CADAM
Concerted Action on Dambreak Modelling

Final Report

February 1998 - January 2000

M W Morris

Project Coordinator

EC Contract number ENV4-CT97-0555
Environment and Climate Programme

Report SR 571
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Contract

The CADAM Concerted Action was funded by the European Commission (EC) Directorate General for Science, Research and Development (DG XII) under the Hydrological Risks component of the Environment and Climate Programme in the European Union Fourth Framework Programme. The parties to the contract were the European Commission and HR Wallingford and the EC Contract Number was ENV4-CT97-0555. The project Coordinator was Mr M W Morris of HR Wallingford and the EC Scientific Officer was initially Dr R Casale followed by Dr P Balabanis until April 1999 and then Ms K Fabbri until completion in January 2000. The project commenced on 1st February 1998 and finished on 31st January 2000. The HR Wallingford project number for the work was RRS0179.

The CADAM Steering Group consisted of representatives from the project partners:

HR Wallingford	(HR)	UK
Electricité de France	(EDF)	France
Université Catholique de Louvain	(UCL)	Belgium
Universität der Bundeswehr München	(UDBM)	Germany
ENEL	(ENEL)	Italy
Universidade Tecnica de Lisboa	(IST)	Portugal
Universidad de Zaragoza	(UDZ)	Spain
Vattenfall Utveckling AB	(VU)	Sweden

In addition, the Department of Transport and the Regions (DETR) provided further support for the activities of HR Wallingford as project coordinator. The Department representative was Richard Vincent.

Prepared by Mark Morris

Project Coordinator

Approved by P G Samuels

(name)

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(Title)

Date ....

Executive Summary

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The CADAM project ran for a period of 2 years from February 1998 until January 2000 and was funded from the Fourth Framework Programme by the European Commission. Four meetings were held during the project to present and review findings from a programme of test cases against which dambreak models were applied and to establish the state of the art for all aspects of dambreak modelling including flood routing, breach formation, debris and sediments and risk management.

In addition to this report, which provides an overview of the whole project, its findings and recommendations, there is an additional publication entitled "Dambreak Modelling – Guidelines and Best Practice". This offers advice on modelling best practice and complements the recent ICOLD publication on dambreak modelling (ICOLD Bulletin 111). Proceedings from each meeting also offer a summary of test findings, conclusions and recommendations, along with papers on related topics.

Key findings from the Concerted Action have been categorised according to 'end user' interests and are summarised below:

Risk Management & Reduction
A wide range of approaches to risk management are currently being considered and undertaken in different countries. It is unclear at this time what the most practical and effective approach will be, however information management through linking targeted monitoring equipment, warning systems and expert systems is likely to play an increasing and effective role.

Since the technique of risk management for dams and reservoirs is a rapidly developing practice, the free exchange of information on methods and practice should be encouraged to ensure continued development of these techniques. Equally, there are many aspects to impact assessment of dambreak floods that require more detailed investigation and research in order to provide reliable data for use in risk assessments. Whilst some countries require full probabilistic analyses to support risk management, it is widely considered that there is insufficient data to support the selection of appropriate probabilities for such an analysis. Collection of historic records and performance data from dams and reservoirs is required to improve the reliability of probabilistic analyses in the future.

Public communication plays a critical role in ensuring that a community understands the risks posed by a dam in relation to the benefits that it offers. Public response to emergency situations is also better if there is prior knowledge of the risks and procedures involved in the event of an emergency. Many countries and organisations restrict access to the results of dambreak assessments however the limited release of flood inundation plans by some organisations has not yet resulted in an adverse public response.

Dambreak Modelling Procedure

It proved impossible within the scope of CADAM to identify a single best model or type of model appropriate to any or all dambreak flow conditions. A more detailed and in depth analysis of data and model performance is required if this is to be achieved. Having said this, however, a number of issues contributing to best practice and modelling accuracy were identified, and are outlined below.

Modelling tests suggested that the flood wave speed is often poorly predicted. 1D models tended to over estimate wave speed (initial inundation estimate too early) whilst 2D models tended to under estimate wave speed (initial inundation estimate too late). This has obvious implications for the use of modelling results for emergency planning. Mesh size (2D) / section spacing (1D) was also found to significantly alter model results. Spacing should be routinely checked to ensure that further increases in density do not significantly alter model results (i.e. that the topography and hydro-dynamic variations are adequately represented).

It is essential that the needs of the end user are considered when planning the modelling work to ensure that results are presented in an appropriate format and level of detail. The selection of model type (i.e. 1D/2D etc.) should be based upon a combination of the end user needs in relation to the topography, and hence the flow conditions that need to be modelled. 1D models may be used to simulate some 2D-flow conditions, however, this requires considerable skill and experience if a reasonable level of accuracy is to be achieved.

The accuracy of dambreak models should not be compared to normal river models. Flow conditions are far more complex and data to validate the models limited. Accuracy will depend greatly upon assumptions made by the modeller and hence his experience. Only experienced modellers familiar with both dambreak conditions and their software packages should undertake this modelling work. Modellers are encouraged to try and compare different scenarios with different assumptions.

The issue of accuracy remains unresolved. Modellers are reluctant to define accuracy since there are so many unknowns and assumptions in the modelling process. Equally many end users are unclear as to what conditions they should work towards – particularly where legislation does not exist. A true assessment of accuracy will not occur until clear guidance on the required level of accuracy is given.

Executive Summary *continued*

The accuracy of numerical models in predicting *general* hydrodynamic conditions is *relatively* good in comparison to other aspects of a dambreak study. Our ability to model *complex* flow conditions, such as flow in urban areas, is relatively poor. Uncertainties within the breach and sediment modelling processes probably offer the greatest contribution to uncertainty within the whole dambreak analysis process. Our current ability to predict the rate and location of breach growth is limited, with an estimated accuracy of ±50% for predicting peak discharge, and the accuracy of predicting the time of formation being considerably worse. Knowledge of failure mechanisms for concrete and masonry structures is also very poor. Given the limited accuracy of breach models it is recommended that discharge predictions are made using a variety of techniques to provide a range of possible solutions. This should be followed with sensitivity analyses to determine the potential variation in flood water level and wave arrival time for areas of interest.

Currently, there is no single recommended breach model. Whilst the US NWS BREACH model is widely used it has significant limitations. A number of researchers are currently working on the provision of improved breach models. There is a clear need to integrate knowledge from both the hydraulics and soil mechanics disciplines in order to advance expertise in this field.

Predicting breach location is important for bunded reservoirs and flood defence embankments. Our current ability to predict breach location is non-existent with no guidance available other than to monitor or undertake local surveys to identify weaknesses in the structure or sub surface geology. Breach growth mechanisms for river banks appear to differ from those for embankment dams.

Large-scale movement of debris and sediment is likely to occur during a dambreak event leading to large variations in valley topography, particularly near to the dam. This is likely to significantly affect predicted water levels. Consideration of these effects should therefore become a part of dambreak analysis.

Data & Monitoring
It is clear that data collection and monitoring systems play an important role in the developing risk management systems for dam safety, however data on all aspects of dam performance is required to support development of these systems. In this manner, the increasingly sophisticated information management tools should allow the present day dam owner to benefit greatly from past experience.

There are also some areas (such as seepage, piping etc.) where our ability to predict failure mechanisms is very limited. Under such conditions, appropriately designed systems (linked to an information management system) can play a very effective role in the early identification and monitoring of any problems.

Technical Advances
There are many areas in dambreak modelling that would benefit from additional research to improve the accuracy and reliability of predictions. Work is active in a number of these areas including information management, monitoring systems, modelling of debris and sediment movement and breach formation, as well as for improving flood routing techniques.

Executive Summary *continued*

Refining, or even providing, our ability to model sediment movement and breach formation under dambreak conditions is likely to offer the most significant improvement in accuracy for predicting potential flood water levels and time of flooding. Currently it is unclear whether existing morphological modelling techniques are appropriate to simulate movement under dambreak conditions. Work has also shown that high-density sediment flow significantly affects the flood wave propagation speed – adding more uncertainty to the prediction of this key parameter in dambreak modelling. It should be recognised that the modelling of sediment movement under dambreak flow will also allow the prediction of potential pollutant dispersal such as may be found during the failure of a mine tailings dam.

Development of improved numerical methods for flood routing continues, however most of this development work is focussed around 2D models, for which user interfaces are not as well established as for 1D models. As the capacity for handling and processing large amounts of data continues to grow, the limitations of 2D modelling will reduce, however the development of a hybrid 1D/2D model for flood routing may offer the best balance between model types for a practical dambreak modelling tool. In the meantime, for 1D modelling, careful application of modern river modelling software can offer a considerably more flexible and powerful tool, compared to earlier dambreak models, and for comparable accuracy of results.

