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Estimating Injury and Loss of Life in Floods: A Deterministic Framework

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Abstract. This paper presents an outline methodology and an operational framework for assessing and mapping the risk of death or serious harm to people from flooding, covering death and physical injuries as a direct and immediate consequence of deep and/or fast flowing floodwaters (usually by drowning), and deaths and physical injuries associated with the flood event (but occurring in the immediate aftermath). The main factors that affect death or injury to people during floods include flow velocity, flow depth, and the degree to which people are exposed to the flood. The exposure potential is related to such factors as the "suddenness" of flooding (and amount of flood warning), the extent of the floodplain, people's location on the floodplain, and the character of their accommodation. In addition, risks to people are affected by social factors including their vulnerability and behaviour. A methodology is described for estimating the likely annual number of deaths/injuries. This is based on defining zones of different flood hazard and, for each zone, estimating the total number of people located there, the proportion that are likely to be exposed to a flood, and the proportion of those exposed who are likely to be injured or killed during a flood event. The results for each zone are combined to give an overall risk for each flood cell and/or community. The objective of the research reported here is to develop a method which could be applied using a map-based approach in which flood risks to people are calculated and displayed spatially for selected areas or communities. The information needed for each part of the process is described in the paper, and the further research to provide the required information is identified.

Key words: floods, loss of life, serious injury, deterministic model, case examples

1. Introduction: The Nature of Risk Assessment

The risk to life and of serious injury from floods in continental Europe is not uncommon, for example in Poland in 1997 and in the Gard *Department* in southern France in 2002. In the UK these flood impacts occur infrequently, although most major flood events such as in 1998 and autumn 2000 see some

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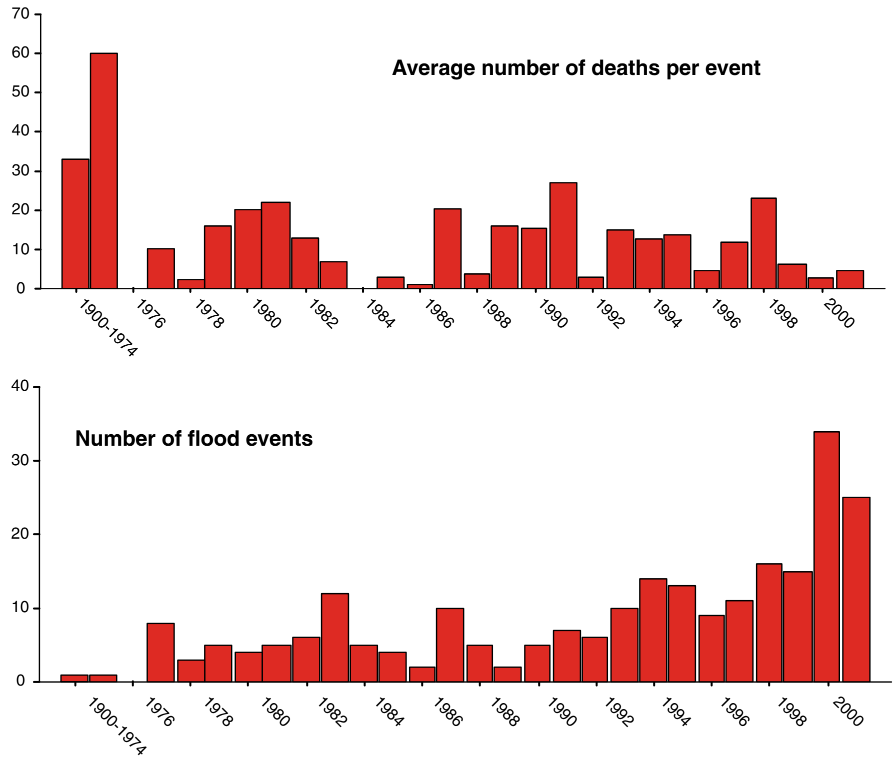

Figure 1. The number of flood events and related deaths in Europe (data for 1900–1974 are means). Source: WHO.

incidents of both. The loss of life in European floods appears generally to be falling, but nevertheless a significant risk remains (Figure 1).

Research on loss of life in floods is sparse, and has so far concentrated on small-scale experiments (Abt *et al.*, 1989) or reviews of broad scale models (Jonkman *et al.*, 2002). This paper presents an outline methodology and an operational framework for assessing and mapping the risk of death or serious harm to people from flooding at an intermediate or ‘‘community’’ scale. We cover death and physical injuries as a direct and immediate consequence of deep and/or fast flowing floodwaters (usually by drowning), and the risk of death and serious physical injuries associated with the flood event (but occurring in the immediate aftermath).

In so doing we recognise that risk is a complex concept, but the use of the term within the field of flood and coastal defence is commonplace. Definitions appear to be converging towards risk being a product of event probability and consequences. Thus the *Project Appraisal Guidance Series* developed by the UK Department of the Environment, Food and Rural Affairs (Defra) covers risk in *FCDPAG 4 – Approaches to Risk* (Defra, 2003a), stating that risk depends on a combination of both the likelihood and consequences of an event.

This reflects definitions used across the risk field. For example, the Royal Society (1992) defined risk as a combination of the probability, or frequency, of occurrence of a defined hazard and the magnitude of the consequences of that occurrence. A similar definition is used by the British Standard Institution (1996). Comparable definitions have been adopted by DG SANCO (European Commission: Directorate-General for Health & Consumer Protection) for a range of risks to EU citizens (European Commission, 2000). The associated definition for "hazard" is the potential of a risk source to cause an adverse effect, and in the UK the *Departmental Guidance for Environmental Risk Assessment and Management* (DETR, 2000) uses "risk" and "hazard" in similar ways.

