Fluvial Freeboard: Background Information

R&D Project Record W5/042/1

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This report summarises the findings of research carried out into the use of freeboard for fluvial flood defences. The information within this document is for use by Environment Agency staff and others involved in the planning, design and implementation of flood defences and development control within river catchments.

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1. LAYOUT OF THE PROJECT RECORD

The Project Record sets out information concerning the research project into Freeboard that is complementary to R&D Technical Report W187. For this research project four areas of information are included in the Project Record:

- information on a questionnaire that was distributed as part of the project;
- background information on the derivation of the methods for estimating hydrological/hydraulic uncertainty;
- consideration of development control issues in relation to freeboard;
- assessment of how the inclusion use of freeboard affects the standard of protection of a defence

Chapter 2 provides a summary of who the questionnaire was sent to, how many responses were received and factual data on the responses.

Chapter 3 provides information on the derivation of the methods used in the Technical Report for estimating hydraulic/hydrological uncertainty. This was considered to be at too great a level of detail to be included in the Technical Report.

Chapter 4 considers the issue of how Development Control Officers may take account of freeboard when giving advice on floor levels in flood risk areas. However a National Group is also looking at the issue.

Chapter 5 is a review of how freeboard affects the standard of a defence compared with not using freeboard and considers a number of case studies where the freeboard methods presented in the Guidance Note have been applied.

2. FREEBOARD QUESTIONNAIRES

2.1 Examples of Questionnaires

Two questionnaires were developed, a detailed questionnaire and a briefer short questionnaire containing only a selection of the questions in the detailed questionnaire. Blank copies of each questionnaire are contained at the end of this section.

The detailed questionnaire was sent out to representatives in each of the eight Agency Regions. Some 225 questionnaires were sent out and about 150 were then distributed by the representatives in each Region to Flood Defence Engineers and Development Control Officers. In addition a number of questionnaires were distributed within Mott MacDonald, Risk & Policy Analysts Ltd (RPA) and to other consultants. Of these questionnaires 65 completed ones were returned, with questionnaires being returned from all Regions. This represents a 40 % response, which was considered a very good response.

The short questionnaire was sent out to 480 CIWEM Rivers and Coastal Group members. 74 completed questionnaires were returned, which represents a 15 % response. This is again considered to be a good response given the unsolicited nature of the questionnaire and the fact that many members are not engineers. Table 2.1 and Table 2.2 show which Regions and organisations responded. A good mix of organisations responded and hence the information received was considered to represent a fair cross section of the flood defence sector.

Table 2.1 Number of responses to Detailed Questionnaire

Detailed Questionnaire	
Region	**Number of respondents**
Anglian	15
Midlands	5
North East	12
South West	8
Southern	5
Welsh	3
Thames	7
North West	7
Other (Consultants)	3
Total	65

Table 2.2 Number of responses to Short Questionnaire

Short Questionnaire	
Employment Type	**Number of respondents**
Consultants	35
Government (Environment Agency, MAFF, Drainage Boards, research bodies)	24
Other (retired or unknown)	15
Total	74

2.2 Responses to Questionnaires

Most people responding (80 %) did not have a standard method for determining freeboard within their organisation and most (85 %) would welcome guidance on a consistent method. There was considerable variation in what people considered was included in their estimates of freeboard. Most agreed that it should include settlement, an allowance for wear/degradation and for wave overtopping but that it should not include for changes occurring in the future, for example, changes in catchment or channel roughness. There was no real consensus whether uncertainties in hydrological and hydraulic processes should be allowed for in freeboard or in the design water level, though the latter was preferred. There was also some variation in what parameters were considered important for determining freeboard though the reliability of hydrological and hydraulic data and analysis, settlement and the consequences of failure scored highly. Such things as wind set up, changes in channel roughness, siltation were not considered to be important factors, neither, interestingly was public confidence.

A number of comments appeared repeatedly, including:

- site specific conditions are important, hence rigid guidelines are unlikely to be helpful;
- the consequences of overtopping are important;
- guidance should be straightforward;
- risk should be considered;
- advice on freeboard in relation to PAGN, high ground, standard of protection is needed.

Figure 2.1 shows which parameters respondents thought was currently included in freeboard allowances. Figure 2.2 shows which parameters respondents thought should be included in freeboard allowances in the future. Figure 2.3 shows which parameters were considered the most important when determining freeboard. Figure 2.4 shows which failure mechanisms respondents considered had caused flooding in their experience.

The written comments to questions in the detailed and the short questionnaires have been summarised and are set out below.

Detailed Freeboard Questionnaire
Summary of Written Comments

PART 2.1

How freeboard is evaluated:

- Built up from main factors (settlement, modelling tolerance, waves, etc)
- Built up from main factors
- Built up from main factors
- Built up from main factors
- Built up from main factors
- Built up from main factors
- Built up from main factors
- Built up from main factors + sensitivity analysis
- DWL + 0.0 m hard, 0.3 m soft
- DWL + 0.15 m hard, 0.25 m soft
- DWL + 0.15 m hard, 0.3 to 0.5 m soft
- DWL + 0.15 m hard, 0.3 m soft
- DWL + 0.15 m hard, 0.3 m soft
- DWL + 0.15 m hard, 0.3 m soft
- DWL + 0.15 to 0.3 m hard, 0.6 m soft
- DWL + 0.3 m hard, 0.5 m soft
- DWL + 0.3 m hard, 0.5 m soft
- DWL + 0.3 m hard, 0.6 m soft
- DWL + 0.3 m hard, 0.6 m soft
- DWL + 0.3 m hard, 0.6 m soft
- DWL + 0.3 m hard, 0.6 m soft
- DWL + 0.3 m hard, 0.6 m soft
- DWL + 0.3 to 0.6 m
- cost and type of additional material, importance of defence
- Welsh Office requirements
- Agency Eng. Dept. Instruction Nr 30 Design Standards for Sea Defences formerly 400 mm fluvial, 600 mm tidal now built up from main factors
- Consequences of overtopping

- Client requirements
- DWL + 0.3 m or velocity head, whichever is higher
- DWL + 0.15 m for hard & soft client requirements
- engineering judgement

PART 2.2

Risk assessment carried out?

- Risk assessment of overall scheme
- Freeboard a potential issue
- Risk could justify any additional costs
- To ensure the factors under engineering judgement are taken into account
- Consider susceptibility to debris & cattle degradation
- Consider blockage at bridges
- not yet but possibility in future
- concept of a "notional" freeboard has been abandoned, additional height is added based on an informal risk assessment
- no but likely in future
- informally when deciding on freeboard
- because confidence in water level and risk of damage varies between projects need final built scheme to be secure to expected standard – so we can all sleep easy at night

PART 2.3

How floor levels are specified/development is controlled:

- 100 year WL
- Tidal – single storey buildings should have access to roof
- DWL + 0.3 m
- DWL + 0.6 to 1.0 m
- DWL or 100 year + 0.6 m
- 100 year WL + freeboard
- 100 year WL or max recorded flood level+ 0.5 m
- 100 year WL for floors and drainage
- 100 year WL for floors and drainage

- 100 year WL +0.5 m for floors, 100 year level for general site levels
- 100 year WL + 0.6 m
- Max recorded flood + 0.5 m or 100 year WL
- Max recorded flood level + 0.6 m or 100 year WL + 0.6 m
- Max recorded flood level + 0.6 m or 100 year WL + 0.6 m
- Max recorded flood level + 0.6 m or 100 year WL + 0.6 m or locally determined flood level + 0.6 m
- Max recorded flood level + 0.6 m or 100 year
- Max recorded flood level + 0.25 m
- Max recorded flood level + 0.3 m
- Max recorded flood level + 0.3 to 0.5 m
- Max recorded flood level + 0.5 m
- Max recorded flood level + 0.5 m
- Max recorded flood level + 0.5 m
- Max recorded flood level + 0.6 m
- Max recorded flood level + 0.6 m
- Max recorded flood level + 0.6 m
- Max recorded flood level + 1.0 m
- Behind existing defence – at same level
- Behind defences, ground level + 0.6 m
- Behind defences, ground level + 0.6 m
- No consistency
- For bridges, some regions specify 100 year level + 0.6 m others 100 year level + 0.3 m, for arched bridges what should be taken as soffit ?
- tidal: 200 year still tide level + 0.6 m + allowance for sea level rise,
- fluvial: 100 year level + 0.6 m or max recorded flood level + 0.6 m
- For bridges Agency often specify 100 year WL + 0.5 m. Is this for afflux ? (which is unlikely to be this large) or for floating debris (which could easily be larger).
- in past max recorded WL + allowance, now asking developers to assess risk based on Agency information

PART 3

Which components included ?

- Design Engineer to choose but document it
- statistical analysis should be carried out
- Siltation – in past not allowed for as maintenance procedures assumed to be in place
- risk of blockage
- size of watercourse
- environmental impact
- sensitivity of water levels to flows

PART 4

What factors are important ?