Real advances have been made in recent years with the handling, processing and presentation of large amounts of data. Information management systems will be key to the longer term development and application of dambreak analysis tools.

Improved tools for end user application (including sediment modelling, breach formation etc.) are unlikely to be available before 2002, and perhaps even later if funding for research work is not forthcoming.

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1. INTRODUCTION

1.1 What is dambreak?

Dambreak may be summarised as the partial or catastrophic failure of a dam leading to the uncontrolled release of water. Such an event can have a major impact on the land and communities downstream of the failed structure. A dambreak may result in a flood wave up to tens of metres deep travelling along a valley at quite high speeds. The impact of such a wave on developed areas can be sufficient to completely destroy infrastructure such as roads, railways and bridges and to demolish buildings. With such destructive force comes an inevitable loss of life if advance warning and evacuation was not possible. Additional features of such extreme flooding include movement of large amounts of sediment (mud) and debris along with the risk of distributing pollutants from any sources such as chemical works or mine workings in the flood risk area.

Failures of dams and water retaining structures continue to occur. Failure of the Malpasset concrete dam in France in 1959 led to 433 casualties and eventually prompted the introduction of dam safety legislation into France. In October 1963, 2000 people died in Italy when a landslide fell into the Vajont reservoir creating a flood wave some 250m high that overtopped the dam and flooded into the downstream valley. In July 1985 about 90% of the 300 people living in Stava near the Stave Dam in Italy also died when this mine tailings dam failed. More recently, in May 1999, a dam failed in Southern Germany causing 4 deaths and over 1 billion Euro of damage. In Spain 1997, failure of a dam on the Guadalquivir river not far from Sevilla caused immense ecological damage from the release of polluted sediments into the river valley. Similarly, in Romania earlier this year failure of a mine tailings dam released lethal quantities of cyanide into the river system so polluting the environment and a major source of drinking water for both Romania and Hungary.

ICOLD has reported that in 1986 there were over 3000 large and major dams in EU countries, approximately 8% of the world total (half the world’s large dams are in China and a further 15% are in the US). Within the EU, Spain has the largest number (over 700) followed by France and Germany (over 500 each) and only Luxembourg and The Netherlands do not have any large dams. The Netherlands, however, has many thousand of kilometres of dikes providing flood defence along the Rhine, Meuse and their tributaries. Hence the risk to the citizens of Europe from the failure of man-made water control structures is distributed across the continent. In many countries the numbers of small dams (below 15 m in height) greatly exceeds the number of large dams. In the UK alone, for example, the number of small dams is approximately 2,500 compared with just over 500 large dams. It is the US experience (Graham, 1998) that about 88% of deaths caused by dam failures during the last 40 years have arisen from the failure of small dams.

The hazard posed by dams, large and small alike, is therefore very real. As public awareness of these potential hazards grows, and tolerance of catastrophic environmental impact and loss of life reduces, managing and minimising the risk from individual structures is becoming an essential requirement rather than a management option. Dambreak modelling forms a fundamental part of this risk management process.

1.2 An overview of dambreak modelling

The first European Law on dambreak was introduced in France in 1968 following the earlier Malpasset Dam failure that was responsible for more than 400 injuries. Since then many countries have also established requirements and in others, dam owners have established unofficial guidelines for assessment. This has led to a variety of techniques and approaches being applied across Europe. The variations in practice cover all aspects of dambreak modelling, including:

- type of code (1D, 2D etc)
- extent of modelling

- scale of modelling
- assumptions for modelling
- detail of sensitivity analysis
- scale of mapping
- type of information output

In addition to flood routing, dambreak modelling also includes assumptions for and modelling of:

- failure mechanisms for the dam (time, extent etc)
- breach formation modelling
- flow interaction with valley infrastructure (bridges, embankments etc)
- flow in urban areas
- movement of sediment and debris

The extreme nature of dambreak floods means that flow conditions will far exceed the magnitude of most natural flood events. Under these conditions flow will behave differently to conditions assumed for normal river flow modelling and areas will be inundated that are not normally considered for flood modelling. Limited case study material means that the accuracy of modelling will depend greatly upon the modelling technique and assumptions, and hence modellers experience. It is therefore essential that well qualified modellers following best practice are employed whenever possible. CADAM aims to assist in this process by defining the current state of the art for modelling and in producing a guidance document for dambreak modelling best practice (Morris & Galland, 2000).

1.3 CADAM aims and objectives

Given the variety of techniques and approaches to dambreak modelling across Europe, the fundamental aim of CADAM was to gather and review knowledge and practice in order to optimise modelling technique and approach. Specific aims and objectives along this path are summarised below:

Aims of the project were to:

- Exchange information on dambreak modelling between participants – particularly to facilitate links between Universities, Research Organisations and Industry.
- Promote the comparison of numerical dambreak models and modelling procedures with analytical, experimental and field data
- Promote the comparison and validation of software packages developed or used by participants
- Define and promote cooperative research

These aims were pursued through a number of objectives:

- To establish the needs of industry
- To link research with industry needs
- To create a database of test cases
- To establish state of the art guidelines and best practice for dambreak modelling (within the technical scope of the Concerted Action)
- To determine future RTD requirements

1.4 The CADAM events

The aims and objectives detailed above were achieved through a undertaking a structured programme of model tests combined with a series of meetings at which model performance was reviewed and, where possible, conclusions drawn. The test programme, including the work undertaken prior to CADAM by the IAHR Working Group, is summarised in Table 1. The aim of this programme was to start with simple test cases for which there were analytical solutions and then to progressively increase the complexity of the tests through the use of flumes, physical models of real valley topography and finally a real dambreak failure itself. In this way the performance of models could be assessed as they dealt with progressively more challenging conditions. By including a real failure test case following a physical model test case it was hoped that a measure of the uncertainties relating to real 'field' effects could be established.

The programme of meetings included:

Meeting 1: Wallingford, UK 2/3rd March 1998 (Expert Meeting)
A review of test cases and modelling work undertaken by the IAHR working group during the previous 6 months. Test cases included idealised dambreak scenarios with physical modelling data provided from flume tests.

Meeting 2: Munich, Germany 8/9th October 1998 (Open Workshop)
A review of modelling breach formation and dambreak sediment conditions. Test cases for breach model comparison included one laboratory model and one large scale field study.

Meeting 3: Milan, Italy 6/7th May 1999 (Expert Meeting)
A review of model performance against physical model data for a real valley with dambreak (Toce River). Additional sessions on breach processes, social / economic impacts and risk management.

Meeting 4: Zaragoza, Spain 18/19th November 1999(Symposium)
A review of model performance against data for a real dambreak event (Malpasset Failure). Additional sessions reviewing current state of breach processes, debris and sediments and risk management.

A summary of progress was also presented to the 1999 IAHR Congress in Graz, Austria.

1.5 Outputs from the Concerted Action

There are a number of outputs from the Concerted Action – the principal outputs being in the form of papers, test data and a best practice guidance document. A summary of all CADAM outputs is given below:

Proceedings
Proceedings from each of the four meetings have been published by the European Commission. Copies may also be downloaded from the project website (see below). The proceedings contain a wide variety of papers covering all aspects of work relating to dambreak analysis.

Project Website
The project website may be found at:

www.hrwallingford.co.uk/projects/CADAM

Best Practice Guidelines
A document summarising best practice for dambreak modelling has been produced. This covers data collection, breach modelling, flood routing and flood mapping and discusses issues such as modelling and mapping accuracy, and the impact of debris and sediment movement. Needs for further research and development are also summarised. An electronic copy may also be downloaded from the project website.

Project Report
This report.

Test Data
Considerable amounts of data were collected during the project. A summary of this data and where it may be obtained from is given below:

The CADAM project evolved from an initial IAHR working group – established by Alain Petitjean of EDF. Prior to the four CADAM meetings there were also 3 workshop meetings during which test cases were defined and model performance compared. The table below provides a summary of both the IAHR and CADAM meetings, the tests considered and references for further information and data. Note that the CADAM project was a Concerted Action project that relied upon the generosity of researchers in providing their time and facilities for research. Much of the project relied upon integrating existing research programmes under a common framework. As such, the availability of some test data for public use is only at the discretion and permission of the original researcher(s).

CD ROM
Note that a CD ROM is also available containing copies of all of the outputs from the CADAM project, including full sets of the test data used. For further information contact the EC Scientific Officer for this project or visit the project website at www.hrwallingford.co.uk/projects/CADAM

1.6 Layout of this report

The body of this final report covers the main conclusions of CADAM as developed by the CADAM Steering Group. The conclusions are identified in bold type in boxes and are presented under the following four themes:

- Dambreak Flood Routing
- Breach Formation
- Debris and Sediments
- Risk Management

Section 6 of this final report presents some challenges to guide further research, development and future practice. Appendix 1 contains a summary of the contractual and administrative arrangements for the CADAM project and Appendix 2 a summary of proceeding contents for each of the four meetings.