This convergence leads us to use the term risk here to denote the probability and severity of an adverse effect/event affecting people following exposure, under defined conditions, to a risk source. In the context of this paper the risk source is floodwater, the hazard is the potential to cause direct injuries, and the risk is the likelihood/probability[1] that such a potential is realised.

2. The Procedure of Risk Assessment

The procedure by which risk is determined is a 'risk assessment': a process of evaluating the likelihood and severity of the adverse effect/event, including identifying the attendant uncertainties. The European Commission's (2000) DG SANCO report defines a risk assessment as comprising hazard identification, hazard characterisation, exposure assessment, and risk characterisation, and we have adopted this four-step sequence (Table I). It is similar to the framework for risk assessment recommended by the DETR (2000) although the terminology differs slightly.

As far as *hazard identification* is concerned the risk source considered here is floodwater and the hazard is the potential of that floodwater to cause physical injury or death during or immediately after flooding (i.e., within days). We are concerned here with these short-term physical effects, and not the longer term physical and psychological effects analysed elsewhere (e.g., Tapsell *et al*., 2002).

The purpose of *hazard characterisation* is to evaluate the effects of being exposed to the risk source. In simple terms, the effects may be characterised by the expression:

[1]It should be noted that "likelihood" here relates to chances per year (i.e. expected frequency) whereas probability is the chance of occurrence within a specified time frame or per event.

Table I. The risk assessment framework

Risk assessment stage	Definition[a]
Hazard identification	The identification of a risk source(s) capable of causing adverse effect(s)/event(s) to humans or the environment, together with a qualitative description of the nature of these effect(s)/event(s)
Hazard characterisation	The quantitative or semi-quantitative evaluation of the nature of the adverse health effects to humans and/or the environment following exposure to a risk source(s). This must, where possible, include a dose/response assessment[b]
Exposure assessment	The quantitative or semi-quantitative evaluation of the likely exposure of humans and/or the environment to risk sources from one or more media
Risk characterisation	The quantitative or semi-quantitative estimate, including attendant uncertainties, of the probability of occurrence and severity of adverse effect(s)/event(s) in a given population under defined exposure conditions based on hazard identification, hazard characterisation and exposure assessment

[a]Definitions taken from European Commission (2000).
[b]A "dose/response assessment" examines the relationships between the scale of the exposure and the scale of the adverse effects.

$$E = f(F, L, P)$$

where E is the nature/extent of effects (on those exposed), F is the flood characteristics (depth; velocity, etc.), L is the location characteristics (inside/outside buildings; nature of housing, etc), and P is the population characteristics (age; health, etc.).

This posits that these 'dose–response' relationships are different for different groups of people (for example, those outdoors, those indoors or those in vehicles). Given such a 'dose–response' assessment, the *exposure assessment* focuses on the relationship between the presence of the floodwaters and the probability that the adverse effects are realised. For example, if people are indoors and upstairs when a flood affects a residential area, no-one will be exposed (directly) to the risk source: this step in the risk assessment examines, in effect, the conditional probabilities that someone present will be exposed to the risk source.

The final step of the risk assessment is *risk characterisation*. This combines the likelihood/probability of a flood (to produce the risk source), the probabilities that people will be exposed (based on the nature/size of population present and associated probabilities of exposure), and the probabilities that those exposed will be injured or will suffer loss of life.

3. The Determining Variables to be Considered

3.1. OVERVIEW: HAZARD IDENTIFICATION, CHARACTERISATION AND EXPOSURE

The research literature suggests that there are three broad sets of characteristics which will influence the degree of immediate harm to people in the event of a flood (see Ramsbottom, *et al.*, 2003; Jonkman *et al.*, 2002). These are the flood's characteristics (depth, velocity, etc.), the location's characteristics (inside/outside, nature of housing), and the population characteristics (age, health, etc.).

Regarding the flood, there is broad agreement that the degree of hazard is primarily associated with depth and velocity, predominantly the latter (Abt *et al.*, 1989). Table II lists other possibly relevant parameters.

At any particular time, people potentially at risk may be outdoors on foot, outdoors in a vehicle, indoors in a basement, or confined by disabilities to the ground floor, etc. The distributions of people amongst these locations (or the probabilities of particular individuals being in a particular location) will vary with nature of the area, the time of day, and the time of year, etc. For example, at night in mid-winter in a small town, people will predominantly be at home, mainly in bedrooms on the first floor. On a summer holiday saturday afternoon many people would be outdoors, in their gardens, in parks, campsites or in shopping centres.

But the usual precursors to flooding are heavy rainfall and/or storms at sea and these circumstances will affect these locational distributions. They will, for example, reduce the numbers of people outdoors on foot. Flood warnings will affect peoples' locations, as will the evacuation of exposed people in extreme cases. At one extreme, the lower stretches of large rivers can receive several days' flood warning, allowing people to be alerted and to take appropriate evasive action. At the other extreme, flooding can occur very quickly – most notably with a failure of a coastal defence – allowing no time for a flood warning and any exposure reduction measures. Significantly, at 18 UK locations flooded from rivers in 2000 surveyed in research on the health impacts of floods (Risk and Policy Analysts, 2003), nearly 70% of 655 respondents received no flood warning prior to their house being flooded.