- maintenance regime
- the relative importance varies enormously between situations therefore we do not rely on written procedure but rely on judgement by experienced staff

PART 5.2

Causes of failure:

- non-main river culverts
- main river – blockages, weed growth
- drainage system failure
- fuse embankment/spillway important
- temporary works in channel
- blockages very common cause of flooding
- failure due to vermin never heard of – but may be because controlled

PART 6.1

Would value guidance on:

- waves and fissuring
- how to deal with PAGN
- standard method

- finished floor levels
- hydraulics/hydrology
- list of parameters to build up freeboard
- weighted factors, build up should be transparent
- risk assessment method using factors in questionnaire
- defence level for soft defences – include topsoil etc or not ?
- climate change
- public confidence
- consistency is the keyword
- consistency
- Clarification of freeboard in PAGN
- statistical analysis
- how to combine probabilities simply
- economic costs and benefits of freeboard
- consistent approach
- separate guidance on tidal/coastal
- tolerance range for each element of freeboard
- energy head
- fissuring and vermin
- advice not needed as Welsh Office guidance used
- freeboard is a factor of ignorance
- guidance on risk analysis
- bridge blockage scenarios
- local effects at bends
- shingle & groyne formation & their effects
- is MAFF grant aid eligible on freeboard if it exceeds the Indicative Standard of Protection ?
- scale of allowances for different parameters
- how should parameters be combined ?
- could risk based approach be preferable ?
- wave run up
- should be assessed on case by case basis

- standard approach useful but needs to cater for specific circumstances / cost / politics. Guidance on sensible range of variables would be useful
- standard approach but not prescriptive

ADDITIONAL COMMENTS

- problem of estimating design standards
- definition of standard of protection (freeboard in or out)
- development seen as major problem
- engineer should be given the freedom to decide
- should consider safe overtopping (spillway etc)
- legislation needed for consistency
- risk based approach
- DWL should be best estimate
- Engineering judgement will always come into play
- New procedures should not increase the amount of modelling work
- maintenance procedures essential to ensure standard maintained
- what about freeboard on soffit levels of bridges culverts etc
- coastal/tidal advice would be useful
- smaller freeboards for higher return periods ?
- risk methodology best way forward
- if method is changed from normal +0.3 hard, +0.6 m soft, then revised advice for development control essential
- remember that water levels not flows cause flooding
- how to approach time related elements(settlement, climate change etc) with respect to PAGN
- designers must pass on information to maintenance teams so design standards can be maintained
- document should be guidance rather than rigid standard as situations vary so much
- peace of mind for riparian residents
- be aware that the sample of experience is small
- are we becoming too design orientated
- site specific knowledge may over ride calculated values
- clear definition of varying parameters essential for this study

- need to define what is included in water level what in freeboard
- if natural ground level is above DWL but below DWL + freeboard what should be done ?
- for situations where high confidence not required then freeboard should be a simple safety factor, where high degree of confidence required (e.g. tidal situations) then greater freeboard/more detailed analysis appropriate
- would like to see leaflet produced to pass to developers advising them what factors should be considered.
- do not want idiots guide, but guidance on main factors and their size
- hope that all questionnaire answers are not treated with equal weight

Short Freeboard Questionnaire
Summary of Comments

PART 2.1

How freeboard is evaluated:

- Built up from site specific elements
- Built up from site specific elements
- Built up from site specific elements
- Built up from site specific elements
- No freeboard except for allowance for settlement – Midlands policy re PAGN
- NRA Standard Practice Document
- DWL + 0.3 m hard, 0.45 m soft
- DWL + 0.3 m hard, 0.45 m soft
- Total inconsistency
- Minimum is $v^2/2g$ above water level
- 0.3 m river banks, 1.0m tidal
- Max recorded + 0.3 m
- DWL + 0.15 hard, 0.3 m soft or velocity head
- DWL + 0.6 m
- DWL + 0.3 m hard, 0.6 m soft
- DWL + 0.3 m

PART 3

What factors are important ?

- security of flood gates/stoplogs
- blockages
- availability of information an issue
- superelevation
- changes in hydraulic structures
- materials
- location from the defence

- access for maintenance
- return period protected against
- flood warning capabilities
- height of defence above protected area
- consequences of failure very important
- client requirements
- visual amenity
- geotechnical data
- height & profile of defence
- land use behind defence

PART 4 ADDITIONAL INFORMATION

- In past catch all, rigorous approach desirable
- Passing on design information to maintenance teams essential
- Assessment of multiple factors weighted combination or similar
- Uncertainty in hydrology main factor
- Allowance for settlement can have adverse effect if embankment designed to be overtopped
- Development and its effect on small catchments serious
- Maintenance practices and “n” values important
- one person’s factor of safety is another person’s factor of danger
- aim to reduce uncertainty rather than quantify it
- difference between flood defence failure and structural failure – what counts is the probability of failure within the design life span.
- Freeboard formerly more applied to recorded events to take account of the uncertainty of the historic flood return period
- Case of replacement flood defences higher than PAGN optimum owing to PR implications of them being overtopped
- Summing components can lead to excessive estimate, joint probability time consuming so use judgement & client requirements
- needs to stand up to rigorous examination in political debate
- maintenance practices important

- designer needs to be clear what event he/she is designing for and whether failure in events that exceed the design are acceptable
- failures due to scour of toe

3. BACKGROUND AND DERIVATION OF HYDROLOGICAL AND HYDRAULIC UNCERTAINTY

3.1 Introduction

In this Chapter some basic definitions related to statistical parameters are defined and the relationship between levels of risk and return period/probability of exceedence are defined in order to set out a basis for future development of freeboard in terms of risk assessment and probabilities.

The combined analysis of hydrological events and corresponding hydraulic responses are used to define design water levels in systems such as rivers, canals and reservoirs. The design water levels can vary randomly with mean value around the design level, and can be regarded as expected water levels at a selected risk level. The randomness in water levels is associated with errors in the estimation of incoming loads (flows) as well as the random nature of the capacity of the system. Traditionally, a freeboard above the design level is allowed for to accommodate the uncertainties associated with the hydrological and hydraulic analysis. This procedure does not give absolute safety against failure at the selected risk level (return period) but does minimise the risk of failure. The terminology return period is traditionally used to define the annual risk of failure. However the level of risk or the long term risk is a function of time and the selected return period. Thus there is a greater risk of failure over a long period than over a shorter period.

3.2 Stochastic Processes

Hydrological processes are generally characterised by deterministic and random/stochastic components and processes of this nature are defined as stochastic processes. When the stochastic component is large in comparison with the deterministic component the process can be considered as purely random. The definition of statistical parameters is given in this Chapter as some understanding of statistical concepts is needed in the uncertainty analysis. Thus over a long time period there is a greater risk of failure than over a short time period.

Probability Density Function (PDF)

The probability density function (PDF) is the functional representation of the probability distribution of a random variable within a range which can vary from finite to infinite values, see Figure 3.1.

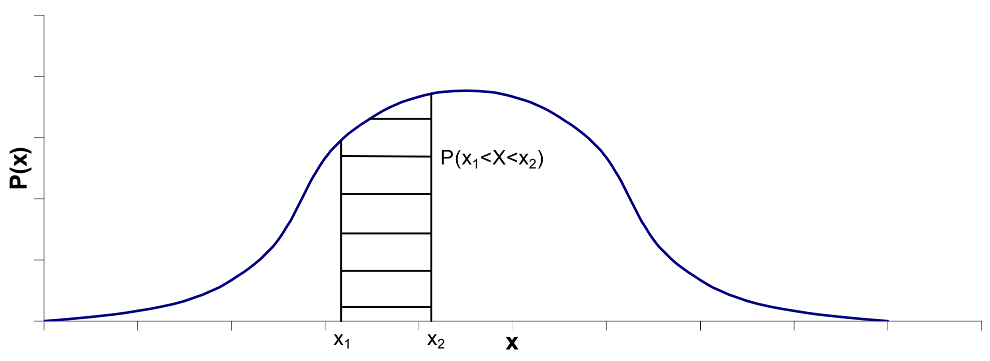
If the PDF of a random variable x is f(x), then the following properties are applicable for the distribution.

- total area under the distribution curve $f(x)$ is one

- the probability of occurrence of a random variable between values x_1 to x_2 is the area under the curve between x_1 and x_2.

It should be noted that the probability of occurrence of a value x is zero which can be mathematically interpreted as the area under a point of data on the distribution curve. Any single value has an infinite number of decimal places so that the exact value may never be truly defined.

Figure 3.1
PROBABILITY DENSITY FUNCTION (PDF)



Cumulative Distribution Function (CDF)

The cumulative distribution function of random variable x is defined as the total area of the PDF from the lower limit of the distribution to the point x. The mathematical relationship between PDF and CDF is given below, see Figure 3.2.

$$F(x) = \int_{-\infty}^{x} f(u)\,du$$

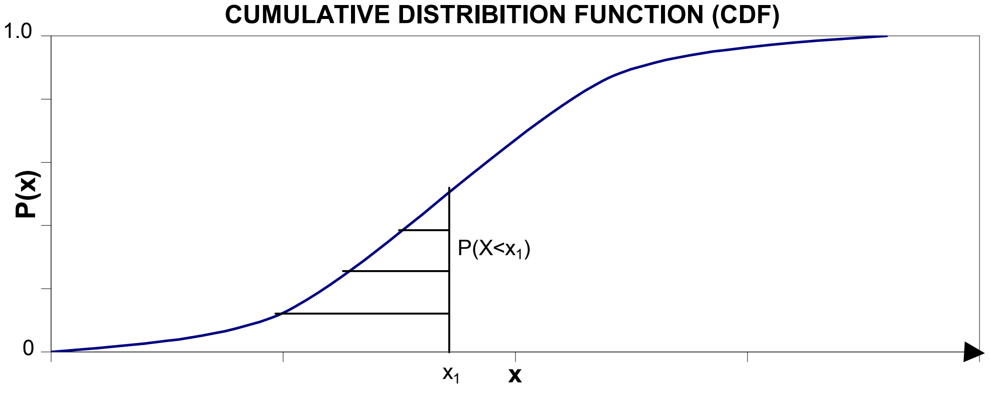
Where

$F(x)$	=	Cumulative distribution function
u	=	Dummy variable of integration

The following properties are applicable for the CDF.