Table 1 Summary of data produced by the IAHR and CADAM working groups

Date	*Meeting Location*	*Test No.*	*Test Description*	*Reference*	*Data Source*
Mar 96	Chatou, France		Initial IAHR workgroup meeting to define scope of group and tests	Compte rendu de la 1ère réunion. Report HE-43/96/057/A. Alain Petitjean	Report: EDF
Nov 96	Lisbon, Portugal	1	Channel with vertical sides, variable width, variable bed. Water at rest – no flow. No bed friction.	Proceedings of the 2nd Workshop on Dambreak Simulation. Report HE-43/97/016/B. N Goutal & F Maurel – (EDF)	Report: EDF (Test Data: EDF)
	Test Series 1	2	Steady flow over bump in channel. Flat bed – no friction:		
		a	Sub critical to sub critical	Plus	
		b	Sub critical to super-critical without shock	Overview paper in Wallingford Proceedings.	Proceedings: EC / Website
		c	Sub-critical to super-critical with shock		
		3	Dambreak with a dry bed – horizontal, rectangular channel – no friction.		
		4	Dambreak with a wet bed – horizontal, rectangular channel – no friction.		
		5	Dambreak with a dry bed – horizontal, rectangular channel – with bed friction.		
Jun 97	Brussels, Belgium	1	Dambreak along a L shaped channel (90˚ bend)	Working group on dambreak modelling. 3rd Meeting on 23/24th June 1997 at UCL@ Louvain-la-Neuve / ULB: Châtelet. Plus Meeting Report – June 1997.Belgium. (containing all data plots) Plus Overview paper in Wallingford Proceedings	Report: UCL (Test Data: UCL)
	Test Series 2	2	Local constriction – flat bed, symmetrical channel constriction		
		3	Floodplain: dambreak flow expanding from constrained channel		Proceedings: EC / Website
Mar 98	Wallingford, UK	1	Dambreak along a L shaped channel (45˚ bend)	Wallingford Proceedings	Proceedings: EC / Website
		2	Dambreak flow over a triangular obstruction in channel	Plus Meeting Report – March 1998. Wallingford. (containing all data plots)	(Test Data: UCL)
Oct 98	Munich, Germany	1	Overtopping breach – flume model	Munich Proceedings	Proceedings: EC / Website
		a	Sand d_{50} = 2.0mm		
		b	Sand d_{50} = 1.5mm		
		2	Overtopping breach – Yahekou Dam (Finnish / Chinese joint research project)		(Test Data: UDBM)
May 99	Milan, Italy	1	Toce River model	Milan Proceedings	Proceedings: EC / Website (Test Data: UCL)
Nov 99	Zaragoza, Spain	1	Malpasset Dam failure	Zaragoza Proceedings	Proceedings: EC / Website
		2	Further Toce river model tests		(Test Data: UCL)

2. DAMBREAK FLOOD ROUTING

2.1 Key issues for flood routing

The objective of dambreak flood routing is to simulate the movement of a dambreak flood wave along a valley – or indeed any area 'downstream' that would flood as a result of dam failure. The key information required at any point of interest within this flood zone is generally:

- time of first arrival of flood water
- peak water level – extent of inundation
- time of peak water level
- depth and velocity of flood water (allowing estimation of damage potential)
- duration of flooding

The format in which this data is provided, and the detail for specified locations, will depend upon the end user. For example, emergency planners will require clear maps showing inundation in relation to areas of population and access routes whilst insurance companies will be more concerned with the potential economic impact of flooding. It is important that both the modeller and the end user consider the way in which the dambreak modelling data is to be used before embarking upon any work. Inappropriately presented results may at best be of little value to the end user and at worst cause confusion and cost lives during an emergency.

CONCLUSION 1:
It is essential that the needs of the end user are considered when planning the modelling work to ensure that results are presented in an appropriate format and level of detail.

2.2 Modelling assumptions

Given the rarity of dambreak events, there is little data against which many models can be validated. The nature of dambreak flood conditions differs significantly from natural events in that:

- the rate of increase in flooding will be very quick (i.e. a flash flood wave rather than gradually rising water levels)
- the magnitude and hence extent of flooding will be much larger; areas not liable to flooding and generally considered above the floodplain will be affected (e.g. forests, urban areas)
- the route of flood flow will not be dictated by the river channel or normal flood defences, but more by the overall valley topography
- flood warning times may be minimal or non existent
- structural damage may occur (i.e. bridges, embankments, housing etc. destroyed)
- large quantities of debris and sediment may be moved leading to erosion and deposition

The dambreak modeller must therefore make a number of modelling decisions based purely on judgement. Studies in the US (Graham, 1998) have shown that these assumptions can significantly affect the modelling results produced – and in particular the prediction of the flood wave arrival time.

CONCLUSION 2:
Assumptions made during modelling can significantly affect the results. Only experienced modellers familiar with both dambreak conditions and their software package should undertake modelling work. Modellers are encouraged to try and compare different scenarios with different assumptions.

In addition to the points listed above, there is considerable uncertainty in the modelling of breach formation. This process defines the flood hydrograph leaving the reservoir. Greater errors exist in the prediction of this hydrograph than in the flood routing modelling. This is covered in more detail under Section 3 of this report.

To limit the error introduced by ‘modeller assumptions’ it is recommended that modellers take into consideration the guidance offered by both the recent ICOLD Bulletin 111 (ICOLD, 1999) and the CADAM – Dambreak Modelling – Guidelines and Best Practice report (Morris & Galland, 2000). Modellers are encouraged to try and compare different scenarios with different assumptions.

2.3 Types of flow model

Types of flow model may be classified according to the number of spatial dimensions they simulate (e.g. 1D, 2D, 3D), the equations upon which their predictions are based (e.g. St Venant Equations) and the numerical system applied to solve these equations during the simulation process.

All of the models applied during the CADAM project used various forms of the *St Venant* or *Shallow Water Equations*. These equations are based on the assumption of gradually varying flow conditions with a hydrostatic pressure distribution. Whilst this may be true for normal river modelling, it is certainly questionable for dambreak flow conditions – particularly close to the dam itself. Whilst this issue was highlighted, no practical alternatives were suggested or tested.

The majority of models applied were 2D finite-volume models using the Roe approximate Riemann solver and to a second order of accuracy. Some 1D models, including variations on DAMBRK and a commercial river modelling package (ISIS) were also applied. ISIS and DAMBRK both use a Preissmann implicit scheme to solve flow equations.

Due to the hyperbolic nature of the St Venant equations shock capturing can be undertaken, depending upon the numerical scheme applied. This allows larger discontinuities to be identified – but not details of smaller disturbances (such as surface waves). Shock capturing, or explicit shock fitting both assist in dambreak modelling where such transitions are likely to be commonplace.

A summary of numerical schemes for solution of the shallow water equations may be found in Baines (1998) under the CADAM Wallingford proceedings. Additional information is also given by ICOLD (1998).

2.4 Model performance

Model performance varied between participants even when similar numerical schemes were being applied (Soares & Alcrudo, 1998). This may be attributed to differences in implementation of the numerical scheme, particularly the treatment of non-linearaties, and in modelling assumptions or errors. As the test programme proceeded and more data collated, it became clear that whilst some general conclusions and trends could be identified it was not going to be possible to identify specific features of model performance without a much more detailed investigation (and hence greater time and cost). The number of factors contributing to any one model output was sufficiently large to mask the true source of differences without a more detailed analysis being undertaken. Some general trends in model performance could, however, be identified and these are outlined in the following sections.

2.4.1 1D versus 2D models

The question of whether to use a 1D or a 2D model is often dictated by trends within a particular country. These trends may result, for example, from the preferences of a government organisation undertaking the majority of dambreak studies in a country (e.g. ENEL in Italy or EDF in France) or may result from market forces such as the widespread use of DAMBRK due to its early and easy availability at very low cost.

CONCLUSION 3:
The selection of model type should be based upon a combination of the end user needs in relation to the topography and hence the flow conditions that need to be modelled.

The tests undertaken within CADAM have shown that in many situations a 1D model offers comparable results to those from 2D models (Soares & Alcrudo (1998), Soares & Testa (1999)). This should not, however, be interpreted as an argument for using 1D models for any and all dambreak studies. Tests have also shown that where the flow is clearly two dimensional, such as the spreading of a flood wave across a flat area, then 1D models are (not unsurprisingly) unable to predict accurately local flood levels. A balance must be made between the speed and ease of use of a 1D model against the flow conditions expected and the need for accuracy in given areas.