Taking a particular flood in a defined area under specified circumstances (with its degree of flood warning, timing, etc.) will indicate the probabilities that people will be exposed to the flood. The probability that a particular individual will suffer serious short-term physical injuries will then depend, to some extent, on their personal characteristics. We would expect the very old to be more at risk and the infirm/disabled/long-term sick to be at greatest risk. Although, theoretically, a young child would be at high risk, it is very unlikely that, say, a 4-year-old would be left alone

Table II. Flood characteristics potentially relevant to loss of life and major injury (in addition to water depth and velocity)

Parameter	Comment
Speed of onset and flood warning	The speed of onset and flood warning are important factors but predominantly affect the probability that people will be exposed rather than the intrinsic hazardous properties of the floodwaters (i.e. speed and depth)
Flood duration	Within Europe, flood durations are likely to range from several hours to a few weeks. Whilst people trapped in their homes in a winter flood for several days are more likely to suffer hypothermia, duration *per se* is unlikely to be a significant factor for immediate serious injuries or worse
Debris	Fast moving floodwaters carrying debris present a greater threat (to both people and structures) than those with no debris. Sources of (large) debris include trees, cars, caravans, ice floes, etc.
Nature of floodwater	Different types of floodwater have varying degrees of damage potential. It is generally acknowledged that seawater causes more damage to buildings than river water. Sewage contamination would be expected to present an increased risk of disease. However, in terms of serious short-term physical human effects, the nature of the floodwater is unlikely to be a significant factor
Level of flood risk and presence of defences	The presence and condition of flood defences together with the past flooding record and predictions of future flooding all relate to the risk of the flood event occurring, and are therefore taken into account in the estimation of flood probability. This includes breaching of defences, where the probability of failure is equal to the probability of the event. The flood hazard is expressed in terms of velocity and depth of the resulting flood
Nature of floodplain	The depth and velocity of floodwaters will vary with distance from the source of the flooding (breach, river, overtopping, etc.) which, in turn, will depend on the nature of the floodplain (topography, presence of obstructions, etc.). As such, knowledge of the floodplain will inform the estimates of flood depth and velocity, as opposed to being a separate variable, except insofar as floodplain size affects evacuation success or otherwise

in a flood situation: their exposure is therefore related to their family or social circumstances at the time (as would be the exposure of many individuals).

More generally, the possibility that direct physical injuries will be a function of other socio-demographic factors such as income, level of education, or employment status, is unsubstantiated. They are known to influence the extent and impact of longer term physical and psychological flood effects (Tapsell *et al.*, 2002; Penning-Rowsell and Wilson, 2003) but that is not our concern here.

3.2. SINGLE FLOOD EVENT ASSESSMENTS

In this methodology, we suggest that the number of deaths and injuries for a single flood event may be estimated as follows:

$$N(I) = N \cdot X \cdot Y$$

where $N(I)$ is the number of deaths/injuries, N is the population within the floodplain, X is the proportion of the population exposed to a chance of suffering death/injury (for a given flood), and Y is the proportion of those at risk who will suffer death/injury.

To calculate $N(I)$, methods are needed to calculate X and Y, having determined the population of the floodplain area (N). Estimating the numbers of people at risk requires we estimate the degree of hazard by location within the floodplain. In essence, this will require determining the numbers of people ($N(Z)$) within different hazard zones, where the degree of hazard can be related to flood depth, velocity and debris content, and where that hazard is broadly constant across the hazard zone. The first step is therefore to define the hazard zones.

Whilst it is clear that the degree of hazard is a function of both velocity (v) and depth (d) (e.g., Abt *et al.*, 1989), and that a flood with depth but no velocity is hazardous, a flood with (virtually) no depth is not. We have used therefore the function $(v + 1.5) \times d$ for this aspect of the degree of hazard. A further factor for debris content is added to reflect the extra hazard in this respect (Table III). This expression is somewhat arbitrary, although it is based on considerable experience of flood hazard estimation. Refinement of this relationship is needed in the future, not least because it is central within this methodology to estimating the fatality rate within those injured in the extreme floods analysed here.

The numbers of people exposed is likely to depend on four factors: the existence of a flood warning, the flood's speed of onset, the nature of the area (type of housing, presence of parks, etc.), and the timing of the flood. Defence overtopping and breaching are a special case, where the speed of onset can be rapid and, whilst severe conditions may be forecast, there may be no warning of the actual flooding. Although all such factors could be calculated probabilistically, we have used a simple scoring system on a three point scale (Table IV) and again there clearly is scope for refinement of this approach.

Table III. Hypothetical example: hazard zones and the number of people at risk [variable $N(Z)$ and the derivation of the Hazard Rating]

Distance from river/ coast (m)	$N(Z)$	Typical depth, d (m)	Typical velocity, v (m/sec)	Debris factor (DF)	Hazard rating = $d(v + 1.5) + DF$
0–50	25	3	2	2 – Likely	12.5
50–100	50	2	1.8	1 – Possible	7.6
100–250	300	1	1.3	0 – Unlikely	2.8
250–500	1000	0.5	1.2	0 – Unlikely	1.35
500–1000	2500	0.1	1	0 – Unlikely	0.25

Table IV. Hypothetical example: area vulnerability's components and their scores

Parameter	1 – Low risk area	2 – Medium risk area	3 – High risk area
Flood warning[a]	Effective tried and tested flood warning and emergency plans	Flood warning system present but limited	No flood warning system
Speed of onset	Onset of flooding is very gradual (many hours)	Onset of flooding is gradual (an hour or so)	Rapid flooding
Nature of area[b]	Multi-storey apartments	Typical residential area (2-storey homes); (low rise) commercial and industrial properties	Bungalows, mobile homes, busy roads, parks, single storey schools, campsites, etc.

