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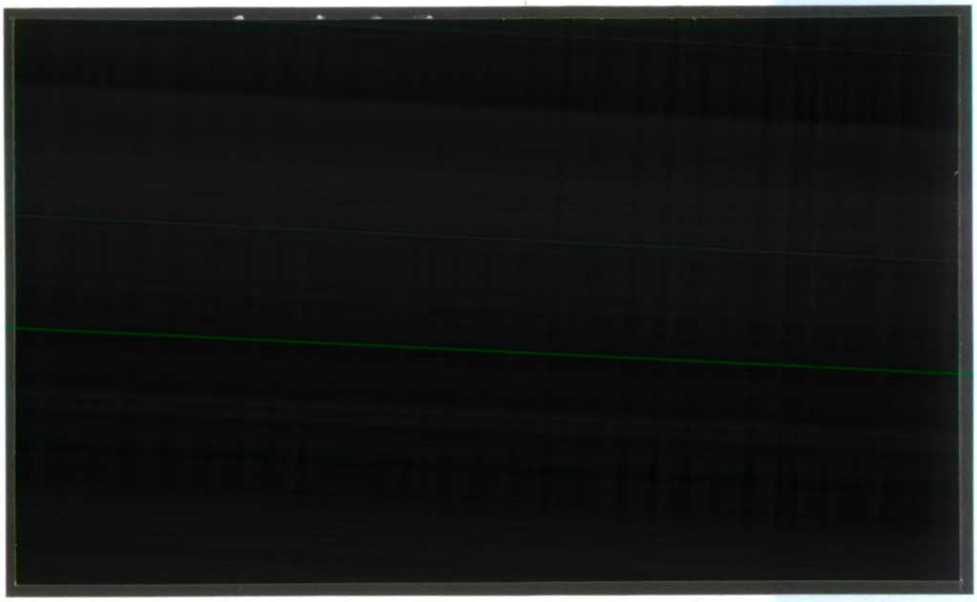

Centre for Ecology & Hydrology
NATURAL ENVIRONMENT RESEARCH COUNCIL

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Definition study for the Sellafield Flood Risk Appraisal

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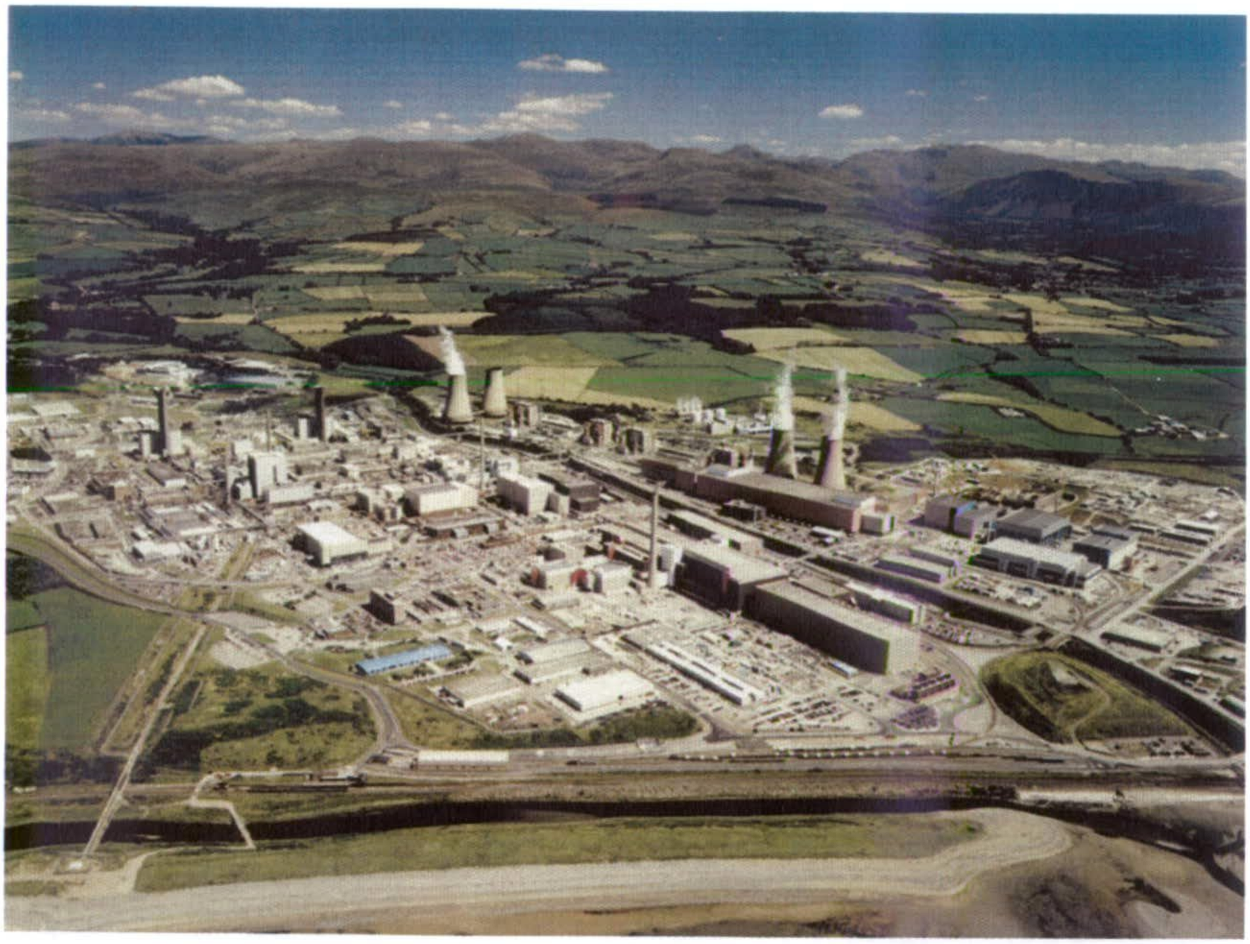


Plate 1 *Sellafield site (top left shows Calder catchment)*

Contents

0 EXECUTIVE SUMMARY

"The direct effect of rainfall, local accumulations of water, and rain falling on or around a building or site must be examined against site specific data, taking account of interactions with abnormal tidal effects (both marine and river) as appropriate. It must be shown that radioactive material is protected from rainfall by structures and is out of reach of flood water, or that facilities exist to contain contaminated run off/overflows."

This quotation from §G6.3.2. of the BNFL's UK Environment, Health and Safety Manual sets the context for the review presented here. While there have been many facility-specific assessments of flood risk, there is need of a comprehensive review and risk assessment for the Sellafield site as a whole to confirm that safety standards are being fully met. This report reviews the nature of flood risks at Sellafield, and specifies an approach to undertaking a comprehensive Sellafield Flood Risk Appraisal.

Without wishing to pre-judge the outcome of the Sellafield Flood Risk Appraisal, it is suggested that the assessment of flood risk arising from a severe rainstorm local to Sellafield requires considerable new work. There is a clear requirement to model how rainwater and local catchment runoff will discharge above and below ground. In addition, the report identifies a concern that the scope for temporary blockage and impoundment of the River Calder upstream of the site has not been adequately investigated and the risk to the Sellafield site assessed.

Flood risk to installations is highly site-specific, and it is not possible to generalise recommendations to other sites. While some of the principles are universal, site-specific factors are always important.

1 Introduction

1.1 CONTEXT

In managing, operating and developing Sellafield, there is a requirement to demonstrate that all plant and procedures are such that the radiological risks from external hazards are tolerable, and as low as reasonably practicable (ALARP). There is a particular requirement to demonstrate, with a high degree of confidence, that key buildings on the Sellafield site will not be flooded in the event of an extreme rainstorm occurring at Sellafield, an extreme flood occurring on the River Calder, an extreme flood occurring on the River Ehen, an extreme flood occurring from the sea, or a combination of the above factors.

The criterion specified is a storm or flood event that has a 0.01% probability of occurrence in any year, commonly referred to as the 10000-year event.

There have been many previous assessments of flood risk at Sellafield, generally to guide drainage and building design for specific facilities such as THORP. Patterns of surface water flooding – which will occur in the event of an extreme storm over the site – are expected to be influenced by relatively detailed features such as road alignments, kerb heights, localised blockages and structures such as buildings that incidentally act as flow-splitters. In consequence, BNFL seeks to develop a detailed and adaptable hydraulic model that can be used to estimate extreme sub-surface and surface flows, and water levels, across the site generally. It is desired that the model should be variable and extendable to test out or incorporate new buildings and drainage designs at Sellafield. In addition, the modelling system should allow a range of hydrological and meteorological design "input" conditions to be assessed, facilitating sensitivity tests (for example, to assess the impact on water levels of a 10% increase in design rainfall intensities arising from possible climate change)..

BNFL had previously invited Expressions of Interest for a flood risk appraisal for the Sellafield site from a range of experienced consultants. The brief given was broadly specified and the submissions received had revealed a wide diversity of proposed methods. Consequently, BNFL seeks an authoritative assessment of the structure and ingredients of a comprehensive appraisal of extreme water levels across the Sellafield site.

1.2 OBJECTIVE

The objective of the current study is to prepare a specification for a comprehensive appraisal of extreme water levels across the Sellafield site, consequent upon extreme rainfall and flood conditions (10000-year events). It was agreed that this definition study would be largely based on the following factors: the accumulated experience of Dr Duncan Reed (CEH Wallingford) and Dr Rodney White (HR Wallingford Ltd.), extensive reading of past reports relevant to Sellafield flood risk appraisals, a site visit, interpretation, and a meeting to discuss the final report.

1.3 PRINCIPAL FLOOD RISK FACTORS

The principal flood risk factors have been introduced in Section 1.1. They are:

- an extreme rainstorm occurring over Sellafield and its local catchment
- an extreme flood occurring on the River Calder (see Figure 1.1),
- an extreme flood occurring on the River Ehen,
- an extreme flood occurring from the sea,
- or a combination of the above factors.

The estimation of hydrological and meteorological extremes associated with exceptionally rare weather conditions is inherently problematic. All assessments of the maximum water level having an annual exceedance probability as small as 10^{-4} (i.e. 0.01%) are liable to error. Although specific parts of an estimation method or modelling technique can be validated, it is generally impractical to validate the final design water levels (or, equivalently, the risks associated with a given maximum water level) themselves. While there are difficulties in modelling – particularly of complex hydraulic situations and of hydrological processes occurring in the upper soil layers – the estimation of extreme input conditions is generally the weaker link in the chain. Thus, while the use of advanced modelling techniques is highly relevant to correctly judging the impact of particular drainage or building designs on flow and water levels across the developed site, large uncertainties inevitably remain as to the actual standard of protection achieved.

Rather than making conservative assumptions at various steps in the flood risk assessment process, recommended practice is to derive best (i.e. "central") estimates of the maximum water level likely to arise in a design flood. Uncertainty is then dealt with principally by making an allowance in the final design. Usually this takes the form of a "freeboard" allowance (e.g. adding a margin of 0.25, 0.5 or 1 metre to relevant flood defence structures) and/or by "oversizing" potential bottlenecks such as a culvert.

In complex and critical cases, such as pertain at Sellafield, the choice of freeboard or oversizing should be informed by sensitivity studies which examine the sensitivity of the derived maximum water level to factors such as: higher rainfall rates in the event of climate change, potential blockages in drainage systems, and possible dependence (in extreme conditions not adequately represented in gauged records) between coastal storm surge and major river flooding. This sensitivity study approach is recommended here.

Not all buildings and facilities at Sellafield are equally sensitive, nor equally exposed to flooding, nor equally exposed to each type of flooding (flooding from the sea, flooding from main rivers, flooding from local storm run-off, flooding from rainfall penetration). Though a complication in some respects, this reality can be used to steer the definition of a Sellafield Flood Risk Appraisal. In other words, some scenarios of flood risk are more critical than others, and can, with due planning, be given appropriate emphasis.