It can be seen that some 2D effects, such as areas of flow re-circulation, storage, momentum losses around bends etc. may be allowed for within a 1D model. This is achieved by first recognising the likely 2D flow features and by then making an appropriate allowance for this by adjusting the 1D model accordingly. This requires skill and experience to firstly identify the key features and secondly to reliably estimate their magnitude.

CONCLUSION 4:
1D models may be used to simulate some 2D flow conditions, however, this requires considerable skill and experience if a reasonable level of accuracy is to be achieved. Only experienced modellers should undertake dambreak analyses.

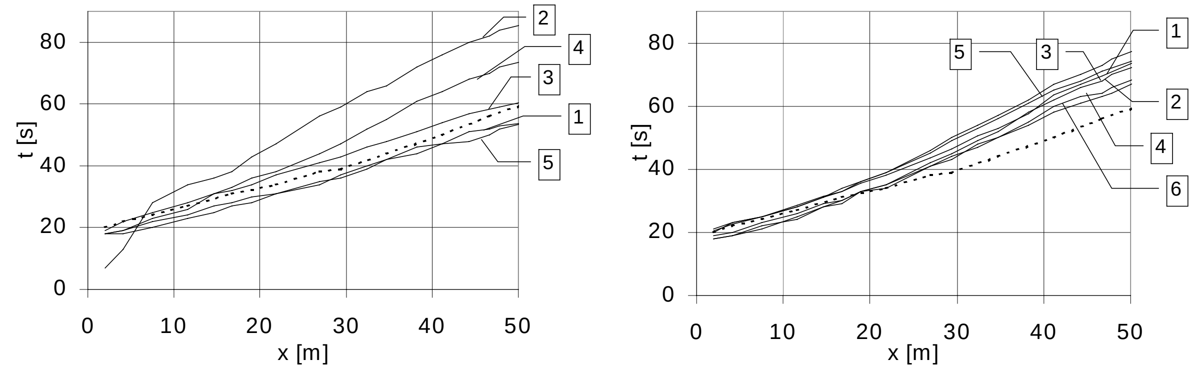
A possible solution to the 1D/2D dilemma may be through the use of a hybrid 1D/2D model. Such a model was presented by EDF (Goutal & Maurel, 1998) and allowed the simulation of flow in quasi 2D at valley junctions, confluences etc and in 1D elsewhere. Further development and validation of this model is required to determine whether it offers significant advantages over the use of traditional 1D or 2D models, however, initial results appeared promising.

CONCLUSION 5:
Development of a hybrid 1D/2D model may offer the best balance between model types for dambreak simulation.

Some of the uncertainties found when modelling dambreak with 1D models, such as identifying 2D flow conditions and using representative cross sections, are no longer an issue when modelling with 2D models. However, implicit with 2D modelling is the need to generate an appropriate grid to represent the topography and the additional processing requirements. Current 2D modelling packages tend not to have ‘user friendly’ interfaces, in comparison to some of the present 1D modelling packages that are ‘Windows’ based systems. As CPU performance continues to increase, user friendly software is developed and GIS systems allow easy handling of large volumes of topographic data it is likely that 2D packages will become increasingly more popular.

2.4.2 Prediction of wave arrival time

A review of results covering tests from initial flume simulations through to the real Malpasset failure (Soares & Alcrudo (1998), Soares & Testa (1999)) has shown a consistent error in our ability to predict the speed of propagation of the flood wave. The cause of this error has not been determined, however, it has been seen that 2D models generally under estimate the speed of the wave. Whilst the results from 1D models were more widely spread, there was a slight tendency, on average, for 1D models to over estimate the speed of the flood wave.



1D models 2D models

······ experimental data
——— modelling results

Figure 1 Front propagation characteristics

Figure 1above shows a comparison of modelled wave speed against physical model data for 1D (left) and 2D (right) models. In this particular case the 2D models are clearly under estimating wave speed whilst the 1D models are spread across the true value. Other tests suggested 1D models tended to over predict wave speed whilst 2D models consistently under predicted wave speed.

CONCLUSION 6:
Modelling test results suggest that:
1D models over estimate wave speed → initial inundation estimate too early
2D models under estimate wave speed → initial inundation estimate too late
This has obvious implications for the use of modelling results for emergency planning.

2.4.3 Mesh Size

It became clear during some of the model tests that modellers had made differing assumptions with regards to their model mesh size (2D) or section spacing (1D). As a matter of routine practice, the mesh size / section spacing should be reviewed to ensure that an acceptable density has been achieved to simulate the topography. Failure to achieve this will significantly affect the accuracy of model results.

CONCLUSION 7:
Mesh size (2D) / section spacing (1D) should be routinely checked to ensure that further increases in density do not significantly alter model results (i.e. that the topography and hydro-dynamic variations are adequately represented).

2.5 Model accuracy

The accuracy of dambreak modelling results should not be confused or compared with normal river modelling results. Flow conditions are far more complex and data against which models may be calibrated very limited or absent. The modeller is required to make a number of assumptions during the analysis (see Section 2.2 and Best Practice Guidelines (Morris & Galland, 2000)) which will contribute to modelling uncertainty.

CONCLUSION 8:
The accuracy of dambreak models should not be compared to normal river models. Flow conditions are far more complex and data to validate the models limited. Accuracy will depend greatly upon assumptions made by the modeller and hence his experience.

In comparison to other aspects of dambreak modelling, such as, for example, breach formation and debris and sediment effects, the accuracy of numerical models in predicting *general* hydrodynamic conditions is *relatively* good. Test results reported at the first CADAM meeting for flow along a flume and around a 45° bend (Soares & Alcrudo (1998)), suggested that all of the models predicted water depths within 20% of the observed levels. In contrast, however, our knowledge of flow interaction with valley infrastructure (bridges, constrictions, embankments, urban areas etc) is limited and hence modelling accuracy likely to be considerably lower.

CONCLUSION 9:
The accuracy of numerical models in predicting *general* hydrodynamic conditions is *relatively* good in comparison to other aspects of a dambreak study. Our ability to model *complex* flow conditions (such as flow in urban areas) is relatively poor.

To the ultimate question of how accurate are the modelling results it is not yet possible to offer a definitive answer. Final dambreak modelling results are based on many different components, each of which has a differing level of accuracy related in turn to a combination of numerical modelling accuracy, data accuracy and accuracy / validity of modelling assumptions made.

From an ‘end user’ perspective, modelling accuracy may be measured in terms of absolute error in the predicted water level, maximum discharge, wave arrival time etc. Under these circumstances it is likely that the predicted level will be more ‘accurate’ for a large open area (floodplain) than for a small constrained area (valley) since a simple volume balance demonstrates that a small increase in floodplain level would require a very large increase in flood water volume. This is not to say that the percentage error is any different, but simply that the absolute error in water level is likely to be smaller.

As an attempt to indicate a potential target order of accuracy (relative to, say, river modelling) it is suggested that the prediction of *general* flood level accuracy for floodplains might be in the range of ±0.5 to 1.0m and flood wave propagation within ±25% (Morris & Galland, 2000). This is indicative only and cannot be demonstrated definitively. Site specific modelling will lead to local variations that could be significantly greater.

CONCLUSION 10:
The issue of accuracy is caught in a loop. Modellers are reluctant to define accuracy since there are so many unknowns and assumptions in the modelling process. Equally many end users are unclear as to what conditions they should work towards – particularly where legislation does not exist. A true assessment of accuracy will not occur until clear guidance on the required level of accuracy is given.

2.6 Choosing a preferred model

One goal of CADAM was to try and identify whether there were clear advantages (in terms of modelling accuracy) offered by any particular model. It has become clear, however, that this is not obviously the case and that a more detailed analysis is required if we are to determine if there are clear advantages and disadvantages with any particular numerical method.

Within CADAM three types of model were applied: finite volume (most modellers), finite difference (Preissmann schemes, Mc Cormack) and finite elements. Whilst no conclusions could be drawn as regards the performances of finite volume versus finite element models, it was observed that standard finite difference methods were not the best choice as weaknesses appeared in the treatment of discontinuities and dry bed initial conditions. However, the latest research on classical finite difference schemes such as the Preissmann Box Scheme used by DAMBRK and ISIS indicates that some of these deficiencies can be overcome relatively easily.

For the finite volume schemes different “flux functions” were tried (Roe, Boltzmann, PFP etc.) but no significant differences were noted. It was noted, however, that the method of implementation of the source terms (friction, topography etc.) could make a noticeable difference. A preferred model should thus feature:

- shock capturing ability
- accurate wave propagation velocity
- adequate treatment of source terms
- conservation of mass (no loss of water in the modelling process)

The level of assessment permitted by CADAM allowed for a comparison by overview of final results – from which it proved difficult to determine consistent behaviour trends. A more detailed level of assessment on test data is required to investigate model performance for each of the wide variety of conditions that the dambreak model must cope with. In summary, therefore, it is not currently possible to recommend a single ‘best’ type of model for dambreak analysis.