[a]In this context, flood warning includes emergency planning, awareness and preparedness of the affected population, and preparing and issuing flood warnings.
[b]High and low 'nature of area' scores are intended to reflect the judgement of the assessor as to whether there are particular features of the area in question which will make people in the area significantly more or less at risk than those in a 'medium risk area'.

The sum of the three factors, with scores ranging from 3 to 9, indicates the vulnerability of the area as opposed to that of the people (Table V). This 'area vulnerability' score is multiplied by the hazard rating derived above to generate the value for X (the % of people exposed to risk) as shown in Table VI. Should the score exceed 100, this is simply taken as 100. Whilst this is not a true percentage, it is used as such and provides a practical approach to quantifying the assessed flood risk.

The final stage is to compute the numbers of deaths/injuries. This is achieved in our hypothetical example by multiplying the number of people exposed to the risk (N(ZE)), from Table IV, by a factor, Y, which is based on

Table V. Hypothetical example: area vulnerability scores

Distance from river/coast (m)	Flood warning	Speed of onset	Nature of area	Sum = area vulnerability
0–50	2	3	2	7
50–100	2	2	1	5
100–250	2	2	3	7
250–500	2	1	2	5
500–1000	2	1	2	5

Table VI. Hypothetical example: generating variable *X* (% of people at risk)

Distance from river/coast (m)	*N*(*Z*)	Hazard rating (HR)	Area vulnerability (AV)	*X* = HR × AV	*N*(ZE)
0–50	25	12.5	7	88%	22
50–100	50	7.6	5	38%	19
100–250	300	2.8	7	20%	59
250–500	1000	1.35	5	7%	68
500–1000	2500	0.25	5	1%	31

N(*Z*) is the population in each hazard zone.
N(ZE) is the number of people exposed to the risk in each hazard zone.

the vulnerability of the people exposed. The factor we have used for *Y* is a function of two parameters that our experience suggests are particularly significant in relation to serious injury and loss of life in floods: the presence of the very old (P1); and those who are at risk due to disabilities or sickness (P2). In the first instance the values shown in Table VII can be used, but again these need further research in the future.

The sum for each area then provides an estimate of the *Y* values for each area which are then multiplied by the numbers of people exposed to the risk (as derived in Table VI) to give the numbers of injuries. In the hypothetical example in the relevant Tables, arbitrary percentages of the very old and infirm within each of the zones have been used to generate values for *Y* (Table VIII).

The resultant number of injuries is then is estimated by multiplying the number of people at risk (from Table VI) by *Y*, as shown in Table IX. In zones with a relatively high hazard rating, there would also be an increased probability of fatalities. We have assumed in this initial development of our method that a factor of twice the hazard rating is appropriate, expressed as a

Table VII. Hypothetical example: components of ‘People Vulnerability’ and their indicative scores

Parameter	10 – Low risk people	25 – Medium risk people	50 – High risk people
The very old (>75)	% well below national average	% around national average	% well above national average (including areas with sheltered housing)
Infirm/disabled/ long-term sick	% well below national average	% around national average	% well above national average (including hospitals)

Table VIII. Hypothetical example: generating values for Y (people vulnerability)

Distance from river /coast (m)	Presence of very old	Factor P1 (10/25/50)	Presence of infirm, etc	Factor P2 (10/25/50)	$Y = \text{P1} + \text{P2}$ (as %)
0–50	Around national average	25	Around national average	25	50
50–100		25	Around national average	25	50
100–250	Above national average	50	Around national average	25	75
250–500	Below national average	10	Below national average	10	20
500–1000		10	Around national average	25	35

percentage, based on the results that this gives for our case studies (see below). Applying this factor in our hypothetical example yields a predicted 89 injuries of which 7 are fatalities (Table IX).

In summary, the above procedures illustrate how the key factors identified from past research are used to estimate the overall numbers of injuries and deaths. Clearly, the methodology could be ‘tuned’ with better weights for the different factors. In line with our aim of developing a map-based system, most of the required parameters are already available for UK floodplains and in many other countries (or there are surrogates for them). The possible

Table IX. Hypothetical example: generating estimates of the numbers of injuries and deaths

Distance from river/coast (m)	N(ZE), from Table VI	Y = P1 + P2 (as %)	No. of injuries including loss of life	Fatality rate = 2 × HR	No. of deaths
0–50	22	50	11	25%	3
50–100	19	50	10	15%	1
100–250	59	75	44	6%	2
250–500	68	20	14	3%	0.5
500–1000	31	35	11	1%	0
All			89		7

exception is data on flood water velocity, which is not collected systematically except at gauging stations.

4. An Application to Three Case Studies

The methodology has been tested by being applied to three historical flood incidents in the UK. Further such tests will be needed to refine the methodology.

4.1. GOWDALL, YORKSHIRE, 2000

Gowdall is a village which was extensively flooded from the River Aire in autumn 2000 to a depth of about 1 m. The estimated return period of the flood was 100 years and more than one hundred properties were flooded.