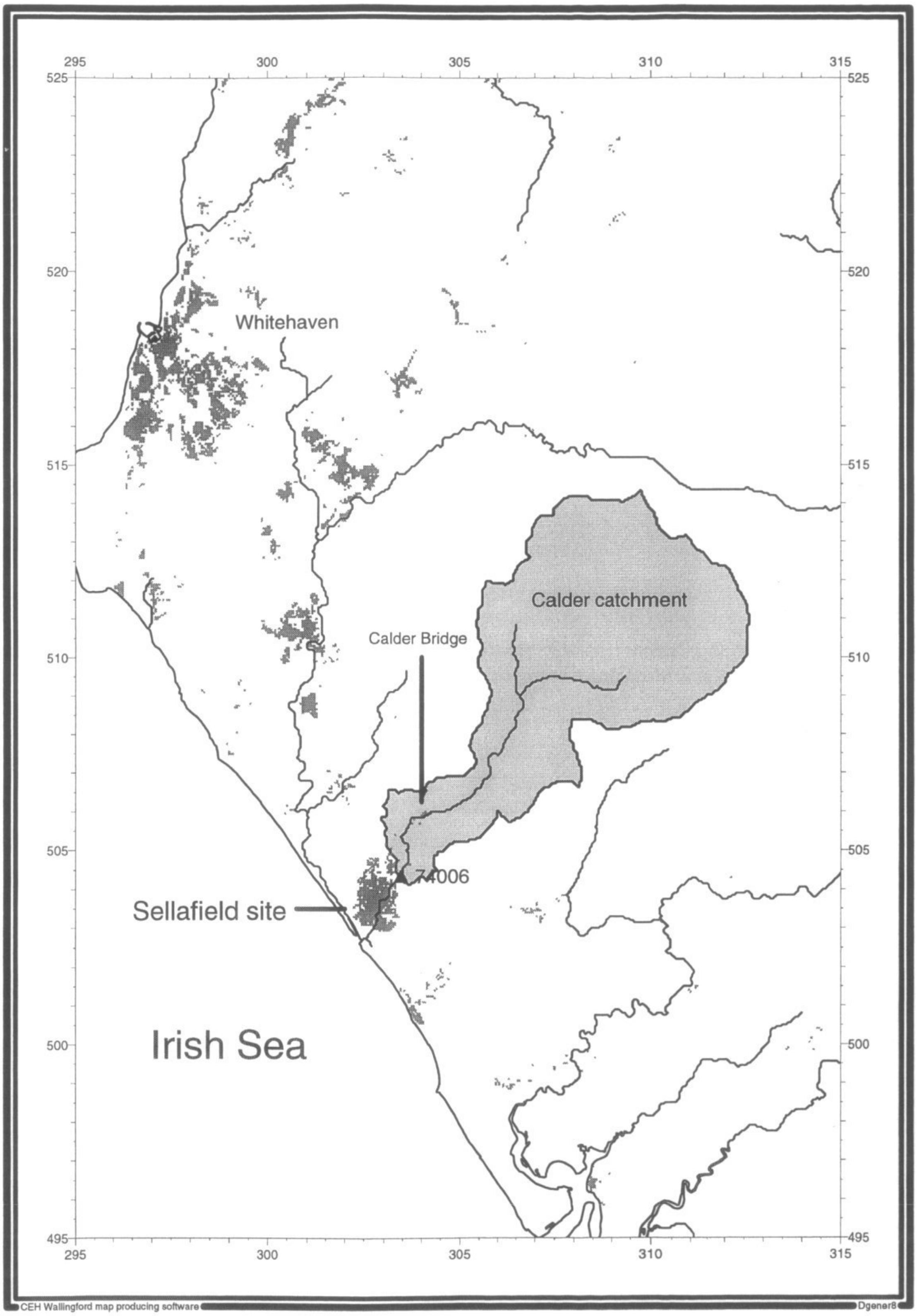


Figure 1.1 *Location plan*

1.4 REPORT STRUCTURE

Section 2 comprises the largest portion of the report and is given over to a review of previous studies. Section 3 considers the Expressions of Interest received by BNFL in 1998. In studying the extensive material summarised in Section 2, one is inevitably drawn to wider thoughts about flood risk factors at Sellafield, and to evidence of past unusual events in the area. These thoughts are gathered together in Section 4, which also highlights information and data sources: some identified from the review of previous studies, and some found from other sources. In addition to recommending methods for the Sellafield Flood Risk Appraisal (Section 5 and Appendix A), we also identify recommended pre-study action in Section 6 and Appendix B. The other appendices attempt to document this definition study. It seems likely that there will be some previous study that we have either not been supplied with or failed to find. Where we have cited a document in Appendix C, we have attempted to distil the most pertinent points. In some cases, documents were incomplete (most often, lacking drawings). We indicate these for the record only.

1.5 APPLICATION TO OTHER SITES

Flood risk to installations is highly site-specific, and it is not possible to generalise recommendations to other sites. The basic approach of using a design rainfall, a rainfall-runoff method of flood formation, and hydraulic modelling may be transferable to other sites. However, the opportunities to refine flood estimates by reference to local historical and gauged data will be site-specific.

Of special importance is the need to assess hazards that may be unique to the installation's setting in the landscape: most obviously, with regard to its proximity to watercourses, rivers, reservoirs and the sea. Morphological factors within the catchment may predispose a river to the formation of debris dams from rainfall-induced landslides into the river valley, or from material transported by the river in extreme flood conditions. Such debris dams are a particular concern because of their ability to impound floodwater temporarily before breaching and releasing an abnormally high flood. Installations sited downstream of man-made reservoirs may be vulnerable to similar effects in the event of the structure failing abruptly. Some installations draw cooling-water from a major river, lake or reservoir. In cases where this is safety-critical, it will be necessary to assess the risk of the water supply being lost through diversion of the river, drainage of the lake, or destruction of the reservoir. One scenario for such a loss may be an extreme flood.

2 Review of previous studies

2.1 DEFINITION OF PROBLEM AND RISK FACTORS

The principal factors giving rise to flood risk at Sellafield (see Section 1.3) have generally been recognised in earlier studies. However, there have been shortfalls in the approach to date. In particular, we judge that insufficient attention has been paid to the risk posed by an extreme rainstorm occurring at Sellafield, affecting the developed site and local watercourses draining to it. This therefore forms a major part of the comprehensive study recommended in Section 5.

Another shortfall might appear to be the lack of a competent study of extreme water levels in the lower Calder and Ehen that might arise from a combination of high sea level (storm surge and wind-driven waves) and major river flooding. This is now reviewed.

Combined effect of different input factors

However, it is difficult to justify such a study given that it appears from simple assessment that the sea level expected to be exceeded with an annual exceedance probability of 10^{-4} is appreciably lower than any critical floor level on the site. In the event of a new assessment showing the 10,000-year maximum sea level to be appreciably higher, it could be appropriate to examine the "joint probability" problem presented by fluvial-tidal interaction more formally. However, from the review of previous analyses, there is no strong evidence to indicate that the site is at particular risk from a combination of coastal and river flooding more than it is exposed to either risk factor individually.

The reason why a formal "joint probability" investigation is possibly inappropriate at Sellafield (in contrast, for example, to flood risk assessments in tidal reaches of a major river) is as follows. In conventional river flood risk assessments, the aim is to provide a uniform level of flood defence service at all reaches along a river. Thus, the required design is to contain a maximum water level of a given "target" return period. In contrast, the practice followed at Sellafield is to impose the criteria that the facility should be designed to safely withstand 10000-year extreme values from each of a number of environmental input variables acting individually to raise water levels on the site. This is a difficult point to put over. But the solution of a "joint probability" problem is only needed when the risk criterion is stipulated on the output variable rather than on the input variables.

An alternate approach is recommended in Section 5.2.

2.2 ESTIMATION OF DESIGN INPUT CONDITIONS

In estimating flood risk from the River Calder, previous studies have generally (correctly) adopted a rainfall-runoff approach to flood estimation. This follows guidance given in the Flood Studies Report (NERC, 1975) and reinforced in reservoir flood safety guidance (ICE, 1979 and later editions). The 10000-year flood hydrograph has generally been estimated from a 10000-year design rainfall calculated according to the rainfall frequency model given in Volume II of the Flood Studies Report. Some studies have also considered estimation of the Probable Maximum Flood for the Calder. Publication of the Flood Estimation Handbook (IH, 1999) has left the PMF procedure largely unchanged. However, the FEH provides a new rainfall frequency model. Application of the FEH rainfall model at 10000-year return periods is currently controversial. This presents an added complication to the consultant undertaking the comprehensive flood risk appraisal at Sellafield (see Appendix A).

Previous studies have made only limited use of gauged rainfall and flood data to refine standard estimates of the 10000-year flood. Several studies in the 1980s recommended more detailed monitoring of rainfall and local runoff at Sellafield. Some studies – notably that by Dee in 1988 – gathered and analysed rainfall-runoff data for a relevant local catchment draining to the site. However, the recommendation to base any local adjustment of standard procedures on the analysis of at least five recorded flood events does not appear to have been followed. With regard to assessments of the flood risk from the River Calder, few investigations appear to have attempted to make use of flood data from the river gauging station upstream of the site. This omission is perhaps understandable given the uncertainty that has dogged flow measurements at this station (see Section 4.2).

There does not appear to have been a concerted attempt to gather, research, interpret and utilise historical information on extreme storms and floods locally. This omission needs to be remedied (see Section 4.4).

2.3 HYDRAULIC MODELLING OF FLOWS AND WATER LEVELS AT KEY LOCATIONS

Based on previous studies, general conclusions are as follows:

a) the drainage system for the whole of the Sellafield site, as influenced by tides, river flows and local rainfall/run-off, has not been looked at in a comprehensive and detailed way and it is not known how it would perform under exceptionally severe weather conditions. Studies have generally been concerned with proposed new buildings or building complexes and the site drainage works have been extended and developed as the site itself has developed.

b) the River Calder through the site has been engineered to protect the site against a catchment event with a probability of 0.01% in any particular year. (Although one study of the River Ehen showed up major differences in computed river flows corresponding to the 0.01% probability level). There has been no consideration of possible sediment deposition in the "oversize" channel through the site during an extreme event. This needs to be checked as this could jeopardise the level of service provided.

c) the site, at ~15 mAOD, is well above any sea level which might have a probability of 0.01% in any particular year.

In the light of the above, the main emphasis should be placed on the site, and its immediate surroundings, and on localised rainfall events. However, careful checks on the possibility of flooding derived from either the sea or the River Calder should also form part of the study.

2.4 SUMMARY

The following table gives the main points of interest from previous studies. Each study is fully referenced.

Table 1 *Notes on documentation of previous studies*

Document	Date/Author	Notes
Model studies of the River Calder [00010274] (Ref 6.3)	02.75 N A J Pointer, UMIST	Report of physical model studies. • Carried out to look at some of the detailed flow conditions at the ends of the re-aligned and enlarged Calder channel through the BNFL site. • New channel predicted to convey 250 m^3s^{-1} flood. • Identifies constriction at Calder Bridge. • Identifies need to maintain channel; erosion expected, particularly on Calder Hall side.
River Calder re-alignment – Second report on probable maximum flood derived from NERC Report 1975 [00010271]	06.75 Rowntree Boddington Associates J B White, UMIST	• Suggests design flood of 387 m^3s^{-1} for channel realignment works based on newly published FSR (compromise estimate after PMF and 10000-year calcs; 9.1 h storm). • Recommends gauging.
Calculation of flood flows for the Calder catchment area [00010263]	07.75 I M Thomas & M Phillips, BNFL	• Used newly published FSR. • Estimated Calder max. flood at 337 m^3s^{-1} from 10.5 h storm depth 272 mm and SPR of 41.7%.
Hazard assessment for the Sellafield Site west of the River Calder – Flooding (Ref 6.25)	07.81 J A Crowder, BNFL	A largely superseded report which looked at probability and consequences of surface water flooding. • Concluded there was an "insignificant" probability of flooding. • Predicted tide level 6.5 mAOD at 0.01% probability level, min ground level 12.2 mAOD. Unconvincing methodology. • River Calder channel capacity ~0.02% flood probability level • Combined tidal/river levels at 0.01% probability estimated at 9.00 mAOD cf ground level of 12.2 mAOD. Unconvincing methodology. • Surface water drainage systems in Drwgs OAE 402027 to 38 (where?). • Daily rainfall of 140 mm expected at the 0.01% probability level. Flawed methodology. • The system coped with 65 mm in one day in October 1977. • No flood hazard from local storages surrounding the Sellafield site. • Water supply to the site < 0.4 m^3/s.
An extreme value analysis of Sellafield meteorological data [00010621]	05.84 C E Miller, BNFL	• Advocates use of Gumbel or log-Gumbel distribution to describe meteorological extremes (single-site analysis). • Tabulates ann. max. wind gusts, ann. max. 1-day rainfalls, ann. min. temperatures and ann. max. temperatures for Sellafield (1950 – 1982/83).
Estimated maximum rainfall, Sellafield [00010630]	Thought to be 09.84 by Ronald Leach & Associates	Tabulation of standard FSR design rainfall depths and intensities for Sellafield location. Graphical presentation of same.
Study of effect of 1 in 10000-year return period rainfall on the THORP Site [...............]	11.85 H F Farley, BNFL	Summarises October 1985 report by R Leach & Associates. • Considers runoff local to the THORP site; infers that 20-minutes storm duration is the most critical. • Recommends sub-daily rainfall gauging at Sellafield.

