharge-duration-frequency curve: Curve showing the relation between the discharge and frequency of occurrence for different durations of flooding.

Discount rate: The annual rate at which future costs or benefits should be reduced (discounted) to express their value at the present time.

Earthquake-resistant design: Methods to design structures and infrastructure such that these can withstand earthquakes of selected intensities.

Equivalent level of protection: Acceptable duration, depth, and frequency of flooding for a given land use is expressed in terms of the frequency of an equivalent peak discharge for comparison with the flood hazard at locations with that land use.

Fault-tree analysis: A method for determining the failure probability for a system or structure where the potential causes of failure are reduced to the most elemental components for which failure probability information is available or may be estimated. These component failures are aggregated into the system failure through a series of "and" and "or" operations laid out in a tree framework.

Flood-damage-reduction plan: A plan that includes measures that decrease damage by reducing discharge, stage and/or damage susceptibility

Frequency analysis: The interpretation of a past record of events in terms of the future probabilities of occurrence, e.g., an estimate of the frequencies of floods, droughts, rainfalls, storm surges, earthquakes, etc.

Frequency transposition: A method for estimating flood frequency at ungauged locations wherein the flood-frequency relation for a gauged location is applied at an ungauged location in a hydrologically similar area. This application involves the use of area ratios and possibly ratios of other physical characteristics to account for differences between the locations.

Hazard: A threatening event, or the probability of occurrence of a potentially damaging phenomenon within a given time period and area.

Human capital approach: A method to determine the economic value of human life wherein the direct out-of-pocket losses associated with premature death (i.e. the present value of expected future earnings) are calculated

Hydraulic-protection works: Levees, banks or other works along a stream, designed to confine flow to a particular channel or direct it along planned floodways.

Implicit vulnerability: When determining or selecting the societally acceptable hazard level and applying this in the design and planning of measures to mitigate damages from natural phenomena, the area of interest is assumed to be vulnerable without evaluating the actual vulnerability of the people, infrastructure and buildings at risk.

Input-output model: A static general-equilibrium model that describes the transactions between various production sectors of an economy and the various final demand sectors.

Minimum life-cycle cost: The minimum value of the cost of a structure designed to withstand earthquakes computed over the life of the structure as a present value. The cost includes construction cost and damage costs, such as the repair and replacement cost, loss of contents, economic impact of structural damage, cost of injuries resulting from structural damage and cost of fatalities resulting from structural damage.

Mitigation: Measures taken in advance of a disaster aimed at decreasing or eliminating its impact on society and the environment.

Mono-frequency synthetic hydrograph: A hydrograph derived from the discharge-duration-frequency curves for a site such that the duration of discharges greater than each magnitude corresponds to the selected frequency. That is, the 50-year mono-frequency synthetic hydrograph has a peak discharge equal to that for the 50-year flood and a duration exceeded once on average in 50 years for all other discharges.

Monte Carlo simulation: In Monte Carlo simulation, probability distributions are proposed for the uncertain variables for the problem (system) being studied. Random values of each of the uncertain variables are generated according to their respective probability distributions and the model describing the system is executed. By repeating the random generation of the variable values and model execution steps many times the statistics and an empirical probability distribution of system output can be determined.

Poisson process: A process in which events occur instantaneously and independently on a time horizon or along a line. The time between such events, or interarrival time, is described by the exponential distribution whose parameter is the mean rate of occurrence of the events

Present worth factor: Factor by which a constant series of annual costs or benefits is multiplied to obtain the equivalent present value of this series. The value of this factor is a function of the discount rate and the duration of the series.

Probability density function: For a continuous variable, the function that gives the probability (=0) for all values of the variable. The integral of this function over the range of the variable must equal 1.

Regional frequency relations: For a hydrologically homogeneous region the frequency relations at the gauged locations are pooled to determine relations between flood frequency and watershed characteristics so that flood-frequency relations may be estimated at ungauged locations.

Reliability: Probability that failure or damage does not occur as the result of a natural phenomenon. The complement of the probability of damage or failure, i.e. one minus the probability of damage or failure.

Revealed preferences: A method to determine the value of lives saved wherein the amount of money people are willing to pay to reduce risk (e.g., purchase of safety devices) or willing to accept in order to do tasks that involve greater risk (i.e. risk premiums in pay) are used to establish the societally acceptable wealth-risk tradeoff

Risk: The expected losses (of lives, persons injured, property damaged and economic activity disrupted) due to a particular hazard for a given area and reference period. Based on mathematical calculations, risk is the product of hazard and vulnerability.

Societally acceptable hazards: The average frequency of occurrence of natural disasters that society is willing to accept, and, thus, mitigation measures are designed and planned to reduce the frequency of damages from natural phenomena to this acceptable frequency. Ideally this frequency should be determined by risk assessment, but often it is selected arbitrarily with an assumption of implicit vulnerability.

Stage-discharge relation. The relation between stage (water level relative to a datum) and discharge of a stream at a given location. At a hydrometric station this relation is represented by the rating curve.

Stage-damage relation: The relation between stage (water level relative to a datum) and flood damages at a given location along a stream.

Standard normal variate: A variable that is normally distributed with a mean of zero and a standard deviation of one.

Storm surge: A sudden rise of sea level as a result of high winds and low atmospheric pressure

Structural capacity: The ability of a structure to withstand loads placed on the structure. These loads might be water levels for floods and storm surges, maximum acceleration for earthquakes, forces generated by winds for tropical storms, etc.

Uncertainty: Future conditions or design conditions for complex natural or human (economic) systems cannot be estimated with certainty. Uncertainties result from natural randomness, inadequate data, improper models of phenomena, improper parameters in these models, among other sources.

Vulnerability: Degree of loss (from 0 to 100 per cent) resulting from a potentially damaging phenomenon.

Wave energy: The capacity of waves to do work. The energy of a wave system is theoretically proportional to the square of the wave height, and the actual height of the waves (being a relatively easily measured parameter) is a useful index to wave energy.

Willingness to pay: The amount of money that a person will pay to reduce fatality and (or) nonfatal risks

Wind set-up: The vertical rise in the still water level on the leeward (downwind) side of a body of water caused by wind stresses on the surface of the water.

100-year flood: The 100-year flood has a fixed magnitude Q_{100} and exceedance frequency 1/100. In each year, there is a 1/100 probability on average that a flood of magnitude Q_{100} or greater will occur.

10 000-year storm surge: The 10 000-year storm surge has a fixed magnitude $H_{10\,000}$ and exceedance frequency 1/10 000. In each year, there is a 1/10 000 probability on average that a storm surge of magnitude $H_{10\,000}$ or greater will occur.

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