For simplicity, the whole of the flooded area was taken as a single hazard zone. Taking a depth of 1.0 m, an assumed velocity of 0.5 m/sec and a debris score of 0 (i.e., debris 'unlikely') gives a hazard rating (HR) of: $\{1 \times (0.5 + 1.5)\} + 0 = 2$. During the event in 2000 there was a flood warning (score 2), the speed of onset was very gradual (score 1) and the area is residential (score 2) to give an area vulnerability (AV) score of $2 + 1 + 2 = 5$. The percentage of those at risk, X, is simply $\mathrm{HR} \times \mathrm{AV} = 2 \times 5 = 10\%$. Taking the flooded population as 250, the population exposed to the risk is then $10\% \times 250 = 25$. A site visit suggested that the numbers of very old and infirm people are not significantly different from the national average. On this basis, the value for $Y = 25 + 25 = 50\%$.

The predicted number of injuries is therefore $25 \times 50\% = 13$. The associated fatality factor is 4% (twice the hazard rating of 2) giving 0.5 fatalities. These results appear reasonable and are consistent with the findings from parallel research on the health impacts of flooding (Risk and Policy Analysts, 2003). Here approximately one third (i.e., 36) of the flooded properties were subject to interviews. Although no fatalities were reported by those interviewed, showing some overestimation of this hazard here, three direct injuries (i.e., physical injuries due to action of floodwaters) and eight indirect injuries (i.e., physical injuries due to over-exertion, etc.) were reported, giving an overall total of 11 to compare with the prediction of 13.

4.2. NORWICH 1912

Norwich suffered extreme flooding in 1912 with some 2,500 people flooded. The flood's estimated return period was 800 years and we have differentiated two hazard zones. The first, with 500 people, is close to the main river channel (within 50 m) and the second, with 2,000 people, is further away (Roberts and Son, 1912; Collins, 1920).

The derivation of the hazard rating is shown in Table X. There was no flood warning (score 3), the speed of onset was very gradual (score 1) and the area is residential (score 2) to give an area vulnerability (AV) score of $3 + 1 + 2 = 6$. The percentage of those at risk, X, is HR $\times$ AV and the population exposed to the risk is then $X \times N(Z)$ (Table XI). Because of the size of the population affected the percentages of very old and infirm people are not likely to be significantly different from the national average. On this basis, the value for Y is again 50%.

The predicted number of injuries is then 50% of the values presented in Table XI. The associated fatality factors are 7.5% and 3.4% (based on twice the hazard rating) for the two hazard zones (Table XII). Once again our methodology somewhat overestimates the fatality rate, in comparison with the reported four fatalities, but at least the result is the right order of magnitude.

Table X. Case study results: hazard rating for the Norwich flood (1912)

Distance from river	$N(Z)$	Typical depth, d (m)	Typical velocity, v (m/s)	Debris factor (DF)	Hazard rating = $d(v + 1.5) + \text{DF}$
<50 m	500	1.5	1	0	3.75
>50 m	2,000	1	0.2	0	1.7

Table XI. Case study results: generating X (% of people at risk) for Norwich, 1912

Distance from river	$N(Z)$	Hazard rating (HR)	Area vulnerability (AV)	X = HR $\times$ AV	N(ZE)
<50 m	500	3.75	6	23%	113
>50 m	2,000	1.7	6	10%	204

Table XII. Case study results: generating numbers of injuries and deaths for Norwich (1912 flood)

Distance from river	N(ZE), Table XI	Y = P1 + P2 (as %)	No. of injuries	Fatality rate = 2 × HR	No. of deaths
<50 m	113	50	56	7.5%	4
>50 m	204	50	102	3.4%	4
All			158		8

4.3. LYNMOUTH, 1952

Lynmouth suffered a devastating flood in August 1952 due to very rapid flow down the East and West Lyn rivers. The estimated return period was 750 years. Three hazard zones are taken here, based on the literature on the flood, related to the numbers of houses destroyed (38), severely damaged (55) and or just damaged (72).

The derivation of the hazard rating is shown in Table XIII. There was no flood warning (score 3), the speed of onset was rapid (score 3) and the area was predominantly residential (score 2) to give an area vulnerability (AV) score of $3 + 3 + 2 = 8$. The percentage of those at risk, X, is simply HR × AV and the population exposed to the risk is then $X \times N(Z)$ (Table XIV). Again, the percentages of very old and infirm people are not

Table XIII. Case study results: hazard rating for Lynmouth, 1952

Distance from river	$N(Z)$	Typical depth, d (m)	Typical velocity, v (m/s)	Debris factor (DF)	Hazard rating = $d(v + 1.5)$ + DF
Very close	100	3	4	2	18.5
Close	100	2	3	2	11
Nearby	200	1	2	1	4.5

Table XIV. Case study results: generating variable X (% of people at risk) for Lynmouth, 1952

Distance from river	$N(Z)$	Hazard rating (HR)	Area vulnerability (AV)	X = HR × AV	N(ZE)
Very close	100	18.5	8	100%[a]	100
Close	100	11	8	88%	88
Nearby	200	4.5	8	36%	72

[a]Since HR × AV = 148 which is greater than 100, X has been taken as 100%.

considered to be significantly different from the national average, so the value for Y is 50%.

The predicted number of injuries is therefore 50% of the values presented in Table XIV. The associated fatality factors are 37, 22 and 9% (again, based on twice the hazard rating) for the three hazard zones (Table XV). We have no precise numbers of people within each hazard zone in 1952, or good estimates of flood depths and velocities, but our assumptions do not appear unreasonable. The resultant prediction of 130 injuries, of which 31 would be fatal, is consistent with the actual death toll in 1952 of 34, this time showing some underestimation by our methodology of the actual loss of life.