CONCLUSION 11:

It proved impossible within the scope of CADAM to identify a single best model or type of model appropriate to any or all dambreak flow conditions. A more detailed and in depth analysis of data and model performance is required if this is to be achieved.

Of great significance, however, is the need to use an appropriate model for the flow conditions (i.e. 2D model for true 2D flow) and for the modelling to be undertaken by experienced dambreak modellers.

3. BREACH FORMATION

Breach formation may be considered as the development of a breach through any water retaining structure, whether it be composed on concrete or earth. Our current ability to predict all aspects of this process is quite limited. This was confirmed during test case modelling within CADAM when modelling results demonstrated a wide scatter of values. These limitations are significant since the breaching process defines the rate at which water is released and hence the degree of potential downstream flooding. It has been suggested that these uncertainties within breach modelling contribute the greatest uncertainty to the whole dambreak analysis process (Wahl, 1998).

CONCLUSION 12:
Uncertainties within the breach modelling process may be the greatest contribution to uncertainty within the whole dambreak analysis process.

It should also be recognised that the effects of variations in the breach formation process are greatest near to the dam. The attenuation of flood flow as it travels away from the dam will tend to reduce the magnitude of potential variations in flood conditions. Where flood conditions near to the dam are of interest, then the breach characteristics will be crucial.

3.1 Key issues for breach formation

The breaching process may be divided broadly into three components:

- breach location
- time / rate of development of the breach (related to removal of material from the breach)
- prediction of flow through the breach

Of these three components our ability to predict the flow through a given hole is the most reliable. Our ability to predict the rate of growth and location of breach is quite limited. Identifying breach location is not usually important for dams in valleys, however, it can be very important when considering bunded reservoirs or long lengths of protective flood embankments.

CONCLUSION 13:
Our current ability to predict the rate and location of breach growth is quite limited.

3.2 Modelling structure failure mechanisms

There is currently no set methodology for modelling the growth of a breach through a concrete or masonry structure. In broad terms the failure will be quick relative to the formation of a breach through an embankment dam. A typical approach is to assume a failure time and breach dimensions based on the structure design (i.e. failure of specific units of the dam structure). For many, the failure time will be taken as ‘instantaneous’ with the potential breach size varying greatly and often depending upon the site-specific design.

This uncertainty may only be addressed by undertaking a sensitivity analysis of the flood routing model to different failure scenarios to determine the potential variation in downstream flood levels resulting from various assumed failure modes.

CONCLUSION 14:
Knowledge of failure mechanisms for concrete and masonry structures is very limited. The only practical solution to this uncertainty is to undertake a sensitivity analysis of flooding downstream in relation to various failure scenarios.

3.3 Modelling breach growth through embankments

3.3.1 Breach process modelling

The modelling of breach formation through embankments can be undertaken using process based models, although the limited accuracy of these models should be recognised. Most breach models are based on steady state sediment equations related to homogeneous banks, adopting predefined growth mechanisms. The modeller must therefore make a significant number of assumptions in order to model the breach, all of which can greatly affect the predicted results (Graham, 1998).

Various members of the CADAM project have undertaken research and development of breach models. Useful summaries of this work are offered by Wahl (1998), Broich (1998a), Lecoint (1998) and Mohamed et al (2000).

Two breach test cases were considered during the CADAM project; one based on laboratory modelling and the other larger scale field work.

3.3.2 Modelling accuracy

Two breach test cases were considered during the CADAM project; one based on laboratory modelling and the other larger scale field work. The wide range of modelling results presented confirmed the view that model accuracy was limited both in terms of predicting peak discharge and particularly the time of failure (rate of growth). Figure 2 below shows a typical example of the wide scatter in modelling results.

For these relatively simple test cases it is estimated that the accuracy of predicting the peak discharge is perhaps ±50%, and the accuracy of predicting the time of formation considerably worse (Broich, 1998b). It should be noted that there are two aspects to breach formation time. Firstly the breach initiation time, which may be described as the time taken from initial seepage or overtopping to the point where significant flow occurs, and secondly breach formation time which encompasses the relatively dynamic growth of the breach through the embankment. Breach initiation time may vary from minutes to days and is by far the most difficult parameter to predict.

CONCLUSION 15:
Breach model accuracy is very limited. An estimate of ±50% for predicting peak discharge is suggested, with the accuracy of predicting the time of formation considerably being worse.

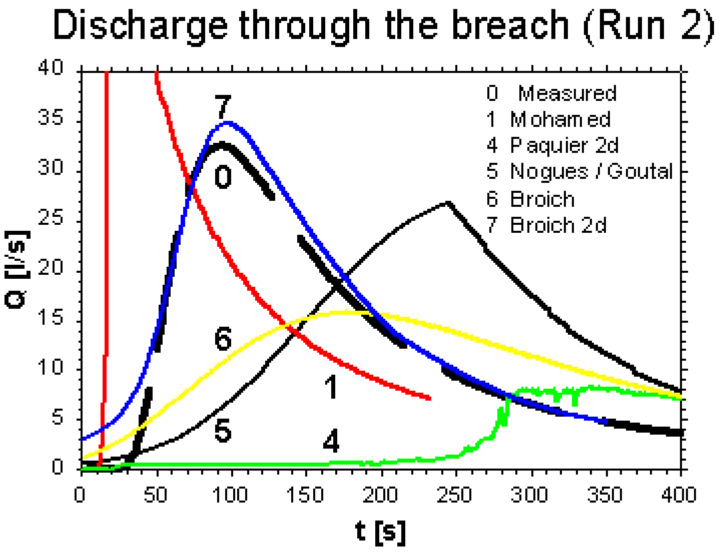


Figure 2 Typically wide range of scatter for breach modelling results

A number of points were observed from the test case results:

- Modelling of sediment erosion (hence rate of breach growth) was poor. For the laboratory test case, this rate was consistently over predicted leading to predicted hydrographs greater than observed. Further research into sediment transport under rapidly varying flow conditions is required.
- Models are very sensitive to the chosen modelling parameters
- There is difficulty in accurately recording data on small scale physical models. Physical modelling for the validation of numerical models should be undertaken at the largest scale possible.

CONCLUSION 16:
Given the limited accuracy of breach models it is recommended that discharge predictions are made using a variety of techniques to provide a range of possible solutions. This should be followed with sensitivity analyses to determine the potential variation in flood water level and wave arrival time for areas of interest.

3.3.3 Choice of a preferred model

Table 2 offers a summary of the most recently developed breach models. Most of these models have not been widely used, but rather developed by universities or end user organisations for their own use. One exception is the NWS BREACH model that is used widely around the world. The widespread use of this model is due to its easy availability since the mid 1980s at very low cost. The model simulates breach growth through a homogeneous non-cohesive bank. Soil properties may be averaged to simulate layered materials. As with the other models, however, its accuracy is limited. The model has only been calibrated on a very limited number of test cases and a number of researchers have reported spurious behaviour and results under certain test conditions (Morris, 2000).

Table 2 Summary of the most recently developed breach models

Model	Author	Breach Morphology	Flow Over The Dam	Sediment Transport	Geo-Mechanics Of The Breach Side Slope
Cristofano	Cristofano (1965)	Trapezoidal with constant bottom width.	Broad crested weir formula.	Cristofano’s empirical formula.	None.
Harris-Wagner (HW)	Harris-Wagner (HW) (1967)	Parabolic with top width equals 3.75 depth.	Broad crested weir formula.	Schoklitsch formula.	None.
BRDAM	Brown & Rogers (1977/ 1981)	Parabolic with 45^o side slopes.	Broad crested weir formula.	Schoklitsch formula.	Failure of the top wedge above pipe.
Ponce – Tsivoglou (PT)	Ponce – Tsivoglou (PT) (1981)	Top width flow rate relation.	Full St. Venant equations.	Exner equation with Mayer-Peter –Muller.	None.
Lou	Lou. (1981)	Most effective stable section (Cosine curve shape)	Full St. Venant equations.	1. Cristofano’s empirical formula. 2. Duboy and Einstein formulae. 3. Lou’s formula.	None.
Nogueira	Nogueira (1984)	Effective shear stress section (Cosine curve shape)	Full St. Venant equations.	Exner equation with Meyer-Peter / Müller	None.
BREACH	Fread (1988)	Rectangular and trapezoidal.	Broad crested weir formula for over topping and orifice for piping.	Meyer-Peter / Müller modified by smart.	1. Breach side slope stability. 2. Top wedge failure during piping or overtopping.