Document	Date/Author	Notes
Design of THORP surface water drainage and effect of extreme rainfall [00010690] (Ref 6.5)	03.86 Ronald Leach & Associates	Outlines the philosophy of design of the surface water drainage for the THORP complex and related changes to the Sellafield main drainage system. • 10000-year design standard. • Computer simulations using the Wallingford procedure. • Recommends installation of autographic raingauge.
An assessment of the flooding risk for the Miscellaneous Beta-Gamma Waste Store [00010678] (Ref 6.7)	05.87 R Stam, BNFL	Looks at the safety of MBGWS from all possible sources of flooding. Risks considered low enough for: • Tidal flooding • River flooding • Rainfall/surface water flooding • Flooding from engineered sources, e.g. cooling-tower pond failure.
Flood study of the BNFL Calder Site, Sellafield [00010269] (Ref 6.8)	03.88 A J Dee, Bolton Institute of Higher Education	Final year BSc project. • Gives 24hr rainfall at the 0.01% probability level of 320 mm by local analysis of ann. max. 1-day rainfalls at Sellafield, 1950-1982. • Concerned with the principles of FSR and the Wallingford Procedure. • Analyses rainfall-runoff for event (11/11/87) on 0.75 km^2 mixed catchment to Manhole B4. 4 hour lag. • Recommends further gauging.
Calder Hall/ Chapelcross Power Stations: Extreme offsite flooding assessment	02.91 S H Booth, BNFL	
Sea and river flooding study of Calder reactors [00010686] (Ref 6.10)	03.91 J Jowett and K P Derewnicki, AEA Technology	A study relating to Calder Hall which assesses the probabilities of flooding from several causes. • River flooding - less than 0.01% annual probability • Marine flooding - "negligible risk" • Combination - "insignificant risk" • Thoughtful study but some of statistical methods used are flawed. For example, it is unsatisfactory to extrapolate "single-site" analyses for 10000-year return period based on 3 years of measurements. Also, the "joint probability" problems are not solved correctly.
Sea and river flooding study of Calder reactors [00010686] (Ref 6.10) Brief comment on findings of study [00010637/ 00010675], (Ref 6.12)	??.91 BNFL	Short internal memo. • Agrees that river flooding from Calder channel is extremely unlikely. • Criticises combined probability sea levels as being too high. • Does not itself interpret the joint probability problems correctly.
Proposed SMP Export Facility effects of extreme rainfall [00010677] (Ref 6.18)	??.94 BNFL	Describes the use of HYDROWORKS to confirm the safety of the proposed SMP Export Facility at Sellafield and reviews the case for providing an additional outfall.

Document	Date/Author	Notes
Sellafield marine study – Extreme water levels at Sellafield [00010279] (Ref 6.16)	02.94 Ove Arup & Partners WS Atkins Consultants Ltd	W S Atkins' MIKE-20 modelling of combined tides and waves. • Quoted highest astronomical tide of 5.36 mAOD. • Quoted max. still water level of 6.7 mAOD at 0.01% probability level. • Combination of tides, surges, waves, etc inadequately covered.
Sellafield flooding study [00010687] (Ref 6.17)	04.03.94 Babtie Shaw and Morton	• A comprehensive account of flooding potential at a site adjacent to Sellafield which included a review of previous studies, hydrology, hydraulics and the evaluation of alternative flood protection schemes. A misleading title in that the study was principally concerned with the River Ehen. • Flow with annual probability of 0.01% increased from 560 m^3/s to 759 m^3/s. • Peak water levels, 8.5 mAOD through the proposed site. • Discusses possible scenarios for flood exacerbation, inc. morphological and debris effects.
SSSF flood studies (SSSF was later renamed SDP) [00010629]	01.95 R V Tann, BNFL	A very brief document of unclear origin. Possibly relates to Sellafield site specific safety case. Useful confirmation of design criteria. • No surcharging of sewers - 5% annual probability. • No surface flooding - 2% annual probability. • No flooding of high risk building - 0.01% annual probability. • Roof drainage - 2% annual probability. • Overflows - 0.01% annual probability.
SDP extreme environmental hazards: Flooding [00010280] (Ref 6.21)	??.96 BNFL	A guide to the procedures to be adopted in assessing the cause and consequence of transient flooding conditions. Considers: • River flooding • Rural catchment • Urban catchment • Marine flooding Essentially a discussion of methodologies.
SDP flood study – Storm design criteria Sellafield [00010628] (Ref 6.20)	??.96 BNFL	A brief table which relates storm frequency to rainfall ratios (4 hour storm) to conditions required on site. • 5-year event - no surcharging • 20-year event - no surcharge of pipes • 50-year event - no flooding from manholes • 10000-year event - no flooding of safety related buildings
Sellafield flood study – Proposal (scope.pdf)	21.10.99 C Swain, BNFL	Draft Terms of Reference for a *Definition study for a flood assessment of the Sellafield site*. • Indicates the importance of simulating very rare events – 10000-year event and 10% above this value. • Indicates the importance of creating an overground model to link up with the existing HYDROWORKS underground model. • Gives 25 references - mainly BNFL documents.
Rainfall event study – draft final report	04.00 Weetwood Services for White Young Green	• Reviews extreme storm of 5 November 1999 in and around Whitehaven. • Some 2 to 12-hr recorded rainfalls assessed to be in the 50 to 100-year return period range. • Some river water level data for the event.

3 Review of 1998 Expressions of Interest

3.1 DEFINITION OF PROBLEM AND RISK FACTORS

The Expressions of Interest sought in 1998 focused primarily on the hydraulic modelling of flows and water levels at key locations across the site (see Section 3.3). To their credit, Flynn & Rothwell specifically noted in their covering letter that the scope of work envisaged in the invitation to pre-tender was too loosely defined.

3.2 ESTIMATION OF DESIGN INPUT CONDITIONS

Binnie, Black & Veatch specifically recommended that use be made of the new Flood Estimation Handbook procedures. At the time of their submission of the Expression of Interest, it was not appreciated that 10000-year rainfall estimates by the FEH procedure have a marked tendency to be higher than those given by the FSR rainfall frequency procedure.

3.3 HYDRAULIC MODELLING OF FLOWS AND WATER LEVELS AT KEY LOCATIONS

BNFL sought expressions of interest from eight firms which were to provide information on:

a) Currently available packages suitable for the proposed model;
b) Recommended package for the proposed model;
c) Benefits/disadvantages of the package compared with others;
d) Model input data quality requirements;
e) Expected model output accuracy;
f) Model construction methodology;
g) Proposed team structure and CVs;
h) Previous relevant company experience;
i) Estimated project duration.

The stated objective of the flood study was:

"To demonstrate to the Nuclear Inspectorate that the buildings on the Calder (sic) site will not be flooded in a 1 in 10000 year storm. (For practical purposes, flood waters must be no higher than 100 mm below ground floor level)."

Expressions of interest were obtained which varied widely in depth and detail. A summary is given in the following table.

Table 2 Summary of expressions of interest

Firm	Hydrology	Urban drainage (Piped plus surface flows within the site)	River and catchment	DTM	Notes
Bullen Consultants	Micro-FSR v2.22 and/or HYFAP v2.2	INFOWORKS (HEC-RAS for tributaries)	ISIS	Key TERRA FIRMA v3.41	• Proposed use of INFOWORKS does not mention surface modelling - implies only sewer modelling. • Sewer system verification mentioned, but should have stressed surcharge verification (non-standard) – in fact a very limited level of verification is proposed. • Method of use of GIS to determine flow paths and surface water levels is unclear. • Use of Key GIS may be as good/better than MapInfo or ARCInfo etc • Use of river records is unlikely to provide adequate extrapolation to the 10000-year event. • Reference to FSR is outdated but presumably FEH would be used. • Mixing HEC-RAS and INFOWORKS and ISIS seems fraught with data transfer problems. • Study could not be done adequately in 3 months.
Flynn & Rothwell	Micro-FSR	HYDROWORKS INFOWORKS	ISIS	MapInfo Professional	• Covering letter (correctly) points to scope of work being too loosely defined. • Proposal indicates that INFOWORKS is a DTM which it is not. • Sensitivity analyses are proposed - a good point. • INFOWORKS proposals are sound. • One of the few proposals which mentioned consideration of roof drainage. • Service trenches mentioned as primary drainage flow paths. • Constraints of inflows not mentioned when surface flows are linked to underground flows. • Suggests estimation of 10000-year design rainfall as largest source of error. Recommends special scrutiny. • Recognises difficulty in verification of primary system drainage. • Indicates importance of impermeable area survey – highly relevant. • Indicates topographic survey and GIS for defining flow paths – important. • No mention of the importance of flood storage on site. • No mention of downstream water level boundary condition. • Description of the way ISIS, for local river(s), would link with HYDROWORKS for underground drainage unconvincing. • Proposes full assessment of 10000-year flood on River Calder, including survey of floodplain and embankments.

Firm	Hydrology	Urban drainage (Piped plus surface flows within the site)	River and catchment	DTM	Notes
Wilde and Partners		INFOWORKS	MIKE-11	MIKE-11 GIS	• Proposal only suggests limited use of overland flow modelling. • Rainfall profile analysis suggested. • Not clear whether undeveloped area to be modelled using MIKE11. • Proposal recognises importance of flood storage areas. • Claims 10 – 20% accuracy. Does this apply to validation or prediction? • Proposal emphasises importance of ground levels for flood routing. • Advises a two stage approach. • Assumes a free outfall to Calder – needs to be confirmed acceptable. • No assessment of the River Calder is proposed. • Spatial rainfall is ignored - probably acceptable.
WS Atkins		HYDROWORKS	MIKE-11	MIKE-11 GIS or MapInfo GIS	• Proposal generally embraces the right methodology. • Calibration/verification is treated in a very superficial manner. • Recognises the importance of considering a range of design storm durations. • The proposal is light on the description of the models, but appears correct. • Downstream water levels are mentioned. • MIKE-11 stability for small streams also mentioned. • Some discussion of sensitivity issues. • No mention of the difficulties of linking surface with subsurface flows. • Ambiguous about need to consider flooding from the River Calder.
Entec		HYDROWORKS or MOUSE	MIKE-11		• Proposal shows insight into types of hydraulic modelling required, and recognises the problem of overland surface runoff. • Very little detail is given.
Montgomery Watson			MIKE-11		• One of two proposals which mentioned the risk of blockage during a major flood event. • Advocates a two stage approach. • Proposes MIKE-11 and suggests a 100 mm accuracy limit – difficult to achieve • Proposal suggests no need to model roads, service ducts etc - wrong.
Halcrow		HYDROWORKS	ISIS		• Proposal suggests there will be residual capacity of sewers during a 10000-year event - untrue. • No suggestion of overland HYDROWORKS modelling. • ISIS overland flow with flows to the sewer system. • Mentions risk of blockage. • Proposes review of rainfall profiles. • Proposes to use FSR for runoff hydrographs.

Firm	Hydrology	Urban drainage (Piped plus surface flows within the site)	River and catchment	DTM	Notes
Binnie Black and Veatch		HYDROWORKS	MIKE-11	MOSS	• Proposes MOSS DTM for flow paths – unsatisfactory. • Uses MIKE-11 as the principal modelling tool. • Interdependence needs to be modelled, but MIKE-11 and HYDROWORKS do not combine easily. • The only proposal to mention building sill levels. • Emphasises importance of rainfall estimation to achieving accurate modelling. • Recommends use of FEH rather than FSR methods. • No above ground modelling with HYDROWORKS. • MIKE-11 above ground flood routing on urban surfaces - unsatisfactory in some instances. • Mentions sensitivity testing

3.4 SUMMARY OF EXPRESSIONS OF INTEREST

- None of the proposals stressed the unusual nature and design standards of the site and its infrastructure. The requirement is to model extraordinary (10000-year) conditions on an extraordinary site.

- The proposals fell into two groups:

  One group proposed ISIS and/or MIKE-11 as the principal tool for flood analysis with linkages to HYDROWORKS for sub-surface pipework. This group fundamentally assumed that the flood waters would be generated by surface runoff from the catchment and that surface flows would be unaffected by conditions underground. They therefore assumed that the sub-surface drainage would not be overloaded by the quantities of water involved. This is almost certainly incorrect for conditions in the 10000-year design event.