4.4. EVALUATING THE TOLERABILITY OF OVERALL RISKS

In the recent UK government risk-based advice to land use planning authorities about development in flood plains – Planning Policy Guidance 25 (Department of Transport, Local Government and the Regions (DTLR), 2001) – flood likelihoods have been assigned degrees of tolerability, as follows:

1. "Little or no risk" – a probability of flooding <0.1% per year (i.e., less than 1 in 1000 per year floodplain);
2. "Low to medium risk" – a probability of flooding 0.1 – 1% per year (i.e., between 1 in 1000 and 1 in 100 per year) for fluvial flooding and 0.1 – 0.5% per year (i.e., between 1 in 1000 and 1 in 200 per year) for coastal flooding;
3. "High risk" – a probability of flooding >1% per year (i.e., greater than 1 in 100 per year floodplain) for fluvial flooding and >0.5% per year (i.e., greater than 1 in 200 per year) for coastal flooding.

A review of major floods since 1900 (JBA, 2000) shows that the risk of drowning is of the order of 1 in 1000 per major UK flood event. The implied borderline of intolerable risk for drowning as a result of fluvial flooding set in the PPG25 Guidance system is of the order of 1% per year ('medium' flood likelihood) × 0.001 (the probability of drowning), i.e., 1 in 100,000 per year.

Table XV. Case study results: generating numbers of injuries and deaths for Lynmouth, 1952

Distance from river	N(ZE) Table XIV	Y = P1 + P2 (as %)	No. of injuries	Fatality rate = 2 × HR	No. of deaths
Very close	100	50	50	37%	19
Close	88	50	44	22%	10
Nearby	72	50	36	9%	3
All			130		31

Table XVI. Presenting flood risks for the three case studies

Event	Likelihood (f) of a flood	Pop. within area (P)	No. of injuries	No. of deaths predicted	Deaths per year ($fN = D$)	Av. ind. risk (per year) (D/P)
Norwich, 1912	1 in 800 per year	2500	158	8	1.0×10^{-2}	1:250,000
Lynmouth, 1952	1 in 750 per year	400	130	31	4.1×10^{-2}	1:10,000
Gowdall, 2000	1 in 100 per year	250	13	0.5	5.0×10^{-2}	1:50,000

Although somewhat oversimplified, the average individual risks from the three case studies are presented in Table XVI. These show that the individual risks at Lynmouth in 1952 and Gowdall in 2000 were above the suggested target level of 1 in 100,000. The risk associated with the 1912 flood in Norwich was below the target level.

5. The Operational Framework and Sources of Data

The general approach to estimating flood risks to people derived from this methodology is outlined below (Figure 2). To avoid the need to collect new data on a large scale, existing or planned national data sets should be used, within a GIS system. In the foreseeable future, application of the methodology in many countries may require data to be collected locally for developing and calibrating the methods before they can be applied more widely.

Data sources will also vary in different countries, and different assumptions will be needed about the appropriateness of surrogate variables to match the needs of the different calculations.

5.1. STEP 1: DEFINE THE HAZARD ZONE

Options include, first, each hazard zone corresponding to a particular flood return period. This has the advantage that it could be derived from standard flood risk maps which have several return periods. Some of these exist already for the UK and others are planned. However this approach would not necessarily reflect accurately the actual hazard. For example, in a wide flat floodplain, the flood risk areas for all return periods will be very similar but the depth and velocity could vary considerably.

A second method could base the boundaries of hazard zones on distances from the river/coast. Standard values could be used for locations with similar characteristics (e.g., river size, valley slope, floodplain width, etc.).

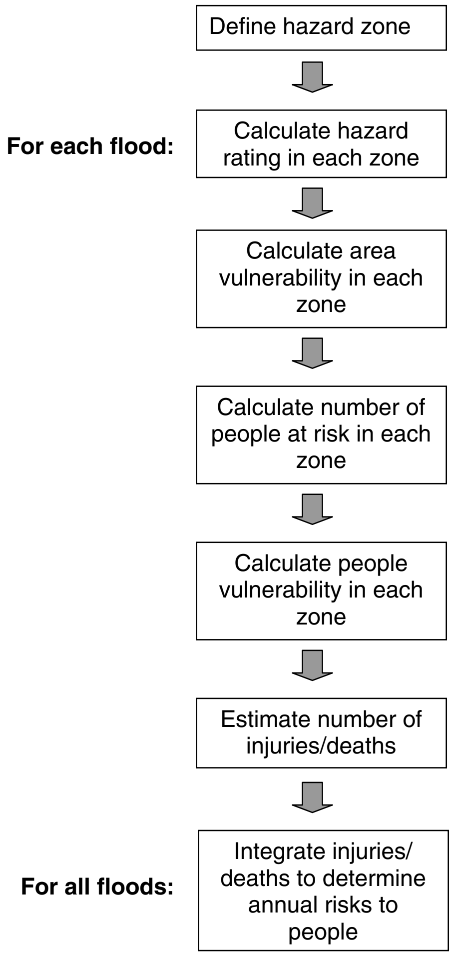

Figure 2. The approach advocated for estimating flood risks of serious of injury and loss of life to people in floods.

Alternatively, thirdly, each hazard zone could correspond to a range of values of flood hazard rating. This is technically a better approach, but requires the calculation of the flood hazard before defining each zone.

As the methodology now stands, we propose that the third approach above is adopted. The zones will be classified according to the degree of risk. For example, the zones may be classified as 'very high', 'high', 'medium' and 'low' risk. 'Very high' risk might correspond to a hazard rating value of greater than 10, and 'high' risk might correspond to a value in the range 7–10. The hazard zones can be based on the estimated 100-year flood (fluvial) and 200-year flood (coastal), and flood maps for these return periods are available for the whole of the UK.