Table 2 Summary of the most recently developed breach models (continued)

Model	Author	Breach Morphology	Flow Over The Dam	Sediment Transport	Geo-Mechanics Of The Breach Side Slope
BEED.	Singh et al (1986 / 1988)	Trapezoidal.	Broad crested weir formula.	Einstein-Brown.	Breach side slope stability.
Sites	NRCS (US) (1998)	3 stages failure: 1. Cover failure. 2. Headcut formation. 3. Headcut erosion.	Principles of hydrology and hydraulics to produce spillway flow-stage curve.	For stage 1 and 2 a detachment model was used. For stage 3 an energy dissipation equation was used.	Spillway exit channel stability.
NCP-BREACH	Coleman et al (1998)	Parabolic	Empirical formula.	Empirical formula.	None.
EDBREACH	Loukola & Huokuna (1998)	Trapezoidal	Broad crested weir formula.	Meyer-Peter / Müller	Top wedge failure during piping.
BRES	Visser (1998)	5 stages failure	Broad crested weir formula.	Four sediment formulae can be used: 1. Bagnold – Visser. 2. Engelund – Hanssen. 3. Van Rijn. 4. Wilson.	None.
DEICH_N2	Broich (1998)	From solution of 2D Exner equation	2D full St Venant equation	Nine different formulae or combinations: 1 Meyer-Peter / Müller (bed load) 2 Engelund / Hansen (suspended load) 3 Bagnold (total load) 4 Smart (bed load) 5 Smart / Bagnold (combined total)	None

Table 2 Summary of the most recently developed breach models (continued)

Model	Author	Breach Morphology	Flow Over The Dam	Sediment Transport	Geo-Mechanics Of The Breach Side Slope
				6 Zanke / Bagnold (combined total) 7 MPM / Bagnold (combined total) 8 Engelund / Hansen (bed load) 9 Smart / Bagnold (combined total for non uniform material)	
HR BREACH	Mohamed (2000)	Slope instability and with continuous erosion	Broad crested weir formula	Yang’s formula (non cohesive sediment)	Detailed methods for slope instability.

More recent work by BROICH, COLEMAN, HUOKUNA and MOHAMED all point towards more complex models for breach prediction, although these models are not yet available commercially. Further details of these models may be found at:

BROICH (Germany)	Add web address / paper reference Email: b61bro@B6AXS1.BauV.UniBw-Muenchen.de
COLEMAN (New Zealand)	ANDREWS et al (1999) Email: s.coleman@auckland.ac.nz
HUOKUNA (Finland)	Add web address / paper reference Email: Mikko.Huokuna@vyh.fi
MOHAMED (UK)	Mohamed et al (1999) Web: www.hrwallingford.co.uk/projects/cadam Email: mam@hrwallingford.co.uk / m.morris@hrwallingford.co.uk

The number of models available that allow an estimate of piping failure are limited and include the NWS BREACH model and models under development by Huokuna and Mohamed (see above) and a model developed jointly by CEMAGREF and EDF for application in France (Paquier et al, 1998).

CONCLUSION 17:
Currently, there is no single recommended breach model. Whilst the NWS BREACH model is widely used it has significant limitations. A number of researchers are currently working on the provision of improved breach models. There is a clear need to integrate knowledge from both the hydraulics and soil mechanics disciplines in order to advance expertise in this field.

3.3.4 Breach location

For many dambreak analyses the identification of probable breach location has little impact on the results. Where the reservoir is created on flat ground by a circular embankment (bunded reservoir) or the issue relates to the failure of flood defence embankments, then the breach location can directly affect the areas liable to flooding. There is a recognised need to be able to identify probable breach locations in order to optimise embankment maintenance and repair operations however our current ability to predict breach location is very limited.

CONCLUSION 18:
Predicting breach location is important for bunded reservoirs and flood defence embankments. Our current ability to predict breach location is non existent with no guidance available other than to monitor or undertake local surveys to identify weaknesses in the structure or sub surface geology.

Initial studies undertaken by Lecoint (1998) show that breach formation processes for river flood embankments differ from breach formation processes through dam embankments. This is due to the difference in flow direction and supply of water. For a reservoir, the water supply is finite whereas for a river the water supply may be maintained at high levels for considerable periods of time. Equally, a river water level may rise and fall quite rapidly. Further research is required to establish true growth mechanisms for river flood embankments.

CONCLUSION 19:
Breach growth mechanisms for river banks appear to differ from those for embankment dams.

4. DEBRIS AND SEDIMENTS

It has been recognised that there is significant movement of debris and sediment during dambreak events. Movement of large amounts of material can both lower and raise valley bed levels and consequently can have a major effect of flood water levels. Predicting possible movements is therefore important if we are to improve the reliability of flood prediction.

4.1 Evidence of movement

Work by Graham (1998b) reviewing historical failures of dams in the US clearly notes the large-scale movement of sediment and debris during dambreak events. The material moved resulted in valley floor changes in the order of metres and tens of metres, particularly in valley regions close to the dam (first 5km downstream). Associated features included:

- debris build up leading to secondary dams, secondary failure and hence secondary flood waves
- debris build up at one bridge was recorded to a depth of 15m
- deposition of eroded dam embankment material
- significant movement of houses and trees
- triggering of local landslides along the valley as bed material is removed
- creation of alluvial fans where dambreak flow spreads across a floodplain, into a larger valley or into the sea

CONCLUSION 20:
Large scale movement of debris and sediment is likely to occur during a dambreak event leading to large variations in valley topography, particularly near to the dam.

4.2 Current modelling practice and knowledge

Currently the routine assessment of sediment and debris movement is not generally undertaken as part of dambreak modelling, however with clear evidence that large-scale movement is likely to take place, there is a strong argument to suggest that it should be investigated as part of any analysis.

CONCLUSION 21:
Large scale movement of sediment and debris is likely to significantly affect predicted water levels. Consideration of these effects should therefore become a part of dambreak analysis.

The probable reason for past studies not including consideration of such effects was our limited ability to model sediment movement in transient flow conditions. In recent years morphological river modelling has become more common. There is a difference, however, between the modelling of long term ‘steady state’ sediment movement as compared to dambreak conditions where movement is ‘short term’ under extreme and rapidly varying flow conditions. Research is required to determine whether morphological river models may be reliably applied to dambreak conditions.

CONCLUSION 22:
Research is required to determine whether existing or modified morphological river models are appropriate to simulate movement of sediments under dambreak conditions.

Where debris and sediment issues are currently considered during a dambreak study it is most likely that the analysis is based on judgement rather than detailed modelling.

There are already a number of research initiatives underway investigating debris flow and sediment movement. Research by Capart et al (1998a, 1998b) and Capart (2000) directly considers the processes of sediment movement under rapidly varying flow conditions. Initial investigations confirmed the field observations by Graham that valley floor levels may vary by metres – or even tens of metres. Additionally, it was found that the density of sediment and debris within the flow significantly affected the speed of wave propagation from the dambreak. This adds a further measure of uncertainty to the already ‘poor’ prediction of flood wave propagation.

CONCLUSION 23:
Research suggests that high-density debris and sediment flow significantly affects the flood wave propagation speed.

In recent years there have been a number of tailing dam failures across Europe that have released heavy metal pollutants into the environment. In such an event, there is a clear need to determine the extent to which these pollutants may be dispersed. The risk of failure and potential dispersal of pollutants may be addressed through a combination of breach and sediment movement modelling.

CONCLUSION 24:
Improved breach and morphological models would assist is determining the risk posed from the potential failure of tailing dams containing heavy metal pollutants.

Advances in other areas of natural hazards may contribute to knowledge in sediment movement by dambreak events, including:

- Debris flow
- Avalanches
- Pyroclastic flows
- Mudflows
- Lehars

All of these phenomena involve fluid – solid interactions and high speed flows.

CONCLUSION 25:
Research in other natural hazard areas involving fluid – solid interfaces with high speed flow may help to understand sediment movement processes under dambreak conditions.

5. RISK MANAGEMENT

Risk management for dams, reservoirs and their downstream valleys is a rapidly developing practice for which different approaches and different levels of detail are being practised in different countries. There is considerable value of undertaking risk management for dams and reservoirs in that it allows:

- flood risk to the valley (and population) to be determined and appropriate emergency plans to be developed. An 'open' risk management approach will allow for clear and rapid warning systems to be established.
- planning and development to be considered in light of the potential flood risk
- utility companies to appreciate potential risks to their systems
- the affected population to better appreciate the role and risks posed by a reservoir
- simulation of emergency situations
- the reservoir owner to determine potential liability
- the reservoir owner to optimise both internal and external responses to incidents
- the reservoir owner to optimise operation and maintenance of the reservoir
- (potentially) insurance companies to determine risk of damage

Since risk management techniques are still being researched and developed there are a wide range of approaches being considered and legal requirements, if any, are still limited. Once the full potential of risk management has been realised it is likely that data requirements of the management systems will drive research and development of more reliable and consistent dambreak modelling practice. Close attention should be paid during the next 5 years to developing practise in this area with the aim of ensuring a wide exchange of information and practise to ensure consistent and workable practices are developed across Europe.