  The second group proposed using HYDROWORKS/INFOWORKS usually supported by MIKE-11 or ISIS for surface water flows. This is the correct approach because it better represents what would actually happen in an extreme event. The sub-surface drainage would be surcharged and there would be extensive interaction between surface and sub-surface flows.

- Most of the proposals recognised the importance of topography in determining the way flood flows would travel through the site in an extremely rare event.

- Not one of the proposals recognised the importance of the head losses and flow constraints which will occur at the interface between surface and sub-surface flows.

- A few of the proposals recognised the importance of surface ditches and sub-surface service ducts.

- Only one proposal, Binnie Black and Veatch, mentioned the requirement for an accurate knowledge of floor levels in buildings. Perhaps the others took this for granted.

- None of the proposals gave adequate consideration of the accuracy requirements for topographic information.

- All of the proposals considered that flooding from the River Calder and/or the sea was of secondary importance.

- Only Entec stressed the complexity of overland rural flows during extreme events.

- Only WS Atkins drew attention to the instabilities which can develop in river models when used for applications other than main river.

- There was limited mention of the importance of downstream water level control.

- Not one of the proposals mentioned the important issue of surcharge verification of the drainage system. This is a major omission.

- There was little discussion of the difficulties in simulating the overland flow in an urban environment where the infrastructure is densely packed and there are large areas which are impermeable. Not one of the proposals mentioned the difficulties and inaccuracies of flood routing with 1-dimensional models under these circumstances. The possibility of using a 2-dimensional numerical model such as Telemac or physical models to overcome these difficulties was not considered.

Further minor comments:

- Mention of HYDROWORKS and not INFOWORKS is not particularly relevant.

- GIS is not seen as being pivotal to the analysis. This is correct. The hydraulic modelling system must talk to appropriate standard GISs for inputting data and presenting the results.

- The timescales quoted for studies were short, suggesting either that the consultants did not appreciate the complexity of the study or that they were prepared to cut corners.

4 Additional factors, information and data sources

This section draws attention to additional factors that may give rise to extreme flooding at Sellafield. It also reviews some of the data sources available to support the Sellafield Flood Risk Appraisal.

4.1 ADDITIONAL RISK FACTORS

There are a number of additional factors that might give rise to extreme flooding at Sellafield. Within the current state-of-the-art, it is impractical to quantify these further risks, making the application of ALARP principles difficult to judge. Most of these factors relate to the River Calder which runs directly through the site. The Calder is significant because of the large quantities of water that it carries during high flow conditions. While current provisions are thought to deal adequately with the direct threat of flooding from the Calder, there are potential difficulties if the river abruptly changes course during a major flood event or if a major blockage occurs within its lower reaches. The discussion is divided into largely natural (geomorphological) factors, and largely man-made factors.

Largely natural factors (River Calder)

The catchment of the River Calder can be considered in two main parts: that upstream of Calder Bridge and that downstream. The catchment upstream of Calder Bridge is relatively steep with well-defined river channels. There are just two areas of natural floodplain in this section that are sufficiently close to Sellafield to cause a potential hazard in the event of the sudden release of stored water during a major flood. These are the floodplain areas directly upstream of Calder Bridge and Stakes Bridge. The situation at Calder Bridge is closer and larger, and therefore appears to be the more likely to cause difficulty in the event of an extreme flood. At least one of the previous studies of Sellafield flood risk draws attention to the exceptional conditions likely to arise at Calder Bridge in an extreme flood (page 2 of *Model studies of the River Calder*, Pointer (1975), document [00010274]). The assertion in that report that stored water would be released only after the flood peak had passed is highly questionable. It is recommended that an assessment is made of the volume of water likely to be released in the event of over-topping and collapse of structures at Calder Bridge and a dam-break analysis undertaken to simulate how the resultant flood wave would propagate down the lower Calder. It would also be helpful to research the impact of recent and historical flood events (see Appendix E) on structures at Calder Bridge.

A second factor is that the River Calder might change course during an extreme flood event. The main scope for this to occur is in the section from Calder Bridge to Sellafield. Contours and drainage paths on current and past maps suggest that there have been phases in history where the River Calder drained to join the current course of the Newmill Beck at Ponsonby Tarn, and phases when the upper reaches of the Newmill Beck joined the current course of the Calder to the north of the Sellafield complex. In essence, the natural course of the River Calder ceases to be well-defined about 800 m downstream of Calder Bridge. It is recommended that a detailed topographic survey establishes land levels between the Calder at Pelham House and the Newmill Beck at Ponsonby Tarn and an assessment made as to whether the 10000-year Calder flood could escape south-eastwards. (Such a diversion would take flood waters away from most of the Sellafield site, but could have implications for flood risk to the south-east corner of the site.) With only minor extension, the topographic survey could also establish the scope for flood water from the upper courses of the Newmill Beck to join the Calder upstream of the Sellafield site. (The receipt of additional flood water from the Newmill Beck is unlikely to increase flood flows in the Calder by more than about 5%. However, such an ingress could encourage the Calder to change course close to its entry to the Sellafield site.) Given the evidence from maps that there have been shifts in the main channel of the Calder prior to the initial development of the site in the mid 20th century, it is relevant – in a comprehensive flood risk appraisal – to examine the scope for the Calder to escape from its present course ***before*** it reaches the engineered river channel that takes it through the Sellafield site. Such escape could prejudice the safety of facilities constructed on reclaimed land, following the major channelisation of the Calder in the 1970s. These facilities include, for example, the MBGWS. Field boundaries marked on a late-Victorian (6":1 mile) map suggest that the natural floodplain had a width of about 200 metres through what is now the Sellafield site (see Figures 4.1 and 4.2).

A third natural factor is the scope for blockage of the lower Calder by fluvial sediment and vegetation, notably trees. Because of the natural and man-made constriction at Calder Bridge, it seems likely that blockages will occur there rather than downstream. However, a check might be made for any particular susceptibility to rainfall-induced landslide into the constricted channel close to Pelham House. The design of the engineered river channel through the Sellafield site foresaw erosion and deposition processes there. A specific recommendation was made (Pointer, 1975) that there should be a regular system of inspection and channel maintenance following all large floods. Subsequent commentators have judged the bed erosion in much of the channel as beneficial to accommodating larger extreme floods, when it is really only a sign of the river's natural reaction against the channelisation. It is difficult to see the major vegetative growth within the channel as enhancing the capability to discharge river floods safely. The Sellafield Flood Risk Appraisal may conclude that the current channel conditions satisfactorily convey the 10000-year Calder flood. However, this needs to be demonstrated.

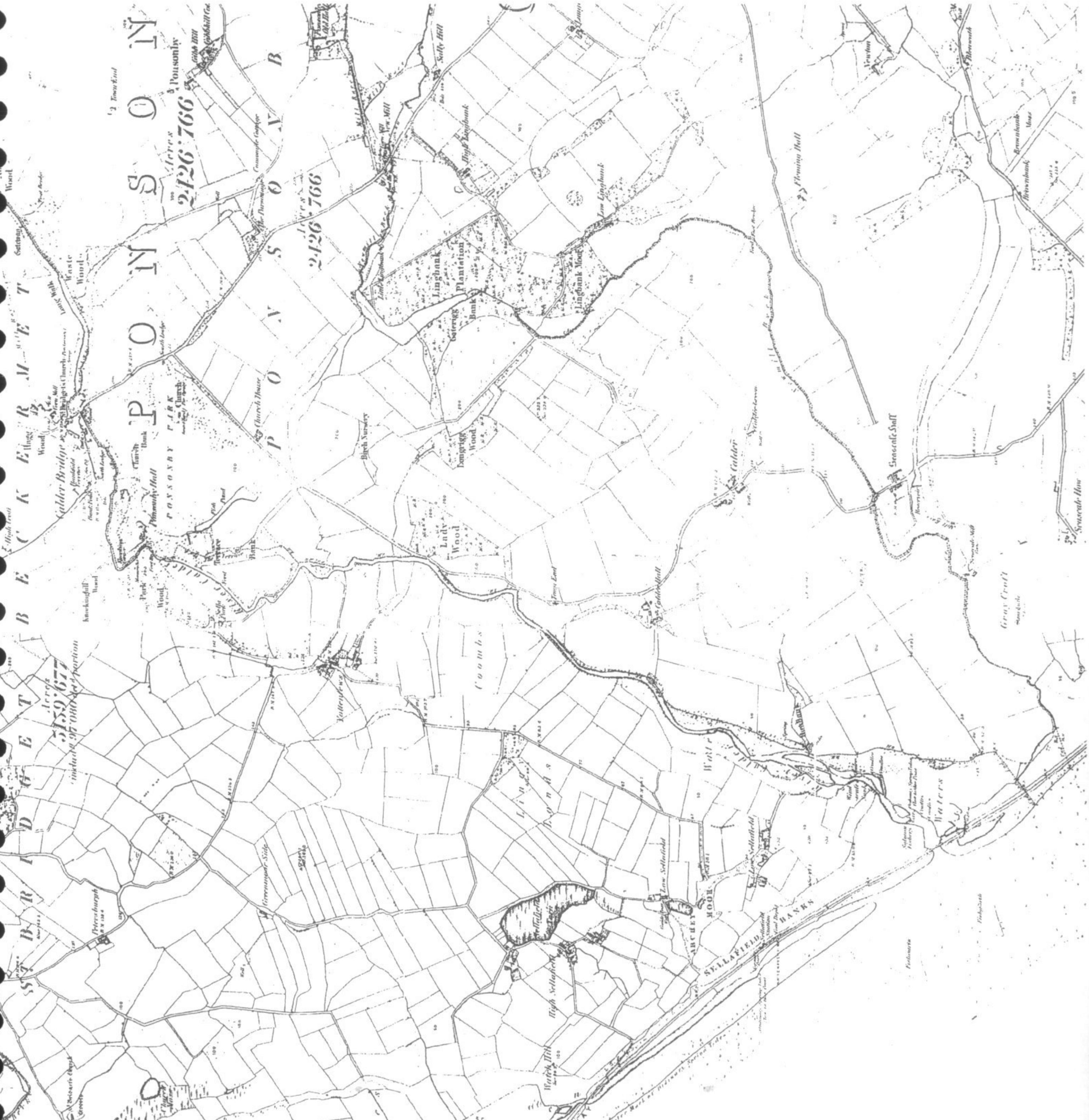
A final consideration is whether there is scope for the outfall of the River Calder to be blocked by sediments deposited in a marine storm. The relative steepness of the engineered channel, and the consequent high velocities of river flow, suggest that there is very little scope for abrupt blockage of the lower Calder by marine sediments. However, it is recommended that the possibility is reviewed and formally eliminated.

Largely man-made factors (River Calder)

Two features of the Sellafield site give particular concern that severe blockages might occur in exceptional flow conditions. These relate primarily to drainage from the site itself, in the event of an extreme localised storm. However, their effect might, in certain circumstances, lead to a trash-dam blocking the River Calder. The two factors are: (i) the large amount of mobile material typically on site (especially building materials and vehicles) and (ii) the very extensive and unusual security fencing. Collection of debris by the fencing is more likely to impede the safe discharge of surface water ***into*** the Calder than to exacerbate flow conditions within the channel. However, in the event of the fence being ruptured, its fine mesh sides and durability might contribute to blockages in the River Calder itself. If the security fence is known to be constructed to withstand very high dynamic loadings, it may be possible to conclude that it is beneficial to containing extreme flood effects within the river channel but detrimental to allowing extreme surface water runoff from the Sellafield site to discharge freely into the River Calder.