Table XVII. UK flood mapping methods: the availability of flood velocity data

Flood mapping type and method	Availability of velocity data for floodplains
Fluvial Section 105 Survey: IH 130 method	Not available
Fluvial/Coastal Section 105 Survey: Historic flood outlines	Not available
Fluvial/Coastal Section 105 Survey: Flood basin model or projection of maximum levels	Not available
Fluvial/Coastal Section 105 Survey: 1-D hydrodynamic modelling	Velocity profile could be generated along a cross-section
Fluvial/Coastal Section 105 Survey: 2-D hydrodynamic modelling	Velocity vectors can be generated
National Fluvial Extreme Flood Outline using JFLOW	Velocity can be generated but accuracy is unknown
National Coastal Extreme Flood Outline (method not known)	Velocity can be generated from 2-D models that are used for about 70% of the coast but accuracy is unknown. The remainder is based on a projection of maximum levels approach (see above)
National fluvial flood mapping using Normal Depth method	Velocity profile can be generated along a cross-section but less accurate than a 1-D model

The main data deficiency is likely to be flow velocity. Only some of the mapping methods currently used in most countries, including the UK's mapping programme (Table XVII), provide relevant data. Where velocity data are unavailable, a velocity-equivalent could be estimated. This requires further investigation but possible methods include an equation of the form velocity $= f$ (depth, slope, roughness) in fluvial floodplains, or empirical equations for velocity where coastal defences fail or are overtopped, based on observations and detailed modelling results. That equation might be of the form velocity $= f$ (defence height, hydraulic head, distance from defence).

Debris potential is also likely to be difficult to determine. It can be a function of the land use in the upstream catchment/floodplain, but methods are not yet available to enable realistic predictions from this of debris concentrations, suggesting that more research is also needed here.

Hazard zones should take account of the proximity of flood defences. In general, areas close to defences should have a 'high' or 'very high' hazard rating. This could be linked to the condition of defences which, for the UK, has been researched under a project on ‘Risk Assessment for Strategic Planning’ (RASP) (DEFRA/Environment Agency, 2003b).

5.2. STEP 2: CALCULATE THE HAZARD RATING IN EACH HAZARD ZONE

The hazard rating is calculated from information on flood depth, velocity and debris load, and for floods of several return periods in order to estimate the annual flood risk. Ideally the delineated hazard zones should then not change, but the hazard rating in each zone will change for different floods.

Applying the hazard rating in each hazard zone is not straightforward. Options include, first, using a single average value for each hazard zone. This will not identify variations within the zone, particularly in cases where a location with a high ‘area vulnerability’ or ‘people vulnerability’ score has a hazard rating value that differs significantly from the zone’s average value. Alternatively, one could sub-divide the hazard zones and calculate a value of hazard rating for each sub-zone. This may be advisable where the area vulnerability score and/or the population vulnerability score vary significantly within the zone.

Over time and with more research the formula for calculating the hazard rating should be reviewed to ensure that it provides consistent values of flood hazard. In the absence of useful flood depth, velocity and debris load data, a first approximation could be made using the simple expression:

$$HR = (D_{max}/D) - 1$$

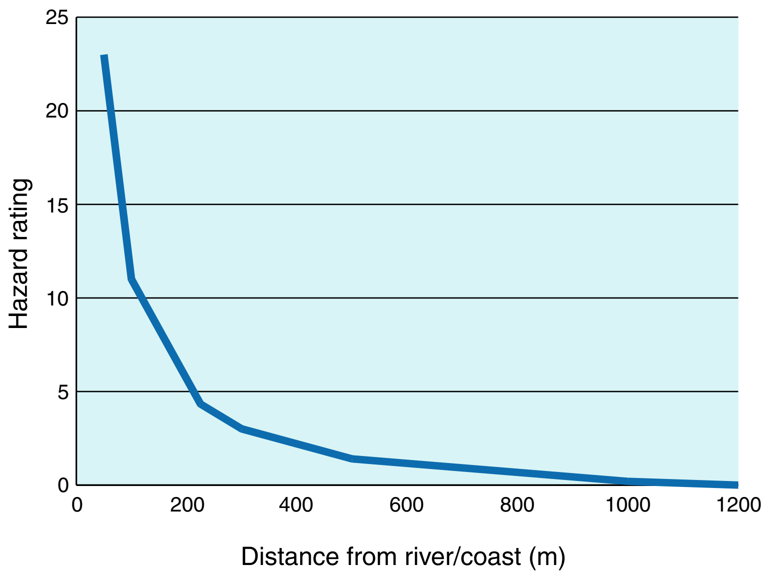

Figure 3. A default approach to assessing the hazard rating (for explanation see text).

where HR is the hazard rating at distance D, D_{max} is the extent of flooding from source (m), and D is the distance from flood source (m).

At $D = D_{max}$, HR = 0 since the flood depth will be zero. Figure 3 gives an illustrative plot of HR against D for $D_{max} = 1200$ m.

5.3. STEP 3: ESTIMATE THE 'AREA VULNERABILITY' IN EACH ZONE

'Area vulnerability' depends on several factors including the speed of onset of flooding, the availability of flood warnings, warning time, flood awareness and emergency planning, and the nature of the area including property types, size of floodplains, etc. Data on all these factors is needed, and combining them to produce an area vulnerability score for each flood hazard zone.