- CDF of a random variable x is the probability of occurrence of a value lesser than x
- The starting value of the CDF for the lower limit is zero and the value of CDF for the upper limit is one
- The derivative of the CDF is the PDF

Figure 3.2
CUMULATIVE DISTRIBITION FUNCTION (CDF)



Expected Value

The expected value is the mean value of the random variable, which also can be defined as the first moment of the variable. The expected value can be defined in terms of the probability density function as follows.

$$E(X) = \mu = \int_l^u xf(x)\,dx$$

Where

E(X)	=	Expected value of *f*(x)
μ	=	Mean
x	=	Random variable
f(x)	=	Probability density function of variable x
l, u	=	Lower and upper limits respectively of the variable x

The estimate for the mean value or the first moment from a sample of size n is represented by the following relationship

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$$

It is essential to have a sample of adequate size which is representative of the population. The sampling errors will decrease with increase in the number of data.

Variance

The variance is the measure of the variability (scatter) of the random process, which can also be defined as the second moment about the mean.

$$E\left[(x-\mu)^2\right] = \sigma^2 = \int_l^u (x-\mu)^2 f(x)dx$$

Where

$E[(x-\mu)^2]$	=	Expected value of $f[(x-\mu)^2]$
σ^2	=	Variance
σ	=	Standard deviation

Coefficient of Skewness

Coefficient of skewness define the shape of the distribution in relation to symmetry. A positive skewness value represent a longer right tail and conversely a negative skewness represent a longer left tail. The extreme value distributions such as Gumbel, Pearson Type III and Gamma conform to positive skewness. These extreme distributions are applicable for annual maximum rainfall or flood flows. The coefficient of skewness is defined as the third moment about the mean and defined by the following expression.

$$E\left[(x-\mu)^3\right] = \int_l^u (x-\mu)^3 f(x)dx$$

$$\gamma = \frac{1}{\sigma^3} E\left[(x-\mu)^3\right]$$

Where

$E[(x-\mu)^3]$	=	Expected value of $f[(x-\mu)^3]$
γ	=	Coefficient of skewness

Coefficient of variation

The coefficient of variation is the standard deviation divided by the mean, which is non-dimensional. This parameter is a non-dimensional measure of the scatter or the spread of the data set. The coefficient of variation is used frequently in this Note for analysis associated with uncertainties.

3.3 Return Period

The frequency of occurrence or probability of exceedence are generally used to assess the risk associated with random variables. The definition of return period is commonly used to assess the risk of flood or to select the magnitude design engineering works.

The return period can be interpreted in the frequency domain as the value of the annual maximum discharge which is likely to be exceeded on average once in a specified return period. The flood corresponding to a T year return period is defined to have an average recurrence interval of T years or the probability exceedence equal to the inverse of the return period.

3.4 Risk Level

The level of risk is defined as the probability of exceeding a design value such as water level, discharge, or capacity of system, within a selected period which is generally the planning horizon of a system. Based on the above definition, the inverse of a return period of an event is the probability of exceeding the event in any year, which is the risk associated in a period of one year. As the period increases the level of risk or the probability of exceeding an event also increases. The risk of exceeding an event x with a probability density function f(x) and during a period of N years is defined by the following expression.

$$R = \left[1 - \left(1 - \int_x^{\infty} f(x) \right)^N \right]$$

Where

R	=	Risk of exceeding event value x
N	=	Number of years

The above equation can also be defined in relation to the return period (T years) with the following expressions.

$$R = \left[1 - \left(1 - \frac{1}{T} \right)^N \right]$$

The plots of level risk versus probability of exceedence are presented in Figure 3.3 for selected periods. Figure 3.3(b) is a continuation of the plots in Figure 3.3(a) for annual exceedance probabilities greater than 0.1.

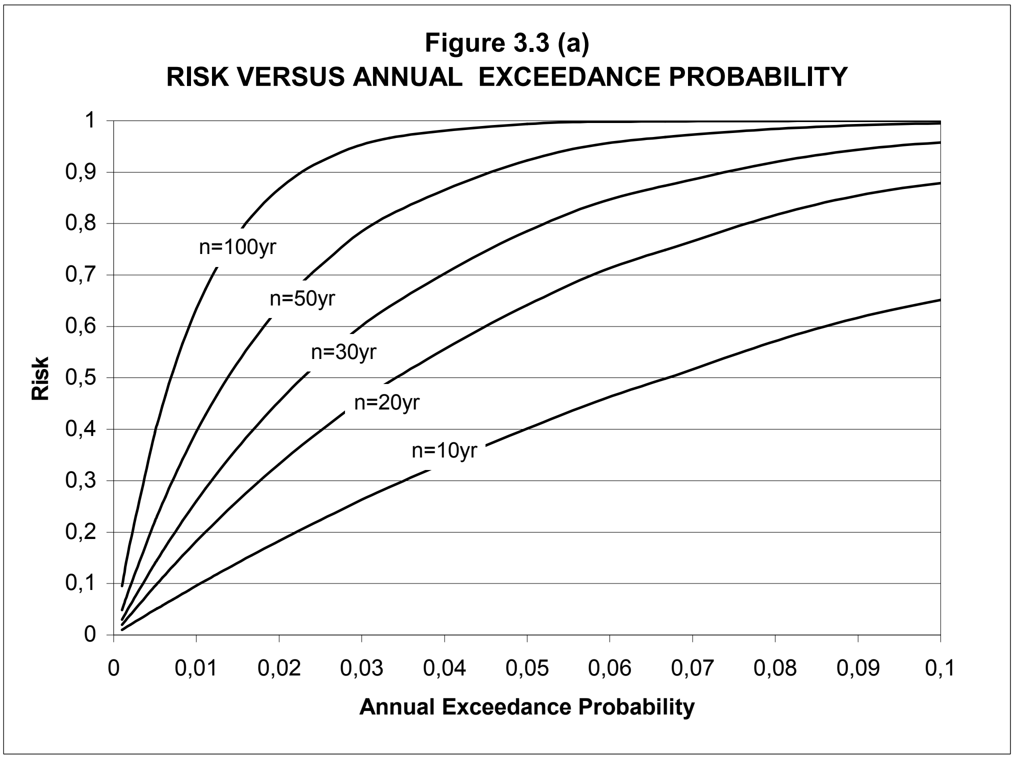


Figure 3.3 (a)
RISK VERSUS ANNUAL EXCEEDANCE PROBABILITY
Risk
Annual Exceedance Probability
n=100yr
n=50yr
n=30yr
n=20yr
n=10yr
0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1
0,01
0,02
0,03
0,04
0,05
0,06
0,07
0,08
0,09

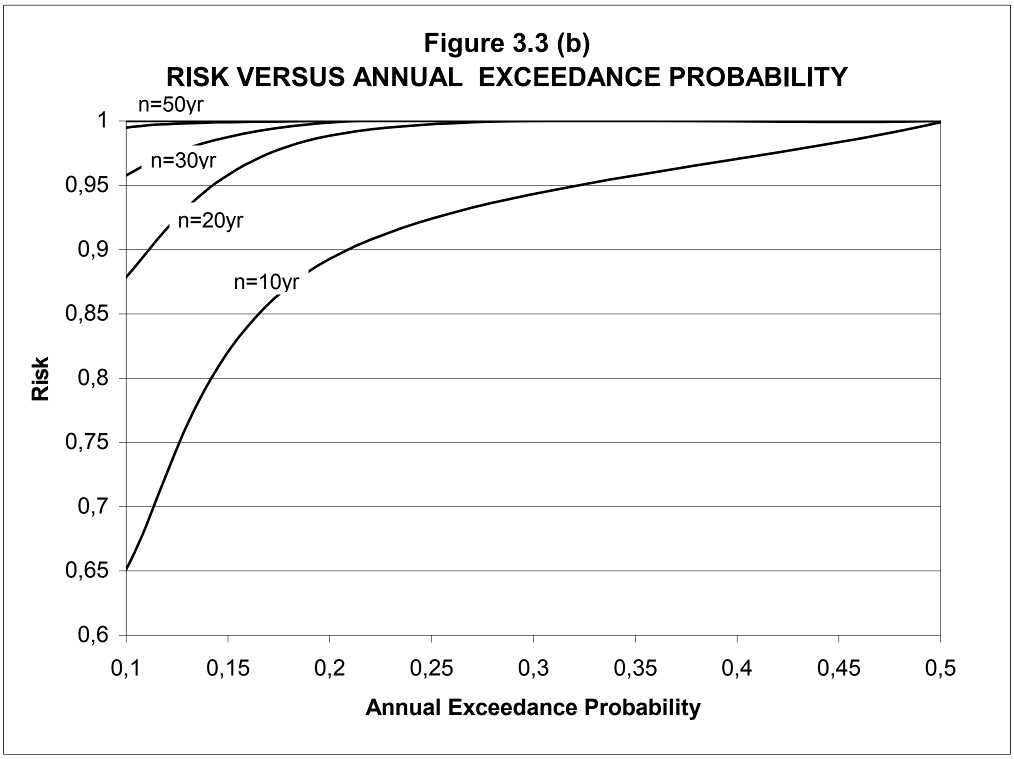


Figure 3.3 (b)
RISK VERSUS ANNUAL EXCEEDANCE PROBABILITY
Risk
Annual Exceedance Probability
n=50yr
n=30yr
n=20yr
n=10yr
0,6
0,65
0,7
0,75
0,8
0,85
0,9
0,95
1
0,1
0,15
0,2
0,25
0,3
0,35
0,4
0,45
0,5

3.5 Stochastic Properties of Linear Systems

River systems are characterised by non-linear behaviour in relation to variation of water level, change in discharges or resistance parameters. However the system may be represented as linear when changes in water level or discharges are small. As the incremental change in level or discharge increases the accuracy of prediction based on linearity becomes less.