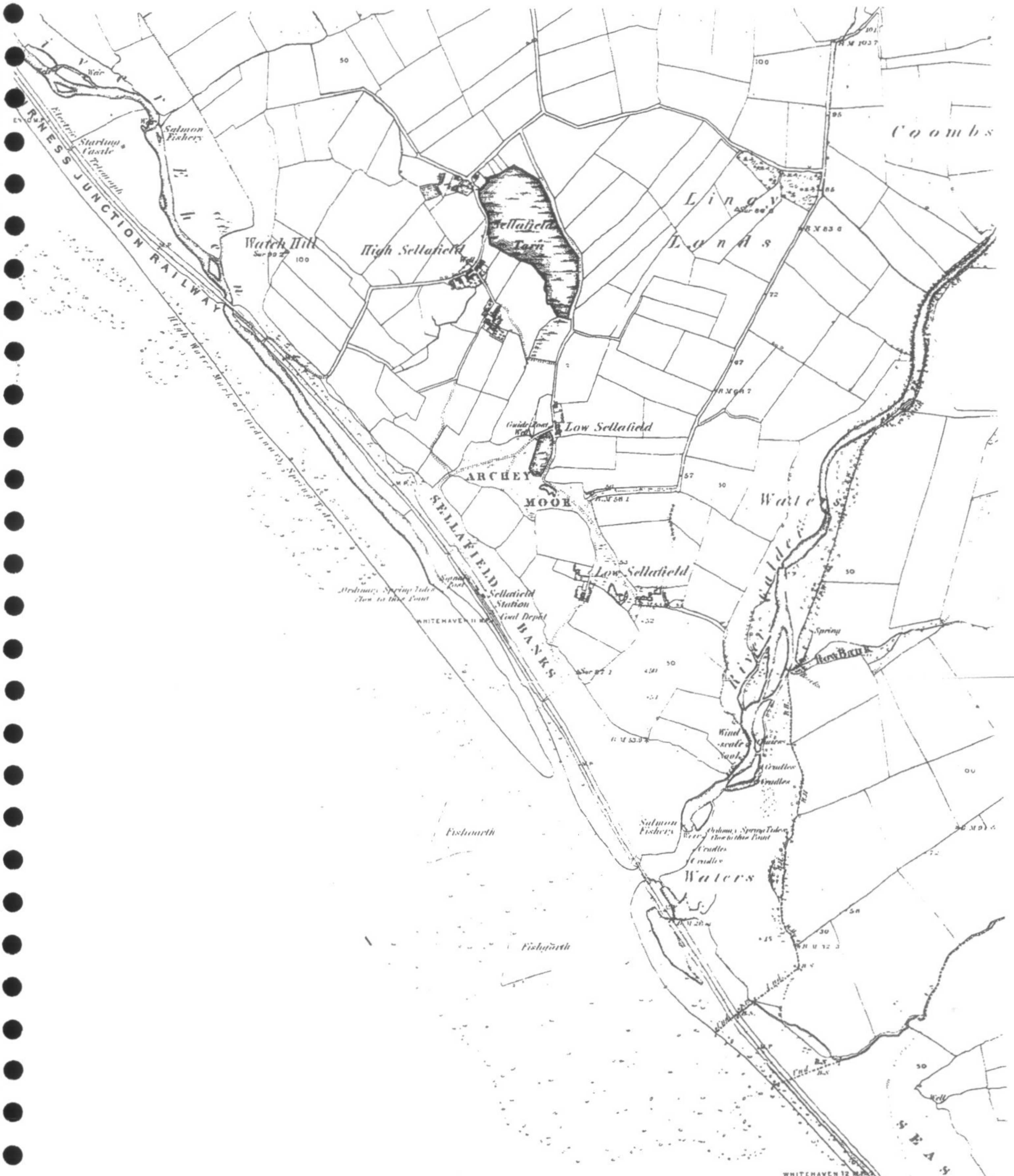
Contrast with reservoir flood safety assessments

The Reservoirs Act 1975, and associated legislation and engineering guides, set down regulations and procedures for reservoir safety in Great Britain. Impounding reservoirs pose a major hazard to communities downstream in the event of a sudden release of stored water. Consequently the dam is designed to discharge a design flood safely, i.e. so that the water in the reservoir does not reach a level high enough to cause structural failure. The reservoir design flood is typically the 10000-year event or, in appropriate cases, the Probable Maximum Flood. Most UK reservoirs are designed to minimise the potential for blockage. Where discharge of the design flood requires operation of a flood gate – either manually or automatically – the safety assessment takes account of the possibility of mechanical, electrical or human failure when assessing how many gates will function during the design flood.



First Edition 1:10,560 County Series (circa. 1867)

Figure 4.1



First Edition 1:10,560 County Series (circa. 1867)

Figure 4.2

The development of methods to estimate floods as rare as the 10000-year event has been largely driven by these applications to reservoir safety. A feature of nearly all extreme floods is the large amount of vegetation, sediment, boulders and other material that are swept into the river channel during the event. Items that float – notably trees, and (sometimes) vehicles and storage tanks - are a particular hazard in extreme river floods. Video footage and photographic surveys have shown such debris to be a particular feature of many extreme floods in Mediterranean countries, including the Vaison la Romaine flood of 22 September 1992 and the Piedmont (Upper Po) flood of 5/6 November 1994. These were rare floods but by no means as extreme as a 10000-year event. It is inevitable that a 10000-year flood event will be accompanied by the transport of much material.

These factors are generally not given very much attention in reservoir flood safety assessments in the UK. This is because reservoirs of any size present a highly effective trap for sediment and debris. Flow velocities decrease sharply as tributaries discharge into a lake, causing much of the sediment to settle. The relevance to flood risk assessments on the River Calder is simple. A 10000-year flood can be expected to entrain much sediment, vegetation and other debris. Because the flood does not pass through a reservoir, the entrained material presents a much greater hazard than in a typical reservoir safety assessment case.

4.2 SOURCES OF HYDROLOGICAL AND METEOROLOGICAL DATA

This section notes hydrological and meteorological data that are thought to have particular relevance to the Sellafield Flood Risk Appraisal.

Daily rainfall data

Figure 4.3 provides a map of daily rainfall stations reporting to the Met. Office and thought to have annual maximum daily rainfall data for at least ten years. Miller (1984) lists annual maximum one-day rainfalls at Sellafield for the period 1950 – 1982, taken from values reported to the Met. Office. Miller abstracts the annual maxima for years beginning 1 July.

Sub-daily rainfall data

Recording raingauges used in the Flood Estimation Handbook (Appendix 1 of Faulkner, 1999) include: Eskmeals (see Table 4.1), St Bees' Head, Seathwaite, Cornhow, Aspatria, and Silloth. Dee (1988) refers to recording rainfall data gathered from 5 November 1987 until 23 January 1988 in connection with runoff response studies at Manhole B4 on the Calder sub-site at Sellafield. A chart is given for a minor storm occurring on 11 November 1987. It is believed that recording raingauge data have been gathered for other short periods in connection with verifying hydraulic models of sub-surface drainage in particular parts of the site.

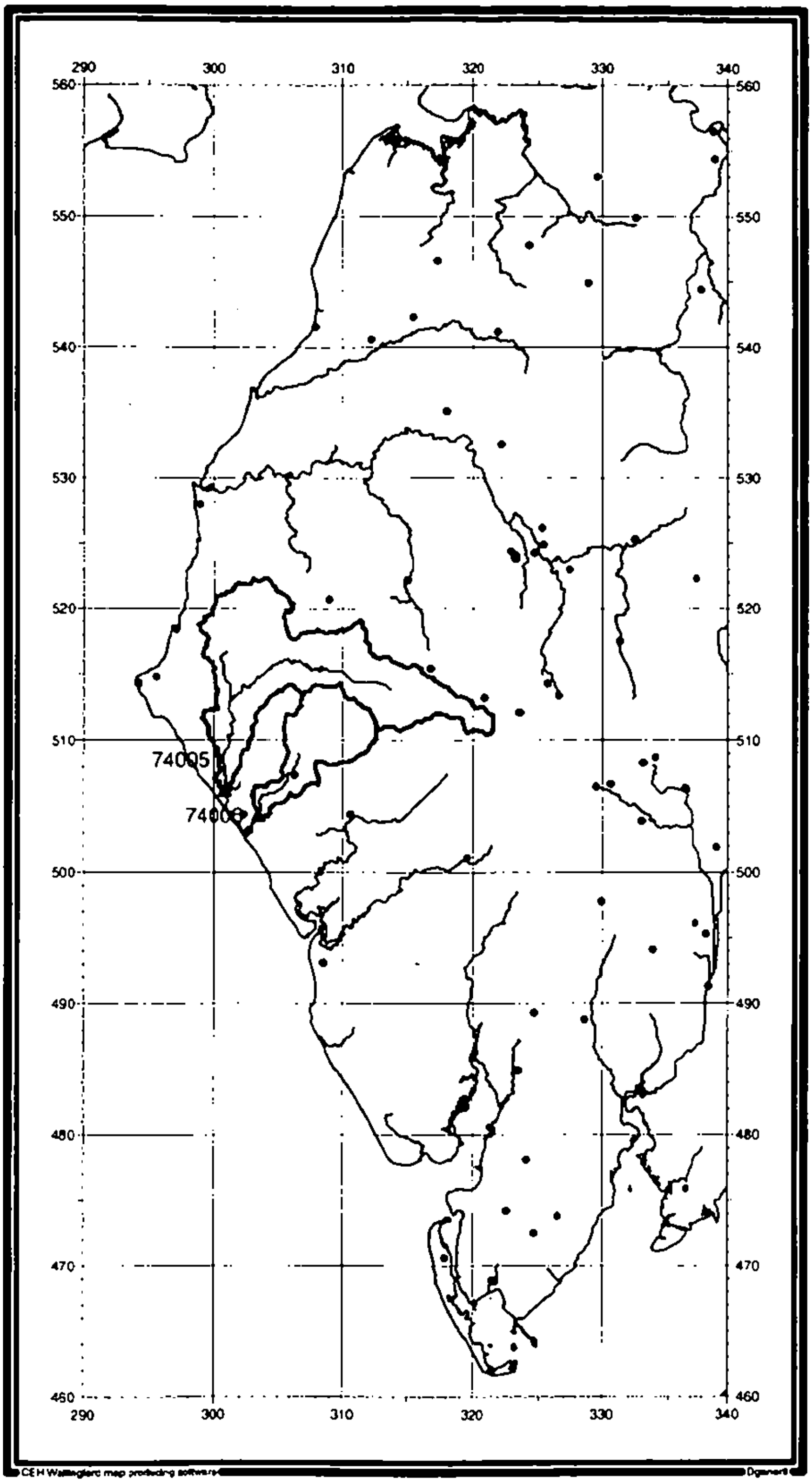
Weetwood Services Ltd (2000) report that the Environment Agency maintain recording raingauges at Calder Hall (the raingauge compound is close to the Calder river gauging station upstream from the Sellafield site), Starling Gill, Wastwater Hotel, Dearham and Summergrove (see Table 4.1). The report presents rainfall data for a major storm which occurred on 5 November 1999.

Table 4.1 *Recording raingauges in West Cumbria*

Name	Grid ref.	Met Office gauge no.	Altitude (m AOD)	Approx. distance and bearing from site
Aspatria	3154 5432	595739		41 km NNE
Calder Hall	3035 5045		28	1 km NE
Cornhow	3150 5222	594201		22 km NNE
Dearham	3081 5365		53	33 km N
Eskmeals	3085 4931	590602		12 km SSE
St Bees' Head	2941 5143	592199	124	14 km NW
Seathwaite	3235 5121	592448		22 km ENE
Silloth	3125 5537	596013		51 km N
Starling Gill	3136 5153		280	15 km NE
Summergrove	2998 5157		85	12 km NNW
Wastwater Hotel	3187 5087		79	16 km ENE

River flows

Flows in the Calder are measured at a formal gauging station, approximately 600 metres upstream from where the river enters the Sellafield site. The station has something of a chequered history. One reference states that flow records have been gathered since 1964 but that the pre-1974 history of the station is obscure. Manuscript records held by the National Water Archive (at CEH Wallingford) indicate that the station became operational on 1 October 1973, when the Cumberland River Authority commissioned the gauging station. Manuscript records held in the NWA include copies of two notes dated April 1982. These point to an apparent change in the rating (i.e. the water level to flow relationship) in 1976. However, for somewhat arbitrary reasons, the new rating equation was applied only with effect from 1 January 1980. The same notes also refer to an uncertainty about the datum level from which water depths are measured.



▲ river flow gauge • rainfall gauge

Figure 4.3 *Daily rainfall stations*

Another note dated 11 May 1991 comments that there was an intermittent leak in the stilling well at a water level of 0.8 metres. This was said to be sealed on 8 October 1989. Independently, Jowett and Derewnicki (1991) state that *"the NRA revealed that the recording well in the station suffered a serious leak between 1973 and the summer of 1975. The leak was then repaired but recurred during the period 1986 to October 1987. As a consequence the NRA cannot guarantee that their data prior to October 1987 reflects accurately the actual level and flow conditions at the site for levels exceeding 0.8 metres which corresponds to flow rates in excess of 14.5 cumecs"*.

It is strongly recommended that the Sellafield Flood Risk Appraisal looks at source information for flood peak data for the Calder (station number 74006), and discusses the record with hydrometric staff in the relevant Environment Agency office. Even if substantial parts of the record are held to be suspect, gauged data for recent important floods (see Section 4.3) could still be of considerable value.