CONCLUSION 26:
Risk management of dams and reservoirs offers many advantages and is a rapidly developing practise around the world. The free exchange of information on methods and practice should be encouraged to ensure continued development of these techniques.

5.1 Current risk management practice

Risk management has always been practised. In its simplest form it comprises decision making based on whatever knowledge or skills may be possessed. Recent advances in computers mean that now it is possible to quickly access a range of information that may include:

- real time performance of a dam / reservoir including rainfall, flow etc.
- monitoring data
- dambreak modelling data for various scenarios – inundation plans etc.
- GIS systems including information on inundation, land use, centres of population, valley infrastructure etc.
- simulation / expert systems for guidance on what if scenarios
- historical data on flooding, dam incidents, dam maintenance

It is becoming widely recognised that efficient monitoring and warning systems are vital for the effective identification and management of key risks. For example, where knowledge of failure mechanisms is limited, such as with piping through an embankment, it is practical to be able to identify any abnormal leakage as soon as possible, to monitor trends and to be able to quantify the potential risk such that emergency procedures may be activated at appropriate times. This requires specific and targeted monitoring equipment, reliable information systems and clear and effective training for both dam operatives and emergency services. This also requires clear dissemination of appropriate information to the public to ensure an efficient response during an event.

The level to which information is being collected and analysed varies from country to country and between individual companies. One of the most detailed studies is being undertaken in Portugal, funded by NATO (Almeida & Viseu, 1997, Almeida, 1999) and an alternative less detailed approach in the UK (Morris, 2000). These are just two examples of many. ICOLD has also established a working group to investigate risk management and databases. This is currently co-ordinated by Jean-Jacques Fry of EDF.

CONCLUSION 27:
A wide range of approaches to risk management are currently being considered / undertaken. It is unclear at this time what the most practical and effective approach will be however information management through linking targeted monitoring equipment, warning systems and expert systems is likely to play an increasing and effective role.

5.2 Issues to be addressed

Common to many of the risk management approaches are the following issues:

Warning Systems

There are many aspects contributing to an effective warning system. These include targeted monitoring equipment (as opposed to equipment installed during dam construction), information support systems and clear emergency response plans. The latter requires training, appropriate communication with relevant external authorities and dissemination of public information. Public response during an event is a key factor in the effectiveness of any emergency plan (see below). The development of a fully integrated system is a complex process but one that can benefit significantly from recent advances in computing for information management. Development and application of such systems would provide a valuable tool to assist in the risk management of dams.

Determining Impact / Vulnerability

In any risk management system it is necessary to determine the potential impact of different scenarios. Determining the impact of catastrophic flooding is a subjective process since there is little direct guidance available on many of the key issues. These issues include:

Societal Response to Flooding and Flood Warning (Risk Perception)

It has been recognised that the response of a population during an emergency depends upon a number of factors including their perception of the threat (proximity to dam), and prior knowledge of the emergency warning system.

Vulnerability of Society to Flood Impact and Estimation of Potential Loss of Life

The vulnerability of society to flood impact depends upon their age, location, education etc. The estimation of potential loss of life depends upon a range of factors but most importantly location with respect to the dam and period of warning time given prior to flood impact. If a reliable estimate of potential loss of life can be calculated, what is an acceptable risk to life?

Flood Impact on Structures and Infrastructure

When trying to determine the impact and / or economic impact of flooding it is necessary to determine the degree of damage that may be caused by the flood flow. This in turn requires an understanding of loading and local scour conditions under which structures are likely to fail (i.e. under what flow conditions would a house collapse?) Work by De Lotto (1999) has started in analyse these conditions within Italy but it should be recognised that construction techniques and typical buildings vary widely across Europe. Consequently, damage curves will be required for each country / area.

Environmental Impact of Flooding

Methods for determining impact on the environment from flooding are limited. Morris (2000) suggests a numerical approach that allows relative ranking of impact from multiple sites. Reliable techniques for the assessment of financial impact are not yet developed.

CONCLUSION 28:

There are many aspects to impact assessment of dambreak floods that require more detailed investigation and research to provide reliable data for use in risk assessments.

Probabilistic or Not?

The question of whether to adopt a probabilistic approach for risk management is a common one. Current experience suggests that whilst it may be appropriate for some aspects of dam risk assessment there is insufficient data to support full probabilistic assessment of the whole dam / reservoir system. Mechanical and electrical systems are perhaps the most appropriate components of a dam for probabilistic risk assessment. If more reliable probabilistic assessments are to be undertaken then it will be necessary to collate historic information on dam and reservoir operation against which probabilities of ‘component’ behaviour may be calibrated. Current database records are limited and insufficient to support full probabilistic analyses.

CONCLUSION 29:

Whilst some countries are persisting with full probabilistic analyses to support risk management, it is widely considered that there is insufficient data to support the selection of appropriate probabilities for such an analysis. Collection of historic records and performance data from dams and reservoirs is required to improve the reliability of probabilistic analyses in the future.

Public Domain

Many dam owners have undertaken dambreak analyses to varying degrees of detail. Some owners have also established emergency plans. In many countries this information is not in the public domain and is often treated as highly confidential. In some situations this is due to a perceived security threat with dams and bridges being identified as important military targets. A common argument for restricting this information, however, is that release of the information will lead to significant public concern and a potential impact on property values. There is typically fear at how the public might respond to discovering that they are within a flood risk area. It is clear from social studies, however, that an awareness of flood risk and emergency procedures prior to an event can significantly improve the response to a flood warning. As such, restricting such information may be at the cost of public safety and thus be negligence by the dam owner.

As pressure grows in many countries for public access to all types of information there is likely to be continued pressure for the results of dambreak analyses to be placed in the public domain. In recent years the Environment Agency in the UK has published inundation plans for main rivers showing estimated 100-year flood levels. Prior to release of this information there was great concern over possible public response and impact on house prices. In practice there was no adverse response to the release of this information.

CONCLUSION 30:

Many countries / organisations restrict access to the results of dambreak assessments. Public response to emergency situations is better if there is prior knowledge of the risks and procedures involved. The limited release of flood inundation plans has not yet resulted in adverse public response.

Insurance Industry

The insurance industry recognises the potential risks involved in a dambreak, however it is unclear how the industry may deal with a major dam failure. Estimates by Stenudd (1999) suggest that a major dam failure in Sweden might cost as much as 6,000MEuro. Such a massive cost cannot be borne by insurance companies, or reinsurance companies. In the event of such a failure it is unclear who (if anyone) would reimburse the damages.

Fuelling the tendency to restrict access to dambreak analysis results, there is also a fear that if inundation plans are placed in the public domain that residents within the inundation areas would find it difficult to buy house insurance, or that premiums had risen. Whilst it can be argued logically that residents should pay insurance based on their location, the transition to this situation could cause significant concern.

CONCLUSION 31:

The cost of impacts from a major dam failure could be so large that no insurance or reinsurance company could cope with the event. Under these conditions it is unclear who or how the damages might be compensated for.

6. CHALLENGES FOR RESEARCH, DEVELOPMENT AND FUTURE PRACTICE

Two of the aims and objectives of CADAM was to establish the needs of industry and identify areas for future research and development. The preceding chapters have summarised the work undertaken by CADAM and highlighted many areas where further development is required. These areas are summarised under the following headings:

- Breach formation
- Debris and sediments
- Flow modelling
- Database
- Risk / Information management

6.1 Breach formation

There is considerable uncertainty related to the modelling of breach formation processes and consequently the accuracy of current breach models is very limited. It has been suggested that uncertainty in breach modelling contributes the greatest towards the uncertainty in the whole dambreak analysis process. Research is required in a number of areas:

Structure Failure Mechanisms
There is very little data to support the current assumptions made when considering failure mechanisms for concrete or masonry dams. Existing guidance suggests a wide range of potential breach sizes with effectively instantaneous failure time. In the absence of supporting research this offers an upper bound estimate of conditions – which may be appropriate for some dam designs but now for others.

Breach Formation Mechanisms
Existing models are limited in accuracy and there is a need for more reliable breach prediction tools. Current limitations in accuracy stem from a lack of knowledge relating to sediment transport under rapidly varying flow conditions and breach growth mechanisms. There is a clear need to integrate the hydraulic and soil mechanic disciplines in order to further our understanding of these processes.

Current breach models typically offer modelling of homogeneous banks made from non-cohesive material. In reality, embankments are composite structures made from a combination of cohesive and non-cohesive materials and typically with a watertight core and protective layers on embankment faces. Research is required to allow simulation of both the basic processes and real embankments.

Any improvement in the reliability of breach modelling will have a significant effect on the reliability of dambreak analyses and hence emergency planning etc.