The design estimates of flows, resistance parameters and water levels include some degree of uncertainty which are inherited from measurement errors, sampling errors and the accuracy of the equations used in the analysis. The predicted parameters can be regarded as random with its mean equal to the estimated value. The priori distribution of a random variable and its statistical parameters can be either obtained from measurements or from analysis or from judgement of the possible state of nature. In this context the priori distribution of independent variables can be related to the inflows, channel resistance or flow area.

The posteriori distribution for the dependent variable such as water level can be evaluated using the priori distribution. Two approaches are recommended to obtain the posteriori distribution. The first one is based on approximation to linear behaviour of the system in relation to the inputs. The second approach is based on evaluating the posteriori distribution by using large number of generated data for the priori distribution and applying an appropriate model or equation to predict the results, which are then analysed to obtain the appropriate distribution. The first approach is also defined as First Order Error Analysis and the latter is commonly termed as Monte Carlo Simulation. Both these approaches are described in the following sections.

3.5.1 First Order Error Analysis (FOEA)

The FOEA requires the estimates of the mean and variance of the independent variables. This information is used to obtain the properties of the dependent variable such as water level at a defined location in a channel. Assume a dependent variable y related to n number of random variables x_1, x_2, x_3 …….and x_n with the following functional relationship.

$$y = f(x_1, x_2, x_3 \;.......... \quad .... \quad x_n)$$

Using Taylor's series expansion about the mean value, the function can be represented in the following form up to first order term.

$$y = f(\bar{x}_1, \bar{x}_2, ...\bar{x}_n) + \sum_{i=1}^{n} \frac{\partial y}{\partial x_i}(x_i - \bar{x}_i)$$

The expected value of y for the above function is given by:

$$\bar{y} = E(Y) = f(\bar{x}_1, \bar{x}_2, ..., \bar{x})$$

The variance of y is defined as:

$$V(y) = \sum_{i=1}^{n} \sum_{j=1}^{n} \frac{\partial y}{\partial x_i} \frac{\partial y}{\partial x_j} Cov(x_i, x_j)$$

When the variables are independent the variance is expressed as:

$$V(y) = \left(\frac{\partial y}{\partial x_1}\right)^2 Var(x_1) + \left(\frac{\partial y}{\partial x_2}\right)^2 Var(x_2) + --------- + \left(\frac{\partial y}{\partial x_n}\right)^2 Var(x_n)$$

and the standard deviation of the dependent variable y is given by:

$$S_y^2 = \left(\frac{\partial y}{\partial x_1}\right)^2 S_1^2 + \left(\frac{\partial y}{\partial x_2}\right)^2 S_2^2 + --------- + \left(\frac{\partial y}{\partial x_n}\right)^2 S_n^2$$

The above expression is useful for the FOEA. The Manning's Equation is generally used to obtain the water level for a given discharge and the equation is given below.

$$Q = \frac{A}{N}\left(\frac{A}{P}\right)^{2/3} S_f$$

Where

Q	-	Discharge in m^3/s
A	-	Flow area in m^2
P	-	Wetted perimeter in m
N	-	Manning's resistance coefficient
S_f	-	Friction slope

Assume Q, N, A, P and S_f are random and independent then the standard deviation of the dependent variable y (water level) is given by:

$$S_y^2 = \left(\frac{\partial y}{\partial Q}\right)^2 S_Q^2 + \left(\frac{\partial y}{\partial N}\right)^2 S_N^2 + \left(\frac{\partial y}{\partial A}\right)^2 S_A^2 + \left(\frac{\partial y}{\partial P}\right)^2 S_P^2 + \left(\frac{\partial y}{\partial S_f}\right)^2 S_{S_f}^2$$

The first partial derivative in the above equation is expressed using Manning's equation as:

$$\frac{\partial y}{\partial Q} = \frac{1}{\left(\frac{5}{3A}\frac{\partial A}{\partial y} - \frac{2}{3P}\frac{\partial P}{\partial y} \right) Q} = \frac{1}{CQ}$$

The partial derivatives for the second variable is derived by using the following relationship:

$$\frac{\partial y}{\partial N} = \left(\frac{\partial Q}{\partial N} \right) \frac{1}{\left(\frac{\partial Q}{\partial y} \right)} = \frac{1}{NC}$$

Similarly the partial derivatives for the other variables are defined below:

$$\frac{\partial y}{\partial A} = \left(\frac{\partial Q}{\partial N} \right) \frac{1}{\left(\frac{\partial Q}{\partial y} \right)} = \frac{5}{3AC}$$

$$\frac{\partial y}{\partial P} = \left(\frac{\partial Q}{\partial P} \right) \frac{1}{\left(\frac{\partial Q}{\partial y} \right)} = \frac{2}{3PC}$$

$$\frac{\partial y}{\partial S_f} = \left(\frac{\partial Q}{\partial S_f} \right) \frac{1}{\left(\frac{\partial Q}{\partial y} \right)} = \frac{1}{2S_f C}$$

Using the above expressions the standard deviation of the dependent variable is expressed by the following equation.

$$S_y = \frac{1}{C}\left[CV_Q^2 + CV_N^2 + \frac{25}{9}CV_A^2 + \frac{4}{9}CV_P^2 + \frac{1}{4}CV_{S_F}^2 \right]^{0.5}$$

Where CV is the coefficient of variation of each variable, which is denoted in the suffix of CV, The above equation can also be derived using differencing technique instead of differentiation. The differencing technique involves applying a small change (or perturbation) for each variable and obtaining the corresponding variation of independent variable. The derivative is then obtained by dividing the change in y with the applied value of perturbation for the corresponding variable. The differencing technique can also be employed in hydraulic models.

In estimating the standard deviation for y, the variables with insignificant variability can be ignored. An example of using Manning's equation for FOEA is given in the main Guidance Note.

3.5.2 Monte Carlo Simulation (MCS)

For non-linear systems, a recommended approach is to obtain the output of the dependent variable by performs repeated simulation using randomised inputs based on their probability distribution. This technique is called the Monte Carlo Simulation is a very useful approach to study the probability distribution characteristics of the output variable. The analysis involves larger number of simulations required to define the PDF of the dependent variable. MCS represents an attractive method and the increase in computer speeds and the robustness of the hydraulic models making this method very attractive for decision makers.

3.6 Composite Exceedance Probability

The risk of failure associated with hydrologic processes is in general defined in terms of probability of exceedance for a defined period. For any design level or return period, there are number of sources of uncertainty in the estimates arising from measurement errors, sampling errors and the accuracy of equations and methodology used in the analysis.

Conventionally design water levels are selected by calculating the water level at a chosen return period. When design water levels are exceeded it is then often assumed that the discharge was greater than the return period designed for. However there is not a one to one relationship between discharge and water level and there are other factors influencing water level other than the magnitude of the discharge. Variations in channel properties such as cross-sectional area and roughness from mean design values, account for variations in water level for any given discharge. Therefore for any return period of discharge there is a range of water levels that can be expected due to these uncertainties.

Composite risk analysis produces an overall risk by combining the uncertainties at all risk levels for the selected design level. For example at a selected design water level which is based on a discharge of certain return period and estimated parameter values such as Manning’s n and area, there is some probability that this water level will be exceeded at all return periods due to the uncertainties in the hydraulic properties of the channel. The actual probability density function is multi-dimensional. Composite risk analysis enables the probability of exceedance (or risk of failure) for any design water level to be estimated.

Using first-order error analysis as described previously the standard deviation of the dependent variable can be obtained knowing the mean and variance of the independent variables. The probability density function at each return period (or risk level) can be defined from which the probability of exceedance at each return period (or risk level) can be calculated for a selected design water level. This probability of exceedance is integrated across the entire range of risk levels to obtain a composite exceedance probability.

Often design procedures account for uncertainties by applying arbitrary safety factors or freeboard. Composite risk analysis can be used to estimate what factor of safety is required to account for the uncertainties in design level prediction.

Composite exceedance probability can be defined by the function:

$$\int_{-\infty}^{\infty} f(x) \int_{y_f}^{\infty} g(x,y)dydx$$

For numerical integration, this equation can be represented by

$$\sum_{x=-\infty}^{\infty} \sum_{y=y_f}^{y=\infty} f(x)\Delta x.g(x,y)\Delta y$$

Where,

f(x) = Probability density function of expected water level x ($\infty < x < -\infty$)

g(x,y) = Probability density function of uncertainty for an expected water level x ($\infty < y < -\infty$)

yf = Selected design water level which is equal to the water level corresponding to the design return period plus the added freeboard.