Sea level data

Various reports, including Crowder (1981) and Jowett and Derewnicki (1991), refer to analyses of sea level data for Silloth, Barrow, Heysham and Fleetwood obtained from predecessors to the Proudman Oceanographic Laboratory (POL), Bidston. In addition, POL hold some sea level data for Workington and the Isle of Man (Port Erin and Douglas). The records are of variable length and quality. For the estimation of maximum stillwater (i.e. excluding wave effects) levels, it is usual to separate the sea level into astronomical and surge components.

Wind data

Miller (1984) lists annual maximum windspeeds at Sellafield for 1950-1982, for years beginning 1 July. These are stated to be 3-second gusts at 10 m. For wave generation, 15-minute or hourly mean windspeeds are move relevant. It may be appropriate to compare any analysis of local data with generalised methods for estimating design windspeeds (BSI, 1995).

4.3 HISTORICAL FLOOD INVESTIGATION

Purpose

Historical precedents help to put substance on risk assessments that might otherwise appear speculative or over-imaginative. A historical review is particularly helpful when examining risk factors for which a quantitative analysis is impractical. One example concerns the movement of sediment and debris in an extreme flood event in an upland area. The precedent may help to confirm that a risk factor warrants full scrutiny.

In addition to supplying information about the worst events and effects that have been experienced locally, a historical flood investigation can strengthen the credibility of those making the flood estimates. This is particularly true where the investigator identifies and interprets information and incidents that have been lost sight of locally.

Historical investigations are often qualitative rather than quantitative, and give scope for subjective interpretations. They are a double-edged sword. Given that the requirement is for a comprehensive flood risk appraisal, and that previous studies do not appear to have researched historical evidence in any great detail, it is recommended that a systematic approach is adopted in the Sellafield Flood Risk Appraisal.

Method

There are three main steps in an historical investigation: identification, investigation and interpretation.

Historical flood incidents can be identified from a range of sources, including:

- previous studies;
- flood marks;
- local histories;
- "British Rainfall" publication;
- scrutiny of particular sites, structures or geomorphological features.

Once identified, historical flood incidents can be investigated by reference to further information such as:

- local newspaper records;
- rainfall data archives (especially, the National Archive at the Met. Office);
- local libraries and public record offices;
- field investigation (e.g. dating of fluvial sediment).

The key requirement is to interpret the impact of an extreme storm or flood. The greatest care is required if notable incidents experienced on other catchments in the region are to be meaningfully interpreted with regard to flood risk at the subject site.

Appendix E lists known dates thought to be worthy of historical flood investigation in respect of flood estimates at Sellafield. Events shown in bold in that list are thought to be of special relevance. The Appendix also lists notable sites/locations thought worthy of investigation, and specific sources of historical information relevant to flood risk in West Cumbria.

5 Summary of recommended methods for the comprehensive flood risk appraisal

5.1 SCENARIOS FOR FLOOD CONDITIONS AT SELLAFIELD

Flooding as a result of tide/storm surges - probably well below the 0.01% risk level but needs a desk study to confirm.

Flooding from the River Calder – probably below the 0.01 % risk level but needs to be demonstrated. Requires a catchment model to simulate river performance and to demonstrate no river derived flooding on site – there may be extensive flooding upstream of the site which needs to be shown as not passing down into site.

Flooding from the site and the local catchment which drains to the site - a very high risk which must be investigated. The method of approach must take into account the densely developed nature of the site and the definable flow paths between buildings. The hydraulic models need to be dynamic and all influencing factors of significance need to be taken into account. The method of approach will be to use a combination of models for surface and sub-surface flows, primarily an urban drainage model, supported by a 2D numerical model and physical models for local areas. GIS will provide geographical data and would receive and present water level prediction data.

Flooding induced by roof drainage - probably not a high risk but needs to be demonstrated. A check is required to establish whether the roof drainage has been consistently designed to cope with the 0.01% probability event and that the impact on the receiving drains and pipework does not cause overloading.

5.2 BASIC APPROACH

Use of rainfall-runoff approach

Flood estimates are generally based either on a direct analysis of peak flows (the statistical approach) or by rainfall-runoff modelling (NERC, 1975; IH, 1999). The statistical approach is deemed appropriate to estimating 10000-year floods for reservoir safety assessment in the UK (e.g. ICE, 1996). Reed and Field (1992) infer that the rainfall-runoff method is preferred because it offers a structured approach to extrapolation. This is though to reduce the scope for gross under or over-estimation of floods that might occur if a statistical distribution were fitted to flood peak data and an extrapolated value read off at T = 1000 years. Making the extrapolation on rainfall depths (to estimate the 10000-year rainfall required in estimating the 10000-year flood by the rainfall-runoff method) is more assured because of the greater regional homogeneity in extreme rainfall and the longer record lengths available for analysis (Reed and Field, 1992).

Use of Flood Estimation Handbook

The Flood Estimation Handbook (IH, 1999) updates the FSR rainfall-runoff method in several respects. First, new methods based on digital catchment data are provided for estimating key parameters of the rainfall-runoff model: in particular, unit hydrograph time-to-peak (Tp) and standard percentage runoff (SPR). Second, recommendations to transfer estimates from gauged to ungauged sites, and to consider hybrid methods (combining rainfall-runoff and statistical estimates) are strengthened. Third, Volume 2 of the FEH presents a new generalisation of rainfall depth-duration-frequency.

The last update is controversial in terms of whether the FEH method of rainfall frequency estimation should supersede the FSR method for applications (principally, reservoir safety assessment) requiring estimates at very long return periods such as 10000 years. A recent review for DETR has been published on http://www.environment.detr.gov.uk/rs/01/index.htm. Differences between FEH and FSR rainfall frequency estimates around Sellafield appear to be relatively modest in comparison to those noted in other regions. Until further research is undertaken, it is reasonable to apply the FEH rainfall depth-duration-frequency model and consider the FSR model only when examining the sensitivity of key findings to this choice.

Treatment of combined effects

For reasons discussed in Section 2.1, a formal "joint probability" analysis is possibly inappropriate. Such analyses are, in any event, problematic (see Reed and Jones, 1999) when applied to estimate exceedingly rare (10000-year) conditions.

It is recommended that it is sufficient and appropriate to sidestep formal "joint probability" analyses by undertaking sensitivity studies. Under this approach a particular flooding condition (e.g. resulting from an extreme storm over Sellafield) is modelled assuming a typical value of another factor (e.g. water level in River Calder) and then a second model run is undertaken assuming an extreme value for this factor (e.g. representing a major flood on the Calder). No further investigation will be required if critical water-levels on site are insensitive to this difference. A similar approach can be applied to consider possible fluvial-tidal effects on water levels in the lower Calder.

5.3 USE OF MODELS

Accuracy requirements

The aim should be to determine the best estimate for "worst case" water levels and to use sensitivity testing for possible freak occurrences e.g. blockages etc.. The accuracy requirement should be ±50 mm in terms of water levels.

To achieve this level of accuracy will require good quality surveys and extensive and detailed modelling. As a general guide the survey should give ground levels to ±20 mm in critical areas and ±50 mm in less-critical areas. The numerical models will require several hundred nodes each and physical models will need to be professionally made and tested.

Hydrological inputs

The hydrology should be based on point and catchment design rainfall depths relevant to the Sellafield site. Testing with different storm duration/intensities will be required.

As indicated in Section 5.2, results using FEH are showing up differences from the earlier FSR estimates because of differences in the rainfall depth-duration-frequency model. The differences are large in the south east but, fortunately, not so great in the north west. However, we are dealing with a short duration rare event for the Sellafield site and hence this aspect needs to be considered. It will be necessary to run certain critical hydraulic simulations with alternate (i.e. FSR) rainfall estimates to look at the sensitivity of the risk assessment (for flood levels around the site) to the decision to adopt the FEH rainfall model.

Application of the models

The site slopes visibly towards the sea and is quite undulating. This is partly natural and partly man-made. The works comprise a mass of buildings, car parks, railway lines, walls, roads, trenches, culverts, fences, service ducts, heaps of building materials, areas of grass and trees, etc. - the ultimate modelling challenge!

It is important to be aware of the fact that the drainage will not cope with the flows without some degree of surcharge and that the flow paths on the surface are fundamental to an accurate analysis of water levels. The linkage between surface and sub-surface flows is essential as is the influence of river levels at the downstream boundary. Inflow constraints into the drainage system need to be investigated.

The site provides flood flow paths along roads between ponding areas and INFOWORKS is able to model this very well. In certain areas of the site there will be large open areas of sheet flow and under these conditions a two dimensional model such as TELEMAC is required. ISIS and/or MIKE-11, which are one dimensional tools generally used for flood plain modelling, are inadequate for this type of application. Complex flow splitting requires the use of a two dimensional model such as TELEMAC or, for more accuracy under extreme conditions, a physical model. Additionally, physical models may be required for any complex structures where flow paths and flow quantities cannot be predicted with sufficient accuracy by 1D or 2D numerical models.

Validating the models

The modelling system which is set up will be highly complicated and it will not be possible to validate the system for the very rare events which the system is required to simulate. Hence there is a very real need to test sections of the modelling system against other methods, such as physical models, and to carry out tests to check the sensitivity of the results to various assumptions.

Technical aspects

We consider that INFOWORKS is superior to MOUSE for surface water modelling due to the iterative convergence technique employed. INFOWORKS is capable of modelling:

- ponding areas using depth storage information.
- drainage pipework.
- the local streams.
- the restriction of gully inflows into the pipes.
- the road network.
- the receiving water levels.

ISIS/MOSS and MIKE-11 routing of floods over flood plains is not adequate for the urban environment. The detailed prediction of water levels is likely to be less accurate than those obtained using INFOWORKS in this environment.

6 Summary of recommended pre-study actions

6.1 SURVEY REQUIREMENTS

A top quality and detailed survey of the site will be required to meet the requirements of this study. The specification for this survey is given in Appendix B.

6.2 SUB-SURFACE DRAINAGE INFRASTRUCTURE AND MODELLING

Previous modelling has been done to design the sub-surface drainage systems. This work needs to be checked and possibly updated. It needs to be presented efficiently to the consultant who carries out the Sellafield Flood Risk Assessment, see Appendix B.

6.3 REVIEW OF RISK FACTORS NOT PREVIOUSLY INVESTIGATED

Section 4.1 drew attention to a number of risk factors that might give rise to a flood threat to Sellafield from the River Calder. These might reasonably be investigated prior to the main study.

6.4 HISTORICAL FLOOD INVESTIGATION

It is recommended in Section 4.4 that systematic searches for historical flood investigation should be carried out. While this could form part of the main study, it requires rather different skills and might reasonably be done as a prior step.

These activities are included in the activity chart presented in Appendix A.

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These are listed in chronological order.

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Appendix A

Specification for Sellafield Flood Risk Appraisal

A.1 INTRODUCTION

All new and existing plants at Sellafield have to be assessed against specific criteria such that the radiological risks from all external hazards are tolerable, and As Low As Reasonably Practicable (ALARP).

External hazards are defined as extreme natural or man-made events originating outside the control of BNFL, and not directly associated with the plant's operation. For natural phenomena, these are typically associated with seismic or climatic factors more extreme than allowed for in the design of conventional industrial installations.

Some external hazards, especially natural events such as earthquakes and winds, are regional and would affect all of the site at the same time. Others, such as flooding are more localised and assessments have to consider the implications of their non-uniformity across the site.

The direct effect of rainfall, local accumulations of water, and rain falling on or around a building or site must be examined against site specific data, taking account of interactions with abnormal tidal effects (both marine and river) as appropriate.

It must be shown that flood water does not cause indirect radiological or chemiotoxic consequence by the damage of key systems, and that radioactive material is protected from rainfall by structures and is out of reach of flood water.

A.2 OBJECTIVE OF THE STUDY

The objective of the study is to demonstrate that "key" buildings on the Sellafield site will not be flooded in a storm event with a 0.01% probability in any year (commonly called the 1 in 10000-year storm). The key buildings will be identified by BNFL prior to commencement of the study. The ground floor may not be the critical level, and other safety functions may be in locations where they are compromised before the ground floor level is reached. The critical levels will be specified by BNFL during the inception phase of the study.

The study will be used to identify shortfalls on the Sellafield site, and seek out improvements to conventional and radiological safety.

A.3 BACKGROUND

Previous studies have been carried out at various times during the development of the Sellafield site, from 1950 onwards. In general they were not comprehensive flood risk studies for the whole site, they were specifically related to planned new developments on the site.