Breach Location
There are many thousands of km of flood embankment across Europe. Our current ability to predict potential breach location is very limited. If tools could be developed to identify relative risk areas this would allow optimal use of resources for maintenance and repair so reducing the likelihood of breaching and improving community safety.

6.2 Debris and sediments

Movement of debris and sediment can significantly affect flood water levels during a dambreak event and may also be the process through which contaminants are dispersed. There is a clear need to incorporate an assessment of these effects within dambreak analyses in order to reduce uncertainties in water level prediction and to allow the risk posed by contaminants, held for example by tailings dams, to be determined.

Change to Valley Topography
Sediment movement under dambreak (i.e. rapidly varying flow) conditions should be investigated with a view to incorporating morphological changes within the ‘dambreak model’. It is likely that mechanisms near the dam will be more extreme and different to those further downstream. Potential changes to bed level should be estimated in order to allow a more reliable estimate of flood water level.

Creation of Blockages and Secondary Dams
There is evidence from case studies of past failures that the large quantities of debris and sediment moved during a dambreak interact with the downstream valley topography and infrastructure to create blockages and even secondary dams. Blockages may lead to the build up of a secondary dam, or may fail as loading increases. A secondary dam creates flood storage that attenuates the initial flow but equally results in a second flood wave if the ‘dam’ collapses. This process creates uncertainty in our ability to predict potential flood conditions – both in terms of flood level and wave arrival time.

There is a need to determine the process by which blockages occur and typical loadings under which these ‘structures’ may fail in order to provide guidance for dambreak modelling and hence more reliable information for emergency planning.

Dispersion of Pollutants
Many mines create tailings dams where water from the mine works is allowed to stand in order for heavy metal pollutants to settle. When such a dam fails, there is an immediate release of polluted water from the reservoir and also the movement of sediment from the bed of the reservoir that contains a high concentration of pollutants. In order to determine the risk posed by such structures (before or after failure) we need to be able to model the movement of pollutants under dambreak flow conditions. This movement may be very similar to the movement of valley sediments (outlined above) and it is recommended that research linked with the prediction of sediment movement is undertaken.

6.3 Flow modelling

The following areas relate to the performance of flow models and the accuracy of predicted results. These have been identified as important areas for further research.

Performance of Flow Models
It was not possible within the scope of the CADAM project to identify specific model performance for specific hydraulic conditions although some trends and hence initial preferences have been identified (see Section 2.6). CADAM has generated a considerable amount of test data that could be analysed in more detail to further understanding in this area. This would allow more specific recommendations as to modelling approach and would reduce the range of uncertainty associated with current dambreak modelling. In particular, issues such as wave propagation time should be investigated further since these predictions significantly affect emergency planning.

Modelling Flow Interaction with Valley Infrastructure
Our ability to predict flow conditions around infrastructure such as bridges, embankments etc. is limited. It is important from an emergency planning perspective to know whether or not an access route is flooded, or indeed destroyed. Research into flow behaviour at such structures and conditions under which they would be destroyed would assist our ability to reliably predict emergency conditions.

Valley Roughness
Any numerical flow model requires a measure of the channel roughness to be specified. Under dambreak conditions, flood levels are generally much greater than natural flood levels, resulting in inundation of forested and urban areas, for example. Our ability to predict roughness conditions for these areas is limited, as is available data against which the models may be calibrated. Research to determine likely roughness values for such areas is recommended.

Modelling Flow in Urban Areas
The extreme nature of dambreak flows means that inundation of urban areas is common. Techniques for modelling flow in urban areas have not been proven or validated with field data. Uncertainty in the prediction of flood levels in urban areas can significantly affect the implementation of emergency plans. Research to determine flow behaviour and the best way in which it may be modelled is strongly recommended.

6.4 Database

The very nature of dambreak and breach events means that there is generally little field data recorded against which modelling and risk management techniques may be validated. During the CADAM project it became clear that the limited data that does exist is generally widely dispersed. It is strongly recommended that a common European database is established to collate such information. Collection of data in the following areas is recommended:

- field data on dambreak events
- field data on breach events
- incidents relating to dams and weir operation / performance
- incidents relating to flood embankment operation / performance
- research data relating to dambreak, breach formation, debris & sediment flow
- data relating to risk management techniques, including social and economic assessment

Such a database would require initial development and then continued long term development / maintenance. The value of collecting this data would be:

- data for the validation of dambreak models
- data for the validation of breach models
- data for the validation of risk management techniques

This would lead to improved risk management affecting both population safety and economic performance.

6.5 Risk / information management

Research in the following areas would significantly aid risk management procedures:

Risk Assessment Methodologies
With a wide variety of approaches currently being considered it is unclear which approach is most appropriate. A continued review of practice should be maintained to determine best approaches. The development of database information to support risk assessment procedures (as outlined above) is strongly recommended.

Use of Information Technology
In recent years advances in both hardware and software mean that considerable amounts of information may be manipulated to assist the risk management process. Consideration should be given to developing tools to directly aid the dam owner in this role. Many countries continue to use limited software developed during the

last two decades. GIS systems linked to databases and modelling tools offer significant potential as information and expert systems.

Warning Systems

The potential exists to establish more efficient and effective warning systems such that in the event of a major dam failure a maximum number of people are evacuated from the potential flood zone. This is the most effective way of minimising the potential loss of life. An effective warning system may comprise information management tools linked with targeted monitoring equipment, well structured emergency procedures and a clear understanding by both staff, emergency authorities and the public of the hazards facing them. To achieve these goals requires development of information management tools, monitoring systems and clear communication with staff, emergency authorities and the public. Understanding human perception of risk and behaviour under such extreme conditions is also a key component to the effective development of emergency procedures. Training, including practice events, is likely to form a key part of this process.

Impact Assessment

There is little guidance on how to determine potential impact of a dambreak flood, and also the economic impact of a flood. Specific areas requiring investigation include:

- environmental impact of flooding (magnitude and cost?)
- damage potential of flooding (when will a structure collapse and what is the cost of this damage?
- human impact of flooding (response under extreme conditions, estimating potential loss of life, vulnerability assessment - what are the factors that make a society vulnerable to flood impact? How will different members of society respond to flood conditions?

Economic Response to a Dambreak

In the event of a major dambreak, who will pay compensation for losses and damage?

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1	Wallingford	UK	HR Wallingford Ltd.	Mark Morris / Paul Samuels
2	Munich	Germany	Universität der Bundeswehr	Marinko Nujic / Karl Broich
3	Milan	Italy	ENEL	Guido Testa
4	Zaragoza	Spain	Universidad de Zaragoza	Francisco Alcrudo

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The project CD-ROM (containing all publications and test case data) was edited by:

S Soares Frazao	Université Catholique de Louvain (Belgium)
M Morris	HR Wallingford Ltd. (UK)
Y Zech	Université Catholique de Louvain (Belgium)

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MOHAMED MAA, SAMUELS P G, GHATAORA G S & MORRIS M W (1999), *A new methodology to model the breaching of non-cohesive homogeneous embankments,* Proceedings of the 4th CADAM Concerted Action Meeting, University of Zaragoza, November 1999. (to be published by the European Commission)

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Appendices

Appendix 1

Final administrative report of the CADAM Concerted Action

Appendix 1 Final administrative report of the CADAM Concerted Action

Concerted Action on Dambreak Modelling

funded by the European Commission
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The duration of the CADAM Concerted Action was for a period of two years between February 1998 and January 2000. To fulfil its objectives, the Concerted Action was committed to organising four events within its area of interest: two expert meetings and two workshops. This programme of events continued on, and expanded from, the work started by an IAHR working group on dambreak modelling.

Between meetings a varying number of participants undertook numerical and physical modelling work in addition to and as part of separate research programmes. The CADAM Concerted Action provided a framework through which this European wide work could be focussed and analysed, and the meetings offered a venue at which results could be presented and conclusions drawn. In this way, CADAM has benefited considerably from the ongoing research programmes of many institutions across Europe.

In addition to expert and workshop meetings a number of steering group meetings have been held. These were generally held in conjunction with the main events and separate meeting notes have been produced. The project coincided with a period of change in the EC. Dr R Casale originally started as Science Officer for the project and was superseded by Dr P Balabanis and then Mrs K Fabbri. The total project expenditure during the contract was 149,902 ECU, as shown on the annual Cost Statements that have accompanied the two annual reports. The original budget for the CADAM Concerted action was 150,000 ECU.

Appendix 2

List of papers in the CADAM proceedings

Proceedings of the 1st CADAM Workshop, Wallingford, March 1998.

Edited by: Mark Morris
Jean Charles Galland
Panagiotis Balabanis

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Edited by: Marinko Nujic
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Edited by: Guido Testa
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CADAM:
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Edited by: Mark Morris
Jean Charles Galland