The probability density function *g(x,y)* is assumed to be represented by a normal distribution. In general the accuracy of a normal distribution increases with the sample size.

The accuracy of the integration in the second equation depends on the chosen intervals for Δx. The smaller the interval, the greater the final accuracy of the summation. The recommended procedure is to adjust Δx in the solution domain until the solution converges to an acceptable level.

4. FREEBOARD AND DEVELOPMENT CONTROL

4.1 Development and Flood Risk Guidelines

Guidance on development in flood risk areas in England and Wales is provided by the Department of the Environment Circular 30/92, Development and Flood Risk (Department of the Environment, 1992). This supersedes Circular 17/82, Development in Flood Risk Areas - Liaison between Planning Authorities and Water Authorities (Department of the Environment 1982). It sets out the process and responsibilities of the Environment Agency in its role as a statutory consultee in the preparation of local authority Development Plans and in its role as a consultant for development in flood risk areas.

Guidelines on planning in flood risk areas in Scotland are provided by the Scottish Office's National Planning Policy Guideline, NPPG7, Planning and Flooding (The Scottish Office, 1995). It provides guidance to planning authorities, developers and the public on flood risk and its consequences that could affect planning and development decisions. Though Scotland is not within the area of responsibility of the Environment Agency it is useful to compare this Guidance.

Neither guidance document gives specific guidance on how or whether freeboard should be taken into account during the preparation of development plans or when responding to consultations on planning applications. Circular 30/92 does however note that development plans and policies relating to development plans in flood risk areas should relate to the degree of flood risk as notified by the Agency, primarily in the form of Section 105 surveys. Freeboard has been used in this Guidance to quantify the degree of flood risk and hence should be considered in development planning and control.

The Environment Agency has developed guidelines on how to respond to consultations on planning applications in the Flood Defence Regulation Manual (Environment Agency Procedural Manual – Volume 31). The Manual provides brief guidance on specifying floor levels in relation to flood levels for developments both within natural floodplains and behind flood defences. The relevant extract from Volume 31 is reproduced below for reference:

'6.6 DEVELOPMENT ADJACENT TO FLOODPLAINS AND IN DEFENDED AREAS (FREEBOARD)

6.6.1 Where development takes place outside the floodplain, there is still a risk of flooding. In areas immediately adjacent to the floodplain we should therefore recommend to the planning authorities and developers that floor levels be raised to be 600 mm above highest recorded flood level or 600 mm above the 1 in 100 year flood level if known. The additional freeboard is to provide a reasonable margin against uncertainty in the flood level and for other factors such as wind or vehicle generated waves.

6.6.2 When consulted over new development in defended areas, the Agency must consider the standard of those defences. The design flood levels, asset condition, arrangements for maintenance and the remaining life of the defences should all be taken into account.

6.6.3 The Agency should object to development proposals behind existing flood or sea defences where those defences are not of an appropriate standard for development. It may be appropriate for the development to take place provided that the developer is required to protect the new property to a suitable standard as part of the development. This may involve upgrading the defences or raising the property threshold levels.

6.6.4 For development in areas protected by a 1 in 100 year defence, we should nevertheless recommend floor levels be raised 600 mm above existing ground level as a nominal protection against overtopping or breach of the defence. If a lesser standard defence protects the area, then property should be raised to be above the 1 in 100 year level at least.

6.6.5 These freeboard recommendations may need to be varied in relation to existing circumstances or local custom and practice.

6.6.6 Adequate provision must always be made for the disposal of surface water runoff from new development in a protected area during flood times when gravity discharge is impeded.'

Section 4.2 discusses the suitability of the above guidelines in the light of the findings of this R&D study.

It should be noted that this Guidance Note's definition of freeboard is the difference between a water level and a defence level. The guidelines above relate water levels to floor levels and hence are outside the strict definition of freeboard. Some of the principles, however, remain the same.

4.2 Suitability of Guidelines

4.2.1 Threshold of flood loss

Clauses 6.6.1 and 6.6.4 of the Flood Defence Regulation Manual provide recommendations on floor levels in relation to flood levels. The first aspect to establish is whether advice should relate to floor levels or whether significant flood damage either begins to occur at a lower level or only occurs at a higher level.

By examining flood damage against flood depth data from the Flood Loss Assessment Information Report (FLAIR) an assessment can be made of the threshold of flood damage for residential and non-residential assets. Figure 4.1 shows flood depth/direct flood loss curves for some typical asset types. The curves show, as might be expected, that for most types of asset flood loss for flood levels below floor levels are relatively small but that once flood levels rise above floor levels then significant damage occurs. This confirms that the threshold of flood loss can in most cases be considered to be floor level.

4.2.2 Developments unprotected by defences

Clause 6.6.1 of the Flood Defence Regulation Manual recommends that floor levels in undefended areas should be 600 mm above the highest recorded flood level or 600 mm above the 100 year flood level.

The adoption of the 100 year flood level as a standard relates to Circular 30/92, which describes it as normally defining the limits of the floodplain. This is also consistent with PAGN's Indicative Standard for urban areas. It may be appropriate to reconsider this as a standard. PAG3, for example, gives a range of return periods for its Indicative Standards, in particular 50 to 200 years for a typical urban area. In addition the Easter 1998 Floods Report by Bye and Horner into the Easter flooding recommends re-evaluation of standards:

> 1.6 (11) 'Underlying standards of flood protection were appropriate prior to Easter but should be re-examined taking account of the resulting changed understandings of risk and having regard to climate change implications.'

Deciding on an appropriate 'benchmark' return period flood is outside the scope and responsibility of this Guidance Note. It is suggested though, that the nature of the development be taken into account when deciding on an appropriate return period flood. As an example it may be appropriate to specify protection against a higher return period flood for a residential care home compared with a retail outlet because of the societal consequences of flooding.

In many areas flood levels associated with specific return periods are not known as statistical analysis of flood records and flood routing has not been carried out. Instead only historical flood levels are known and frequently only the highest recorded level has been recorded. In these cases unless a statistical analysis is carried out it will not be known whether the highest recorded flood level has a higher or a lower return period than the 'benchmark' return period flood level.

There is therefore greater uncertainty associated with using the highest recorded flood level. Hence any planning recommendation should take this into account and where appropriate request that the developer carries out investigations to obtain flood level information. At its most basic this may take the form of using the Flood Studies Report, or its replacement the Flood Estimation Handbook, to develop the flood hydrograph for the 'benchmark' flood at the site and assume steady state conditions to estimate the flood water level.

Clause 6.6.1 describes the 600 mm allowance above the flood level as an allowance for uncertainty in the flood level and for other factors such as wind or vehicle generated waves. How appropriate 600 mm is as an allowance can be considered in relation to the findings of Chapters 4 to 6. Section 4.3 gives a method for determining a wind generated wave surcharge allowance.

However, this method is used to determine an allowance to reduce the risk of failure of a flood defence embankment. The method cannot therefore be compared directly with avoiding flood damage as a result of wind generated wave action. Vehicles traversing flooded roads generate waves in a similar manner to boatwash and this can have an impact on the flood damage to nearby properties. It therefore appears reasonable to make an allowance for wind and vehicle generated waves. Experience would suggest that an allowance of between 200 and 300 mm for combined wind and vehicular wave action would be appropriate.

It is suggested that this allowance be determined using the multi-attribute technique set out in Chapter 5.

4.2.3 Developments protected by defences

Clause 6.6.4 of the Agency's guidance document recommends floor levels for developments protected by existing flood defences. For developments protected by defences of a 1 in 100 year standard, floor levels 600 mm above ground level are specified. Where the defence is of less than a 1 in 100 year standard then floor levels at or above the 100 year return period flood level are recommended.

The raising of floor levels above ground level for new developments behind existing defences appears to be a valid common sense approach. It means that if defences fail, or are bypassed, or if there is flooding owing to surface drainage problems then properties have a safety margin against flooding.

Whether 600 mm is an appropriate safety margin behind defences protected to a 100 year standard is open to debate. Determining a different safety margin for each development would require a consideration of how a flood wave might propagate from, for example, a breach. Analysis of flood wave propagation is complex and highly dependent on the shape of the flood hydrograph, the breach mechanism and topography. Hence generalisations based on the physical response of the area being flooded are difficult to make. An allowance of 600 mm appears a reasonable value. However where either of the following two situations apply, a different allowance may have to be considered.

- development immediately behind a defence;
- development in floodplains with a limited amount of storage where the flood water level in the floodplain would rapidly rise to river flood level.

For developments behind defences which have a standard of less than 100 years the recommendation given in Clause 6.6.4 is that floor levels should be set to at least the 100 year flood level. The concept behind this recommendation would appear to be that developments should be protected to a reasonable and consistent standard even if existing adjacent properties/assets are not currently being protected to that standard. It may be that the investment to improve the protection of those existing properties has not yet been made or it may be the case that improvements are not justifiable economically.

The recommendation is less stringent than the recommendation for areas unprotected by defences. This is probably based on two assumptions:

- there is a probability that the defence will in fact protect to a higher standard;
- when flooding does occur, flood levels behind the defence may not rise to the same level as the flood water level in the river.