Based on these previous studies, general conclusions can be drawn as follows:

a) the drainage system for the whole of the Sellafield site, as influenced by tides, river flows and local rainfall/run-off, has not been looked at in a comprehensive and detailed way and it is not known how it would perform under exceptionally severe weather conditions. Studies have generally been concerned with proposed new buildings or building complexes and the site drainage works have been extended and developed as the site itself has developed.

b) the River Calder through the site was engineered to protect the site against a catchment event with a probability of 0.01% in any particular year. (Although one study of the River Ehen showed up major differences in computed river flows corresponding to the 0.01% probability level). There has been no consideration of possible sediment deposition in the "oversize" channel through the site during an extreme event. This needs to be checked.

c) the site, at ~15 mAOD, was found to be above any sea level which might have a probability of 0.01% in any particular year.

In the light of the above, the main emphasis for this Sellafield Flood Risk Appraisal should be placed on the site, and its immediate surroundings, and on localised rainfall events. However, careful checks on the possibility of flooding derived from either the sea or the River Calder form part of the study.

A.4 AVAILABLE INFORMATION

A.4.1 Urban drainage models

The individual urban drainage catchments have been modelled using HYDROWORKS, and have been verified for non-surcharge events.

A.4.2 Surface features

Available mapping includes:

- a site map showing the location of buildings, roads, etc..
- an approximate contour map of the site (not of sufficient accuracy for the study).
- a plan showing the location of the urban drainage system.
- Aerial Photographs (1947, 1983, 1998)
- Historical Mapping (1860, 1900)
- Current Ordnance Survey (Landline, 1:50000, Panorama)

Detailed contour mapping of the area is in hand and will be available to the consultant.

A.4.3 Previous flood studies reports

Available reports/information are listed in Section 8 (References/Background information.)

A.5 SCENARIOS FOR FLOOD CONDITIONS AT SELLAFIELD

Flooding as a result of tide/storm surges - probably well below the 0.01% risk level but needs a desk study to confirm.

Flooding from the River Calder – probably below the 0.01% risk level but needs to be demonstrated. Requires a catchment model to simulate river performance and to demonstrate no river derived flooding on site – there may be extensive flooding upstream of the site which needs to be shown as not passing down into site.

Flooding from the site and the local catchment which drains to the site - potentially a high risk which must be investigated thoroughly. The method of approach must take into account the densely developed nature of the site and the definable flow paths between buildings. The hydraulic models need to be dynamic and all influencing factors of significance taken into account. The method of approach will be to use a combination of models for surface and sub-surface flows including an urban drainage model, a 2D numerical model and physical models for local areas where appropriate. GIS will be used for geographical data and will receive and present water level prediction data.

It is important to be aware of the fact that the drainage will not cope with the flows without some degree of surcharge and that the flow paths on the surface are fundamental to an accurate analysis of water levels. The linkage between surface and sub-surface flows is essential as is the influence of river levels at downstream boundaries.

Flooding induced by roof drainage - probably not a high risk but needs to be demonstrated. For the key buildings a check is required to establish whether the roof drainage has been consistently designed to cope with the 0.01% probability event and whether the receiving drains and pipework have sufficient capacity.

A.6 MODELLING REQUIREMENTS

A.6.1 General

Numerical model(s) should meet the following requirements:

- generated in fully supported, validated and quality controlled computer package(s).
- enable future maintenance, and revisions to the site layout to be easily incorporated.

Physical model(s) should meet the following requirements:

- be constructed and tested at an established hydraulics laboratory with appropriate facilities and a proven track record.

All model(s) should be capable of providing the following information:

- depths of flood water at given locations.
- the overland flow paths of flood water.
- velocities of flow at given locations.

A.6.2 Accuracy

The complexity of the Sellafield site should not be underestimated. It is anticipated that highway kerbs, railway lines service trenches, etc. will form flow paths across the site. The degree of accuracy of the model(s) shall be such as to be able to realistically reflect the effects of these features.

The aim should be to determine the best estimate for "worst case" water levels and to use sensitivity testing for possible freak occurrences e.g. blockages etc.. The accuracy requirement is ±50 mm in terms of water levels.

To achieve this level of accuracy will require good quality surveys and extensive and detailed modelling. As a general guide the survey should give ground levels to ±20 mm in critical areas and ±50 mm in less-critical areas. The numerical models are likely to require several hundred nodes each and physical models will need to be professionally made and tested.

A.6.3 Verification

The modelling system which is to be set up will be highly complex and it will not be possible to validate the system for the very rare events which the system is required to simulate. The consultants shall explain in their offer how this difficulty is to be overcome.

A.6.4 Hydrological inputs

The hydrological inputs shall be based on:

- point storm values for considerations of local rainfall at Sellafield.
- area storm values for considerations of the catchment of the River Calder.

Input hydrographs for a range of storm durations for the 0.01% probability in any year event shall be evaluated for the appropriate areas under consideration, based on both FSR and FEH.

A.6.5 Sensitivity testing

Sensitivity testing shall be undertaken to investigate the following:

- input hydrographs based on FEH rainfall as compared with hydrographs based on FSR rainfall.
- a 10% increase in all input flows to simulate effects such as global warming.
- blockage due to movement of debris on site.
- vegetation and sediment movement in the River Calder.
- sensitivity of site drainage to tailwater level in River Calder.

A.7 SCOPE OF SELLAFIELD FLOOD RISK APPRAISAL STUDY

A.7.1 Reviews

The consultant shall review the extreme event data previously determined for the Sellafield site and compare this with data derived by the consultant for FSR and FEH hydrological conditions.

The consultant shall review previous flood studies for the Sellafield site and extract relevant information for the current study.

The consultant shall review current knowledge of global warming and determine implications for the Sellafield site.

The consultant, in collaboration with BNFL, shall review emergency response procedures during/after an extreme event.

A.7.2 Potential flooding from the sea

The consultant shall review previous work on potential marine flooding and shall update the findings in the light of any inadequacies in previous methods and/or new knowledge on the subject. As a result of this work the consultant shall establish whether buildings on the Sellafield site will or will not be flooded during a marine event with a 0.01% probability in any year.

A.7.3 Potential flooding from the River Calder

The consultant shall model the catchment of the River Calder and determine peak flows in the river at the Sellafield site during a catchment area event with a 0.01% probability in any year. The river through the Sellafield site will be modelled in detail to establish peak water levels and hence to determine whether inundation of the site will occur.

Sensitivity testing shall be undertaken to investigate the sensitivity to sea level at the Calder outfall, and to the possible effects of sediment movement in the river and the retarding effect of vegetation.

A.7.4 Potential flooding of the site during an extreme local rainfall event

The consultant shall build a modelling system which is capable of simulating flow conditions at the Sellafield site. This system shall comprise an integrated, dynamic suite of models which may comprise some or all of the following:

- a numerical model to simulate the sub-surface flows.
- one or more numerical models to simulate surface flows.
- physical models to provide data in areas of complex geometry.
- connecting models/algorithms to simulate transfer from surface flows to sub-surface flows and vice versa.

The modelling system shall be capable of simulating flows and levels in relation to:

- buildings.
- drainage pipework.
- flow paths as determined by railway lines, walls, trenches, culverts, fences, service ducts etc..
- gullies (inflows and outflows).
- local streams.
- open areas such as car parks, level or sloping.
- ponding areas.
- receiving steams (water levels).
- road network.
- undeveloped areas with natural vegetation.

The modelling system, comprising linked surface and sub-surface numerical models, is to be built up in a staged way, gradually introducing more features and details until it can be demonstrated that the accuracy requirements given in Section A.6.2 are met.

The consultant shall use the modelling system to determine water levels, flood depths and flow velocities across the Sellafield site for the extreme event with a 0.01% probability in any year, taking into account the following:

- storm durations of 1, 2, 4, 6, 9 and 12 hours.
- FSR and FEH design rainfalls.
- possible increased flows due to global warming or other causes.
- possible changes in flow paths due to potential surface and/or sub-surface blockages.
- sensitivity to assumed concurrent tailwater level in River Calder.

A.7.5 Potential flooding of individual key buildings from direct rainfall

The consultant shall review previous work on potential flooding of individual buildings and shall update the findings in the light of any new knowledge on the subject. A series of spot checks on the capacity of the connections between the roof and sub-surface drainage system shall be made. As a result of this work the consultants shall establish whether individual buildings on the Sellafield site will or will not be flooded during a direct rainfall event with a 0.01% probability in any year.

A.7.6 Work programme and reporting

A suggested work programme is given in Figure A.1.

Reports shall be issued by the consultant as follows:

Number	Report	Copies	Elapsed time (months)
1	Inception Report	2	2
2	Reviews (7.1)	6	15
3	Potential flooding from the sea (7.2)	6	8
4	Potential flooding of individual buildings from direct rainfall (7.5)	6	11
5	Potential flooding from the River Calder (7.3)	6	17
6	Modelling system, design, construction, operation (7.4)	2	20
7	Potential flooding of the site during an local rainfall event (7.4)	6	24
8	Summary Report	24	24

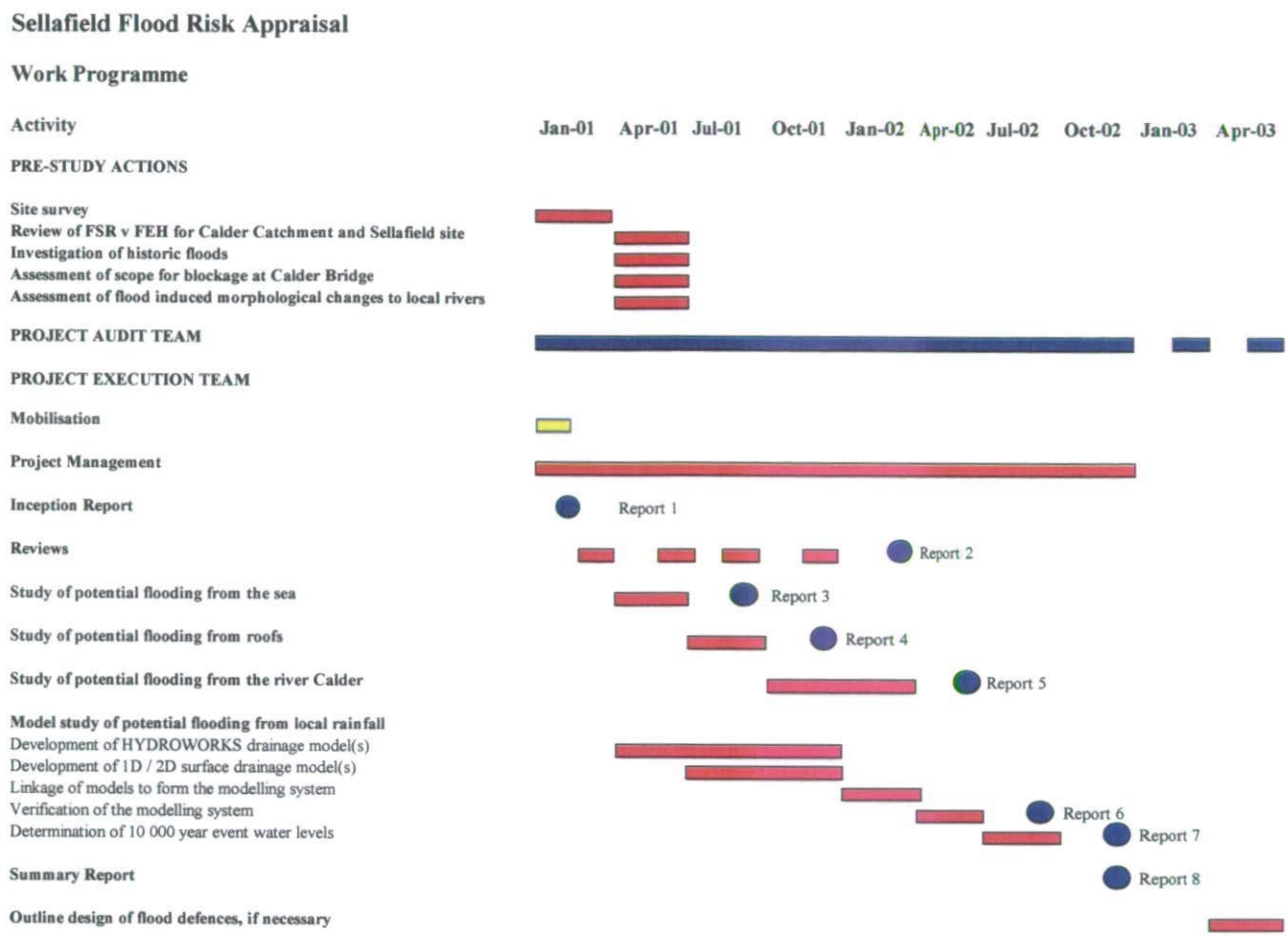

Figure A.1 *Work Programme*

A.8 REFERENCES/BACKGROUND INFORMATION

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Weetwood Services Ltd. (2000). Rainfall event study. Draft final report to BNFL via White Young Green consulting engineers, April 2000.