Data on the speed of onset of flooding is often patchy. Most catchment or meteorological agencies aim to provide flood warnings, so flood warning data is likely to be available in three categories of location: areas with a flood warning system; areas without a warning system because the available warning time is too short; and areas without a warning system for other reasons. Identifying locations where the warning time is less than 2 hours will be important, as these are where dangerous flash floods may occur.

Speed of onset is also affected by the presence of flood defences, as failure or overtopping of defences can cause very rapid flooding. Ideally a GIS layer showing relevant defences (i.e., raised embankments, walls and dams) should be developed but the greater difficulty here is predicting failure probability. This is generally low but the potential consequences are high. In the UK, RASP data could be used (DEFRA/Environment Agency, 2003b), since that research includes assessing the probability of defence failure.

Data on floodplain nature and extent should be readily available (e.g., on the UK Environment Agency flood maps). Property types in the floodplain may come from large and relatively detailed tax-related or other databases, or from databases capturing all properties to which mail is sent. In the UK for example the AddressPoint and Focus databases embrace the latter approach and they usefully include seasonal features such as campsites (DEFRA/Environment Agency, 2002b). Such databases may have limitations, however, such as not separating single storey dwellings. Either other databases should be sought, or local knowledge on property type will be needed, especially for high-risk areas.

5.4. STEP 4: CALCULATE THE NUMBER OF PEOPLE AT RISK IN EACH ZONE

Population data is generally available from national censuses. For the UK, data relates to Enumeration Districts (c. 200 properties), and calculations could be based on the existing methodology in the Modelling and Decision Support Framework (the MDSF) developed for catchment flood management planning (DEFRA/Environment Agency, 2002b). This approach uses census data for each Enumeration District, and 'spreads' the population across the District in proportion to the number of residential properties there. An alternative approach would assume a constant population density throughout each District but this could lead to large errors because floodplains are often less developed than adjacent areas within the same census unit.

5.5. STEP 5: CALCULATE THE 'PEOPLE VULNERABILITY' IN EACH ZONE

The 'people vulnerability' measure requires information on the age and health of the population at risk, including the number of people with disabilities or sickness. Again, national population censuses should be useful.

For the UK some of this data is available from the national census and, in the MDSF system, a Social Flood Vulnerability Index (SFVI) has been calculated and mapped (DEFRA/Environment Agency, 2002, Tapsell *et al.*, 2002a). This Index is concerned with the overall 'intangible' impacts of flooding, not just the risk of death/injury, and is based on three social variables (the elderly aged 75+; single parents; and the long-term sick) and four financial deprivation indicators (unemployment; overcrowding in households; non car-ownership; and non home-ownership). The rationale for the variables used is given in Tapsell *et al.* (2002) and was constrained by the need to use data that is available both for the whole of England and Wales and for small geographical areas to match the size of UK floodplains.

5.6. STEP 6: ESTIMATE THE NUMBER OF INJURIES/DEATHS

We outlined above the method for estimating the numbers of injuries/deaths. Some further work may be required to refine the method although the lack of reliable data currently on injuries in flood events – as opposed to fatalities – will make calibration difficult. Our three case examples appear to provide some reasonable results but these may not be typical of other situations. The overall error of prediction of fatalities across all three cases is less than 4%, but this error is smaller than one might expect. In reality we are not unduly dissatisfied with the Norwich result, given the low numbers involved, where the error is 50%.

5.7. STEP 7: DETERMINE ANNUAL RISKS

The method of determining annual risks needs data for a number of floods of different return periods. The results are then plotted against frequency of occurrence, and integrated to estimate the average annual risks (as with annual average damages (Penning-Rowsell *et al.*, 2003)). In many countries including the UK, with sparse data nationally for a range of floods at any one site, it may be possible to develop only an estimate of annual average risk based on a small number of flood events.

6. Assessment

The causes of death and serious injury due to flooding are many and varied, yet we have attempted to develop a simple model so as to try to predict their occurrence. From a review of the research literature we have proposed an approach to risk assessment that embraces the three groups of variables which appear to be most important in this respect, to take account of the likelihood of a flood, whether people will be exposed to it, and whether those exposed to that flood will be killed or seriously injured. The methodology presents flood risk in both societal terms (i.e. the estimated number of deaths per year caused by flooding in a unit of land, for example a flood cell) and in individual terms (i.e., the annual probability that an individual in a unit of land will die as a result of flooding).

Our method for estimating the number of deaths/injuries is based on determining a 'hazard rating' for different zones of the floodplain, a score for the 'area vulnerability' (in terms of flooding lead time, etc.), the population at risk and the population's vulnerability. The approach has been tested against three case study floods (Norwich 1912, Lynmouth 1952 and Gowdall 2000) and a satisfactory level of prediction appears to have been obtained.

However we recognise that the errors in predicting both serious injury and fatalities may in reality not match those found in our case examples, and more research is needed to put sensible confidence limits around the point estimates that the model generates. Better data is needed to refine the flood hazard rating formula, in different flood situations and in different countries. We need better ways of assessing the impacts of flood warning on risks to people, and on peoples' behaviour during floods.

To make the method readily applicable, such that policy makers could use it with some confidence, will require refinement of the overall methodology, the development of a GIS-based method, pilot testing of the method, more information on errors of prediction, and a system to guide careful interpretation of the results. Nevertheless we believe that we have made useful progress in developing a community scale model of loss of life and serious injury in floods, and that further research can build on this in the future.

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