In many cases the recommendation will result in floor levels being set to greater than 600 mm above ground level but in other cases, particularly at the edges of floodplains, floor levels will be less than 600 mm above the ground level.

As discussed in Section 4.2.2, use of the 100 year flood level and the 100 year defence standard may have to be reviewed in the light of the Easter 1998 Floods Report.

4.2.4 Other recommendations

The advice given in Clause 6.6.5 of the Flood Defence Regulation Manual that freeboard recommendations should suit the particular circumstances is considered to be apt, though it does make consistency nationwide more difficult.

4.3 Section 105 Surveys

Section 105 (2) of the Water Resources Act 1991 requires the Environment Agency to carry out surveys to identify the extent of floodplains and land liable to flood. The surveys are underway and are being used for development planning and development control. An example of their influence was given in the 1998 MAFF Conference (Ramsbottom *et al*, 1998). At a development in Oxfordshire, land on the river side of the 100 year flood envelope was valued at £4 000 per hectare whereas land immediately outside the flood envelope was valued at £600 000 per hectare. The difference was owing to planning permission being granted for land outside the flood envelope.

However, it must be borne in mind that the flood envelopes are only best estimates and have a degree of uncertainty associated with them. The uncertainty arises from reasons including uncertainties in the methods used to derive or estimate the flood level, changes in land use within the catchment, changes in maintenance practices, assumptions regarding the operation of structures, assumptions about blockages and possibly future climate change.

There is therefore a valid argument to add an allowance for uncertainty on to the best estimate of the flood level when developing flood maps, to avoid under-estimation of the flood extent. This approach may face opposition from local authorities and developers given the pressure on land use and the effect of flood limits on land values. As a first step towards a discussion on this issue those commissioning and using Section 105 surveys should be aware that flood envelopes have a degree of uncertainty and the size of that uncertainty will be related, amongst other things, to the type of method used to undertake the survey.

5 REVIEW OF PROJECT APPRIASAL IMPLICATIONS

5.1 Purpose of Review

5.1.1 Freeboard and Project Appraisal

Chapter 2 of the Freeboard Guidance Note sets out the approach to be used for taking account of freeboard during the Project Appraisal process and in particular during the analysis of costs and benefits and when assigning Standards of Protection to existing or proposed defences. The approach is summarised below and illustrated in Section 5.1.2:

From PAG3:

'Freeboard should only be used to take account of uncertainty in scheme performance…. Where the height of the defence (including freeboard) is then designed to accommodate such uncertainty the benefits of the defence should be those appropriate to the calculated design standard.

For example if a 50 year standard defence is constructed with an additional crest height to allow for uncertainty in the hydrology and hydraulic analysis then the only benefits that should be assumed to accrue will be those appropriate to the 50 year standard (ie 0.02 probability of overtopping).'

Advice:
Freeboard does not change the assumed threshold of flooding used in the economic analysis

Flood defences are designed to provide a "standard of protection" which has traditionally been expressed as the frequency or return period of the design flood (e.g. the 1 in 50 year flood, or simply the 50 year flood). This does not mean, of course, that the level of the defence is set at the estimated water level for this event. A freeboard (or safety margin) is usually added to give a **high degree of confidence** that the defence will provide protection of the standard intended throughout its design life.

This system works well for the design of new defences, but can cause problems when determining the standard of protection of an existing defence. To provide a consistent approach, an allowance for uncertainty and physical processes (i.e. freeboard) should be deducted from the existing defence level to derive a flood level. There is then a **high degree of confidence** that the defence will protect against this flood level. The return period of the flood level is the standard of protection.

It is important to note that the standard of protection and the threshold of flooding/overtopping of a defence are **not** the same. The former is the standard that will be withstood with a high degree of certainty. The latter is the best estimate of how the defence would respond to floods.

Threshold of Flooding ≠ Standard of Protection

5.1.2 Illustration of the use of Freeboard in Scheme Appraisal

Figure 5.1 shows an example of a typical water level–return period relationship. Confidence limits, shown dashed, can be derived for this relationship. The figure shows the inter-relationship between water level, freeboard, defence level and return period.

With reference to Figure 5.1, if:

A = allowance for physical processes

B = allowance for Uncertainties

then the following applies for determining benefits:

Assessment of Return Period (Y) for the onset of flooding – **Existing Defence**

This should be assessed as the return period at which the water level = level of existing defence minus A.

Assessment of Return Period (Z) for the onset of residual flooding – **Proposed Defence**

This should be assessed as the return period at which the water level = level of proposed defence minus A minus B.

In addition the following applies when stating Standards of Protection:

Assessment of the Standard of Protection (X)– **Existing Defence**

This should be assessed as the return period at which the water level = level of existing defence minus A minus B

Assessment of the Standard of Protection (Z)– **Proposed Defence**

This should be assessed as the return period at which the water level = level of proposed defence minus A minus B

Once constructed the Proposed Defence becomes an Existing Defence and:

Assessment of Return Period (W) for the onset of flooding – **Now an Existing Defence**

This should be assessed as the return period at which the water level = level of defence minus A.

5.1.3 Issues raised by Approach

The purpose of the review was to consider how this approach compares with an approach that does not consider an allowance for freeboard. In particular two issues are raised:

Existing Defence

Threshold of Flooding ≠ Standard of Protection so how does the threshold of flooding (Y in Figure 5.1) compare with Standard of Protection (X in Figure 5.1).

Proposed Defence

How does the Standard of Protection of a proposed defence (Z in Figure 5.1) compare with the threshold of flooding if that defence is analysed in the future (W in Figure 5.1).

5.1.4 Comment on Review

Chapter 6 of the Guidance Note shows that the current (deterministic) methods for determining the water level- return period relationship are underestimating the probability of occurrence of flood levels compared with probabilistic methods. Thus the issue raised by the review is not a straightforward comparison of "including freeboard" versus "not including freeboard" and the consequences for Project Appraisal. Instead it in fact compares the current deterministic method with the use of probabilistic methods.

5.1.5 Methodology

Four case studies were reviewed with the aim that they represented a reasonable cross-section of situations that will occur in practice. The Case Studies are:

River Cam

This case study was used in the main Guidance Note and therefore information was readily available to analyse. It represents a medium sized lowland river (Q_{50} = 50 m^3/s approximately) for which there is a good flow record (50 years in length).

River Cam – short record

Of interest in the review is the effect that a short length of flow records would have on freeboard. Therefore the flow record for the River Cam was artificially shortened to 10 years and compared with the main River Cam Case Study.

River Ouse at Selby

A Flood Alleviation Scheme is currently under consideration at Selby to protect against flooding from the River Ouse. The freeboard approach used in the Guidance Note was tested on the scheme. Appendix A is a Design Note summarising the findings. The Ouse at Selby is tidal hence strictly it is outside the scope of the Guidance Note. However the methods were developed to apply in this situation. The Ouse represents a large river (Q_{50} > 500 m^3/s).

Clipstone Brook

This is a fairly small (Q_{50} = 22 m^3/s) river in Hertfordshire for which a short flow record (13 years) was readily available. Clipstone Brook represents a small flashy rural stream.

The three stages in the review methodology are summarised below:

1) Derive the standard deviation in water level

The standard deviation in water level was derived using the method of first order error analysis (FOEA) described in Chapter 6 of the Guidance Note. Five return period events were considered in each Case Study: 10, 20, 50, 100 and 200 year events each with different standard deviations in water level.

Chapter 6 proposes that to account for uncertainty in the hydraulic/hydrological processes between half and one standard deviations in water level should be added to the water level derived from current (deterministic methods) as a freeboard allowance.

2) Show graphically the water level – return period relationship

The water level – return period relationship was determined (or was available from previous work) and was plotted graphically.
Curves were added to this graph for:
water level + 0.5 standard deviations
water level + 1.0 standard deviations

3) Compare return periods

Two comparisons were made from the graphs as summarised in Section 5.1.3:

Existing Defence

Threshold of Flooding ≠ Standard of Protection so how does the threshold of flooding (Y in Figure 5.1) compare with Standard of Protection (X in Figure 5.1).

Proposed Defence

How does the Standard of Protection of a proposed defence (Z in Figure 5.1) compare with the threshold of flooding if that defence is analysed in the future (W in Figure 5.1).

The comparisons were made for each of the five return period events for:
a freeboard allowance of 0.5 standard deviations
a freeboard allowance of 1.0 standard deviations
The details of how this was carried out is shown in the example below:

Example of Comparison

Figure 5.2 shows the water-level return period relationship for the River Cam with a curve added showing water level + 1.0 standard deviations.

From the figure the following can be determined:

1) For an existing defence with a crest level of 4.25 mAOD, the onset of flooding would be at a return period (Y) of 50 years. The Standard of Protection (X) claimed would be equivalent to the return period that corresponds with a water level = 4.25 – 0.20 (1.0 standard deviation) = 4.05 mAOD. The water level return period relationship shows that for this water level the return period is 17 years.
2) For a proposed defence that will have a 20 year Standard of Protection (Z) the defence would be constructed to a crest level of 4.07 + 0.22 (1.0 standard deviation) = 4.29 mAOD. In the future if this defence is analysed the onset of flooding would occur when the water level reaches 4.29 mAOD. The water level return period relationship shows that for this water level the return period (W) is 62 years.