Appendix B

Recommended pre-study data collection and actions

B.1 SPECIFICATION FOR SITE SURVEY

B.1.1 Introduction

A Flood Risk Appraisal Study is being commissioned by BNFL with the principal objective of establishing whether the sensitive buildings on the Sellafield site have floor levels at least 100 mm above the water levels which will occur during an extreme flood event which has a probability of occurrence of 0.01% in any year.

During such an extreme event there will be extensive surface flooding which will include areas of ponding and areas where surface streams drain across the site. There will also be extensive interaction between surface and sub-surface flows.

The modelling of flood conditions at Sellafield during such an extreme event requires extensive details of the many features of the site which will influence the way the storm flows dissipate. The accuracy requirement of the predictions to be made by the modelling system are high and this means that the input data, in terms of the topography of the site and the details of buildings, roads and other infrastructure, has also to be of high accuracy.

This Appendix gives the specification for the site survey.

B.1.2 Purpose

The purpose of the site survey is to provide information about the topography of the Sellafield site and the infrastructure which has been built at Sellafield to sufficient accuracy for flood modelling.

B.1.3 Accuracy requirements

Ground elevations within 10 m of sensitive buildings	±20 mm
Ground elevations in other paved areas	±50 mm
Ground elevations in unpaved areas	±150 mm
All elevations shall be to a common datum.	
Plan location and dimensions of buildings	±200 mm
Plan location of roads	±200 mm
Plan location of walls, fences and other infrastructure	±200 mm
Widths of defined flow paths e.g. streams, service ducts	±200 mm or 5% of width whichever is less
Dimension of road culverts and other restricted sections	±100 mm or 5% of largest dimension whichever is less

B.1.4 Features to be included

The extent of the survey shall be the whole of the Sellafield site plus any catchment area adjacent to the site which drains directly onto the site. The topography of this area shall be determined to the accuracy specified above.

Within the defined area the following features shall be identified to the accuracies specified above:

- buildings;
- car parks and other open areas;
- culverts and bridges;
- embankments;
- gullies;
- paths;
- paved and unpaved areas;
- railway lines;
- River Calder;
- roads, including kerbs;
- significant vegetation (trees and well established shrubs);
- surface streams;
- walls, fences and other "longitudinal" features of significance.

Temporary buildings and loose materials are not to be surveyed.

B.1.5 Presentation of results

The results are to be presented in electronic and graphical formats.

For direct import into the hydraulic modelling system and presentation of the hydraulic predictions, the data shall be presented in a format to be agreed with BNFL (MapInfo Professional or ArcView GIS electronic formats).

Plans shall be presented at a scale of 1:5,000 for the whole area and 1:1,000 for sections of the area (full coverage required). These plans shall show:

- contours (50 mm in paved areas, 150 mm in unpaved areas);
- the features listed above.

Additional drawings showing details of structures such as culverts and bridges shall be provided at appropriate scales.

B.2 SUB-SURFACE DRAINAGE INFRASTRUCTURE

The sub-surface drainage has been modelled and verified for modest storms. The drainage models and the data on which they are based will be required by the consultant who carries out the Sellafield Flood Risk Assessment.

These data and models should be catalogued and presented in a form such that they can be efficiently handed over to the consultant.

Any doubts about the reliability of the data on which these models are based should be resolved before letting the contract for the Sellafield Flood Risk Assessment study. It may be necessary to check the dimensions of key structures and/or to update the models to take into account any recent changes to the drainage network.

CCTV surveys should be considered to check the structural integrity of the urban drainage system and to identify any sedimentation within the system.

B.3 OTHER PRE-STUDY ACTIONS

In addition to the site survey, the work programme (Figure A.1) identifies four other actions which might be undertaken outside the main study.

Appendix C

Additional documents studied

Institute of Hydrology (1985), Methods of flood estimation.

Ronald Leach & Associates Ltd. (1986), Investigation of flooding and drainage performance for extreme rainfall conditions, Building B14.1, Windscale. Volume 2 Computer printouts of drainage analysis. [Ref. 00010707]

Meteorological Office (1988), A report on extreme values for 1:10000-year return periods at Sellafield.

BNFL (1991), Extreme environmental hazards: Study of the effect of the 1 in 10000-year return period rainfall on the THORP site, TSWP/85/P58 Rev 3.

BNFL (1991), Calder Hall/Chapel Cross Power Stations: Extreme weather hazard assessment, RDNSC (91) Issue 1.

BNFL (1994), The Sellafield site-specific safety case (for proposed PWR Power Station), RDNSC (93) Issue 5.

BNFL (1994), SMP 1: 10000-year flood study – Calculations

BNFL (1996), SDP flood study - Rainfall data.

Hazard assessment for the Sellafield site - west of the River Calder - Flooding.

Appendix D

Copy of proposal for definition study

be

Document title: **Sellafield Flood Study - Proposal**

Department: Civil, Structural and Architectural
Contract title: Sellafield Flood Study
Contract number:

Author(s): Carl Swain,
BNFL Engineering Ltd,

Document ref:
Checked by:
Date of issue: 21 Oct 1999
Issue status: P1
Approved by: Stuart Dagnall

Approver's signature

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1. Introduction

All new and existing plants at Sellafield have to be assessed against specific criteria such that the radiological risks from all external hazards is As Low As Reasonably Practicable (ALARP).

External hazards are defined as extreme natural or man-made events originating outside the control of the operator of a plant and not directly associated with its operation. For natural phenomena, these are typically associated with seismic or climatic factors more extreme than allowed for in the design of conventional industrial installations.

Some external hazards, especially natural events such as earthquakes and winds, are regional and would affect all of a site at the same time. Others, such as flooding are more localised and assessments have to consider the implications of their non-uniformity across a site.

The direct effect of rainfall, local accumulations of water, and rain falling on or around a building or site must be examined against site specific data, taking account of interactions with abnormal tidal effects (both marine and river) as appropriate.

It must be shown that radioactive material is protected from rainfall by structures and is out of reach of flood water, or that facilities exist to contain contaminated run off/ overflows.

2. Project Description

A 1 in 10,000 year flood model is required for the whole of the Sellafield site to support the Continued Operation Safety Review (COSR) programme, and future development.

The model will enable areas of significant flooding to be identified, and the risks to buildings containing a nuclear inventory effect to be assessed.

The 1 in 10,000 return period event will be used as a base, but the model must be capable of assessing an event with a 10% greater intensity, to enable the sensitivity to be investigated.

The project is required to consider the effect of rainfall events on and local to the site, wave/tidal action, and extreme flows in the Rivers Calder and Ehen.

3. Model Requirements

3.1 General

Model(s) should meet the following requirements:

- generated in a fully supported, validated, computer package/s.
- enable future maintenance, and revisions to the site layout to be easily incorporated.

Model(s) should be capable of providing the following information:

- depths of flood water at given locations.
- the overland flow paths of flood water.
- peak velocities of flow at given control sections.

3.2 **Accuracy**

It is anticipated that the highway kerbs, railway lines, and service trenches will form flow paths across the site. The degree of accuracy of the model(s) shall be such as to be able to accurately reflect the effects of these features.

The accuracy/level of confidence of any model will have to be assessed as part of the modelling process.

3.3 **Extreme Events**

- Profiles for 1 in 10,000 year rainfall events have been established for the Sellafield site.
- Extreme wave and tidal action has been assessed for historic projects.
- The 1:10,000 flood for the River Calder catchment was assessed prior to the river being straightened.
- The 1:10,000 flood for the River Ehen has was assessed as part of the Nuclear Generation Study.

As part of the study, these profiles will be need to be confirmed as 'up to date'.

3.4 **Global Warming**

Many existing and future plants, especially those associated with waste retrieval and storage at Sellafield, are likely to operate for many decades. Predictions by the Department of the Environment suggest that small but perceptible changes may occur to the magnitude and probability of some natural phenomena over the next 50 years. The effects of global warming are unlikely to be very significant in safety terms over this sort of period, and no special allowances are generally considered necessary. However, localised rainfall is one area where it is suggested that it would be prudent, on a case by case basis, to assume a (10 per cent) higher 'cliff edge' value as a sensitivity check and show that safety is insensitive to such changes as part of ALARP considerations.

3.5 **Verification**

Consideration and recommendations will need to be made as to whether the models can be verified.

4. Available Information

4.1 **Hydraulic Drainage Models**

The individual urban drainage catchments have been modelled using HYDROWORKS, and verified.

4.2 Surface Features

Site layout information (2D) for the Sellafield site is available showing surface features. Limited level information exists as (2D) spot levels on the site layout. (*The generation of a digital terrain model for flood routing will require additional survey work to be carried out.*)

4.3 Historic Flood Studies Reports

Available reports/information are listed in Section 6 (*References/Background Information*)

5. Proposed Scope

1. Review existing extreme event data, and confirm as 'up to date'
2. Generate digital terrain model for on and off site catchments.
3. Identify low areas susceptible to flooding.
4. Generate hydraulic model for the above ground flow paths. (ie modelling roads, railways etc. as open channels), and combine with existing below ground drainage models.
5. Assessment of the flood from the off-site catchments
6. Routing of the flood across the site
7. Combine flood routing with local site drainage system response.
8. Identification of any areas of flooding
9. Assessment of the effect of such flooding.
10. Review effect on buildings and services.
11. Review Emergency response during/after extreme event.
12. Review adjacent catchments (ie. River Calder and Ehen)
13. Review combined effects (ie. Rainfall and Tide)
14. Review effects of global warming.

6. References/Background Information

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25. J.A. Crowder (1981), Hazard Assessment for the Sellafield Site - West of the River Calder – Flooding
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27. M.J.Tooley, Sea-Level Changes during the last 9000 years in North-West England
28. Halcrow (1989), Flood Appraisal for the River Ehen, Sellafield
29. Hazard Assessments for Calder Works – Flooding CR/CC/RSWP(80)P109

Appendix E

Provisional chronology of floods and storms

22	August	1749	Exceptionally severe cloudburst in north Lake District (NW slopes of Great Dodd Fell).
	November	1771	Carlisle
	February	1822	Carlisle
		1854	ice
	December	1856	Carlisle
28	January	1870	ice
17	January	1872	
7	October	1874	Kendal
	January	1879	ice
17	October	1879	
30	June	1881	
29	January	1883	
11	September	1885	
30	September	1890	
18	September	1892	
		1895	ice
12	**November**	**1897**	
2	**November**	**1898**	
22	**December**	**1900**	
14	December	1902	
8	November	1904	
30	October	1911	
14	January	1912	
13	December	1912	
8	August	1914	
15	September	1918	
4	October	1918	
26-29	December	1924	
	January	**1925**	fluvial-tidal interaction
27	October	1927	Kendal
	January	1929	ice
14	**June**	**1931**	Bootle
3	November	1931	
12	December	1932	
31	January	1933	
29	**July**	**1938**	
	August	1938	
	later	1938	
18	**October**	**1954**	
2	December	1954	
~20	August	1966	
23	**March**	**1968**	
30	**October**	**1977**	**65 mm rainfall in one day at Sellafield**
		1988	Flood study of Skirting Beck, Egremont – was this prompted by a recent event?
30	**August**	**1989**	
3	**August**	**1998**	
5	**November**	**1999**	**Exceptional storm at Whitehaven – see Weetwood Services Ltd. draft final report to BNFL, April 2000**
2	**July**	**2000**	**Isle of Walney**

Sources of information

Cumbria County Record Office – New branch in Whitehaven covers Copeland D.C.

Cumbria County Library – inc. Whitehaven, Egremont and Seascale

Cumberland and Westmorland Antiquarian and Archaeological Society. Cumbrian County Archaeologist based in Kendal.

Cumbrian Newspapers Group

The History of the County of Cumberland by William Hutchinson (1794)

Garret (1818)

British Rainfall (1931) pp75-78

Local newspapers

West Cumberland Times and Star

Cumberland News

Cumberland and Westmorland Herald

Carlisle Journal

Manchester Guardian – historically provided good coverage of news throughout NW England.

Locations of particular interest when searching

Calder Bridge – St Bridget's Church
– bridge
– other structures

Calder Abbey – sited on floodplain ~1 km upstream of Calder Bridge
– founded from Furness Abbey in 1134
– dissolved in 1536

Pelham House – sited ~800 m downstream of Calder Bridge
– formerly a school

Monk's Bridge (grid reference 3064 5103) – ancient packhorse bridge on Upper Calder (10.7 km^2)

Beckermet

Ponsonby