5.2 River Cam Case Study

The standard deviation in water level was derived during work carried out for the Case Study in the Guidance Note for a full range of return periods. Figure 5.3 shows the water level return period relationship for the River Cam and curves of water level + 0.5 and + 1.0 standard deviations. Comparisons were made between return periods 'X' and 'Y' and between return periods 'Z' and 'W' as described in Section 5.1.5. The results are summarised in Table 5.1:

Table 5.1 River Cam – Comparison of Return Periods

	Threshold of flooding Y (years)	**Standard of Protection X (years)**	
		0.5 standard deviations	**1.0 standard deviations**
Existing Defence	10	6.9	4.9
	20	13	8.5
	50	25	17
	100	49	28
	200	91	48
	Standard of Protection Z (years)	**Future threshold of flooding W (years)**	
		0.5 standard deviations	**1.0 standard deviations**
Proposed Defence	10	16	25
	20	34	62
	50	105	210
	100	225	500
	200	480	> 1000

5.3 River Cam – Short Record Case Study

The main River Cam Case Study uses a flow record of 50 years length. This was artificially truncated to a flow record of 10 years to examine the effect that this would have on freeboard. The same discharge - return period relationship as for the Main Case Study was used for this Case Study but with the discharges having larger standard deviations to reflect the greater uncertainty in discharge for the smaller flow record. The standard deviation in water level was derived using FOEA for a range of return periods. This is plotted along with the water level – return period relationship on Figure 5.4.

The increase in standard deviation in water level compared with the Main Case Study was of the order of 50 to 100 mm. For example for the 10 year return period event the standard deviation in water level was 0.20 m for the 50 year flow record and 0.26 m for the 10 year flow record. Similarly for the 100 year return period event the standard deviations were 0.26 m and 0.35 m for the 50 year and the 10 year flow records respectively. This represents an increase of about 30 % in the standard deviation and hence in the magnitude of freeboard that would be adopted for design.

Comparisons were made between return periods ‘X’ and ‘Y’ and between return periods ‘Z’ and ‘W’ as described in Section 5.1.6. The results are summarised in Table 5.2:

Table 5.2 River Cam Short Record – Comparison of Return Periods

	Threshold of flooding Y (years)	**Standard of Protection X (years)**	
		0.5 standard deviations	**1.0 standard deviations**
Existing Defence	10	6.3	4.4
	20	11	7.1
	50	24	13
	100	40	21
	200	73	32
	Standard of Protection Z (years)	**Future threshold of flooding W (years)**	
		0.5 standard deviations	**1.0 standard deviations**
Proposed Defence	10	18	33
	20	41	95
	50	130	330
	100	300	>500
	200	>500	>1000

5.4 River Ouse at Selby Case Study

A flood alleviation scheme is currently under appraisal for the River Ouse at Selby. As part of the appraisal a suitable value for freeboard was determined. The Ouse at Selby is tidal hence the freeboard procedure developed in the Guidance Note was adjusted to apply for this situation. Both the Quick Method and the FOEA were used to estimate a freeboard value for a 200 years standard flood alleviation scheme. The Quick Method indicated an allowance for uncertainty of 0.15 m was appropriate while the FOEA indicated that 0.10 m was appropriate. This was considered a reasonable correlation between methods given the assumptions made. Appendix A summarises the procedure used and serves as an example of the use of the methods in practice.

For this review the standard deviation in water level was determined for a range of return periods and is plotted in Figure 5.5 on the water level return period graph.

Comparisons were made between return periods 'X' and 'Y' and between return periods 'Z' and 'W' as described in Section 5.1.5. The results are summarised in Table 5.3:

Table 5.3 River Ouse at Selby – Comparison of Return Periods

	Threshold of flooding Y (years)	**Standard of Protection X (years)**	
		0.5 standard deviations	**1.0 standard deviations**
Existing Defence	10	8.7	7.7
	20	14	10
	50	27	16
	100	59	30
	200	67	45
	Standard of Protection Z (years)	**Future threshold of flooding W (years)**	
		0.5 standard deviations	**1.0 standard deviations**
Proposed Defence	10	14	20
	20	36	67
	50	83	210
	100	300	900
	200	600	>1000

5.5 Clipstone Brook Case Study

Clipstone Brook is a small rural stream for which 13 years of flow records and some limited topographic survey were available. It was therefore considered to represent the situation where relatively limited data is available for a small flood alleviation scheme.

The flow record was analysed and a discharge - return period relationship was determined. A steady state computational hydraulic model was set up using HYDRO of a short length (about 500 m) of the Brook and a stage - discharge relationship at the location being considered was determined. Hence a water level - return period relationship was derived. An allowance for uncertainty was determined using both the Quick Method and FOEA for a range of return periods. The results given by the different methods compared well: for the 50 year water level a standard deviation from FOEA of 0.24 m was determined, while the Quick Method gave an allowance of 0.26 m. Appendix B summarises the results of both methods.

The water level - return period relationship was plotted and curves of 0.5 and 1.0 standard deviations were added, see Figure 5.6.

Comparisons were made between return periods 'X' and 'Y' and between return periods 'Z' and 'W' as described in Section 5.1.5. The results are summarised in Table 5.4:

Table 5.4 Clipstone Brook – Comparison of Return Periods

	Threshold of flooding Y (years)	**Standard of Protection X (years)**	
		0.5 standard deviations	**1.0 standard deviations**
Existing Defence	10	7.1	5.3
	20	12	9.1
	50	29	18
	100	42	25
	200	63	33
	Standard of Protection Z (years)	**Future threshold of flooding W (years)**	
		0.5 standard deviations	**1.0 standard deviations**
Proposed Defence	10	17	28
	20	33	63
	50	145	500
	100	330	1000
	200	700	>1000

5.6 Summary of Results

Comparison of the results of the Case Studies shows that results are consistent between Case Studies irrespective of whether there is a high or low degree of uncertainty in the water level predicted. There is a wider variation between whether 0.5 or 1.0 standard deviations are used as an uncertainty allowance than between Case Studies. Figures 5.7 and 5.8 compare, for an existing defence, the threshold of flooding(Y) with the Standard of Protection (X) for uncertainty allowances of 0.5 and 1.0 standard deviations respectively.

Figure 5.9 and 5.10 compare, for a proposed defence, the Standard of Protection (Z) with the threshold of flooding if that defence is analysed in the future (W) for uncertainty allowances of 0.5 and 1.0 standard deviations respectively.

Table 5.5 summarises the typical range of results:

Table 5.5 Summary of Results

Existing Defence	
Threshold of flooding Y = 1/Probability of exceedance	**Standard of Protection X (years)**
10	5 – 7
20	9 – 13
50	17 – 28
100	28 – 50
200	40 – 80
Proposed Defence	
Standard of Protection Z (years)	**Future Threshold of flooding W = 1/Probability of exceedance**
10	17 – 27
20	38 – 70
50	110 – 300
100	300 – 650
200	550 - >1000

Note: lower bound is for uncertainty allowance of 0.5 standard deviations, upper bound for 1.0 standard deviations

A reasonable difference in return periods/probabilities is apparent between X and Y and between Z and W. This does not however mean that the analysis is flawed or that it is over-conservative, instead it demonstrates what is intuitively known that:

- the difference in water level between return periods is often less then the uncertainty in water level prediction;
- there are dangers in the deterministic approach where the uncertainty in water level is not considered as this can lead to the construction of defences that will not protect against lower than design standard floods with a high degree of confidence.

Overarching this is the principle described at the start of this Chapter that the current (deterministic) methods for determining the water level- return period relationship are underestimating the probability of occurrence of flood levels compared with probabilistic methods, which the table above demonstrates.

Another conclusion that can be drawn for this review is the value of a good flow record. The Cam Case Study showed a 30 % decrease in uncertainty as the length of the flow record increased from 10 years to 50 years.

The review also looked at the effect that the inclusion of freeboard would have on the choice of scheme during Project Appraisal compared with a situation where freeboard was not considered.

The River Cam Case Study was used as an example. The additional cost of constructing a floodwall to various standards with freeboard was compared with the cost of construction without freeboard. A cost benefit analysis was carried out for both conditions. The cost benefit analyses showed that the inclusion of freeboard did not affect which option was the preferred option. It's only effect was to reduce the benefit-cost ratios of all options by a small amount (less than 5 %).

APPENDIX A: SELBY FLOOD ALLEVIATION SCHEME DESIGN NOTE – FREEBOARD

A.1 Introduction

This design note summarises the analysis carried out to determine appropriate freeboard values for the proposed Selby Flood Alleviation Scheme. The analysis uses the methods set out in the Agency's Fluvial Freeboard Guidance Note R&D Technical Report W187. The Guidance Note, though not yet published, and in the public domain is in its final draft. The Guidance Note is intended for use on fluvial river only. Thus the methods have had to be developed to be appropriate to the tidal conditions experienced during flood events at Selby.

A.2 Summary of Methodology

The concept behind the Guidance Note is to move away from fixed freeboards for flood defences and instead consider the processes that may affect the integrity of a defence on a case by case basis. Freeboard can be divided into two elements:

- an allowance for physical processes (other than water level) that affect the integrity of the defence level e.g. waves, settlement
- an allowance for uncertainty in our predictions of water level etc (i.e. a safety factor)

The methodology used is outlined in the attached Figure 3.1 from the Guidance Note. Freeboard determination cannot be isolated from the other parts of the design or project appraisal process. Therefore once a freeboard has been estimated it should be reviewed in the wider context of the scheme e.g. how the defences will perform during floods in excess of the design flood, and may need revising, see attached Figure 3.2.

A.3 Physical Processes

A.3.1 Defence Elements

Different parts of the Selby flood defences may require different freeboards. The following defence elements have been considered:

- embankment, adjacent to river
- floodwalls, through Selby
- embankment set back from river (north of Bank House Farm)
- bends

A.3.2 Wave Overtopping Allowance

The allowance is to avoid failure of the defence owing to wind generated waves during the design flood.

Floodwalls

No allowance for floodwalls is necessary.

Embankment adjacent to river

The Guidance Note gives a rapid method for estimating a wave overtopping allowance for rivers less than 50 m wide. However the River Ouse at Selby has a typical effective fetch of about 55 m. The method presented in ICE Floods and Reservoir Safety was therefore used to estimate a wave overtopping allowance. An allowance of **0.175 m** was estimated for an embankment with grassed crest and backslope.

Embankment set back from river

Waves can be generated between the low bund next to the river and the main embankment. Using F&RS an allowance of **0.65m** was estimated. NB Waves may be limited by the low water depth in the floodplain between the main embankment and the bund.

A.3.3 Settlement Allowance

The allowance is to ensure that the defence provides the design defence level throughout its design life.

Floodwalls

No allowance for floodwalls is necessary.

Embankments

Ground conditions were judged from the draft Interpretive Report on Ground Investigation, Volume 2, July 1999 and consolidation test results. The foundation material for the embankment raising was assumed to be alluvial silt with m_v values of 0.05 to 0.2 m^2/MN. Given that embankment raising is relatively small (about 0.75m), setttlements are estimated to be of the order of 0 to 0.05m. Settlement of existing embankments is assumed to be negligible. No allowance for settlement is considered necessary though it is recommended that the construction contract is worded to ensure that the contractor accepts that settlement during construction is his risk, and that the embankments are to the design level at the end of the Defects Correction Period.

A.3.4 Superelevation

Superelevation at the two main bends in the Ouse was checked but found to be insignificant during the design flood event.

A.3.5 Other effects

No other physical effects were considered to affect the design defence level.

A.4 Uncertainty

A.4.1 Quick method

A quick method for estimating uncertainty is presented in the Guidance Note. It is a qualitative method that uses a scoring and weighting system:

Six 'uncertainty parameters' are considered and given a score from 1 to 5 where 1 represents low uncertainty and 5 represents high uncertainty. The parameters are not directly applicable to tidal conditions but judgement has been used to apply the scoring system to Selby FAS.

Parameter	Score
Accuracy of hydrological data Selby water levels strongly influenced by tide levels derived from a good 70 year tide level record at Goole	2
Accuracy of hydrological method Routing of tide levels Goole to Barmby to Selby introduces some uncertainty	3
Accuracy of hydraulic data Well defined hydraulic data. Sedimentation may affect predicted water levels to minor extent	2
Accuracy of hydraulic model Well calibrated model. Selby water levels fairly well defined by boundary conditions at Barmby. Fluvial-tidal interaction modelled by Bullens	1
Significance of physical effects (waves etc) Wave overtopping only main concern and then only for embankments	2
Consequences of failure Urban area at risk	4

The scores are summed and then converted to an uncertainty allowance using the formula given below.

$$\text{Uncertainty Allowance(m)} = k \times \frac{\text{Overall score (in range 6 - 30)}}{30} \times (\text{FL} - \text{MAMWL})$$

where FL = derived flood level (m)

MAMWL = Mean Annual Maximum Water Level (m) as derived from the mean annual maximum flow

k = a factor, initially proposed as 0.5

Uncertainty allowance = 0.5 x 14/30 x (6.56 – 5.92) = **0.15 m**

Reality Check: seems reasonable value.

A.4.2 Detailed Method

The detailed method presented in the Guidance Note analyses the uncertainty in the derivation of design water level by considering the sources and size of error in the water level prediction. A similar method can be applied to the Selby FAS.

There are three main elements to the derivation of water levels at Selby each introduces uncertainty or error in the water level prediction:

- derivation of the tidal relationship at Goole
- correlation of water levels at Goole to water levels at Barmby (downstream boundary of model)
- routing between Barmby and Selby

The tide level vs return period relationship at Goole is based on 70 years of record with a standard deviation at the 200 year return period of 0.053 m (Humber Tidal Defences Data Collection and Analysis Final Report May '91, Posford Duvivier).

Tide levels at Goole are correlated to tide levels at Barmby by comparing observed tide levels (Table 9.6, Lower Ouse Hydraulic Study Ouse/Wharfe Hydrological Report, September 1998, Bullen Consultants). The data has a standard deviation of 0.085m.

Water levels are derived at Selby using the Ouse/Wharfe hydraulic model. Correlation between predicted and observed water levels at Selby appear good, relatively low errors are predicted. Standard deviation in water level estimated to be of the order of 0.02 m.

These uncertainties in the three elements can be combined to determine the overall expected uncertainty in water level at Selby. Combination of these uncertainties gives an estimated standard deviation in water level at Selby of about **0.10m.** It is recommended that this be used as the uncertainty allowance for the Selby FAS.

Reality Check: compares reasonably with Quick Method.

A.5 Conclusions

The following freeboard allowances have been estimated:

	Defence Type		
	Embankment	**Flood Wall**	**Embankment North of Bank House Farm**
Wave Allowance	0.175	nil	0.65
Settlement Allowance	nil	nil	nil
Superelevation	nil	nil	nil
Other	nil	nil	nil
Uncertainty Allowance	0.10	0.10	0.10
Total Freeboard Allowance	**0.275 m**[1]	**0.10 m**	**0.75 m**

[1] In view of construction tolerance on earthworks, it is suggested that this is rounded up to **0.30 m.**

However three further aspects should be considered before setting the final defence level:

- the wave allowance for the embankment north of Bank House Farm is high and further analysis would be worthwhile to check that this is suitable if this defence will be a significant part of the Selby FAS.
- the flooding mechanism for floods in excess of the design flood must be considered. The flood walls through the centre of town have a lower freeboard than the embankments in the more outlying areas. What can be done to reduce the risk that when flooding occurs it will start in heavily built up areas?
- the difference in water level between the upstream end of Selby CS28 and the downstream end CS33 may mean that it is worthwhile varying the defence level through Selby accordingly.

APPENDIX B: CLIPSTONE BROOK UNCERTAINTY ALLOWANCE

The text below summaries the analysis carried out to determine an uncertainty allowance for Clipstone Brook. The 50 year water level has been used as an example.

B.1 Quick method

A quick method for estimating uncertainty is presented in the Guidance Note. It is a qualitative method that uses a scoring and weighting system:

Parameter	Score
Accuracy of hydrological data	
Small catchment, gauging station nearby	2
Accuracy of hydrological method	
Relatively short record (13 years)	3
Accuracy of hydraulic data	
Hydraulic conditions fairly well defined, limited floodplain flow	3
Accuracy of hydraulic model	
Simple steady state model, no complex flow interactions	3
Significance of physical effects (waves etc)	
Other effects not of great significance	2
Consequences of failure	
High grade agricultural land and some properties at risk	3

The scores are summed and then converted to an uncertainty allowance using the formula given below.

$$\text{Uncertainty Allowance(m)} = k \times \frac{\text{Overall score (in range 6 – 30)}}{30} \times (\text{FL} - \text{MAMWL})$$

where FL = derived flood level (m)

MAMWL = Mean Annual Maximum Water Level (m) as derived from the mean annual maximum flow

k = a factor, initially proposed as 0.5

MAMWL = 85.98 mAOD
Design flood level (50 year) = 86.94 mAOD

Uncertainty allowance = 0.5 x 16/30 x (85.98 – 86.94) = **0.26 m**

Reality Check: seems reasonable value.

B.2 First order Error Analysis

Step 1 Determine the Standard Deviation in the main variables

Discharge Q

From 13 years flow record the standard deviation in flow at the 50 year return period = 4.62 m^3/s.

Area

The standard deviation in area is estimated to be of the order of 5% of the flow area at the 50 year discharge = 0.05 x 16.0 = 0.8 m^2.

Roughness n

The mean channel roughness was determined to be 0.05. From Figure 6.4 of the Guidance Note the standard deviation in roughness is estimated to be 0.017.

Step 2 Calculate the change in water level for a small change in the main variable

The hydraulic model was used to determine water levels for a small change in variable:

Variable	Small change in variable	Change in y (dy)	Derivative
Discharge Q	dQ = 1m^3/s	0.025	dy/dQ = 0.025
Area A	dA = 0.4 m^2	0.031	dy/dA = 0.0775
Roughness n	dn = 0.005	0.058	dy/dn =11.6

Step 3 Determine the standard deviation in water level

$$S_y^{\,2} = \left(\frac{\partial y}{\partial Q}\right)^2 S_Q^{\,2} + \left(\frac{\partial y}{\partial n}\right)^2 S_n^{\,2} + \left(\frac{\partial y}{\partial A}\right)^2 S_A^{\,2}$$

Therefore:

$S_y^2 = 0.025^2 \times 4.62^2 + 0.0775^2 \times 0.8^2 + 11.6^2 \times 0.017^2$

Standard deviation in water level S_y = 0.237 m