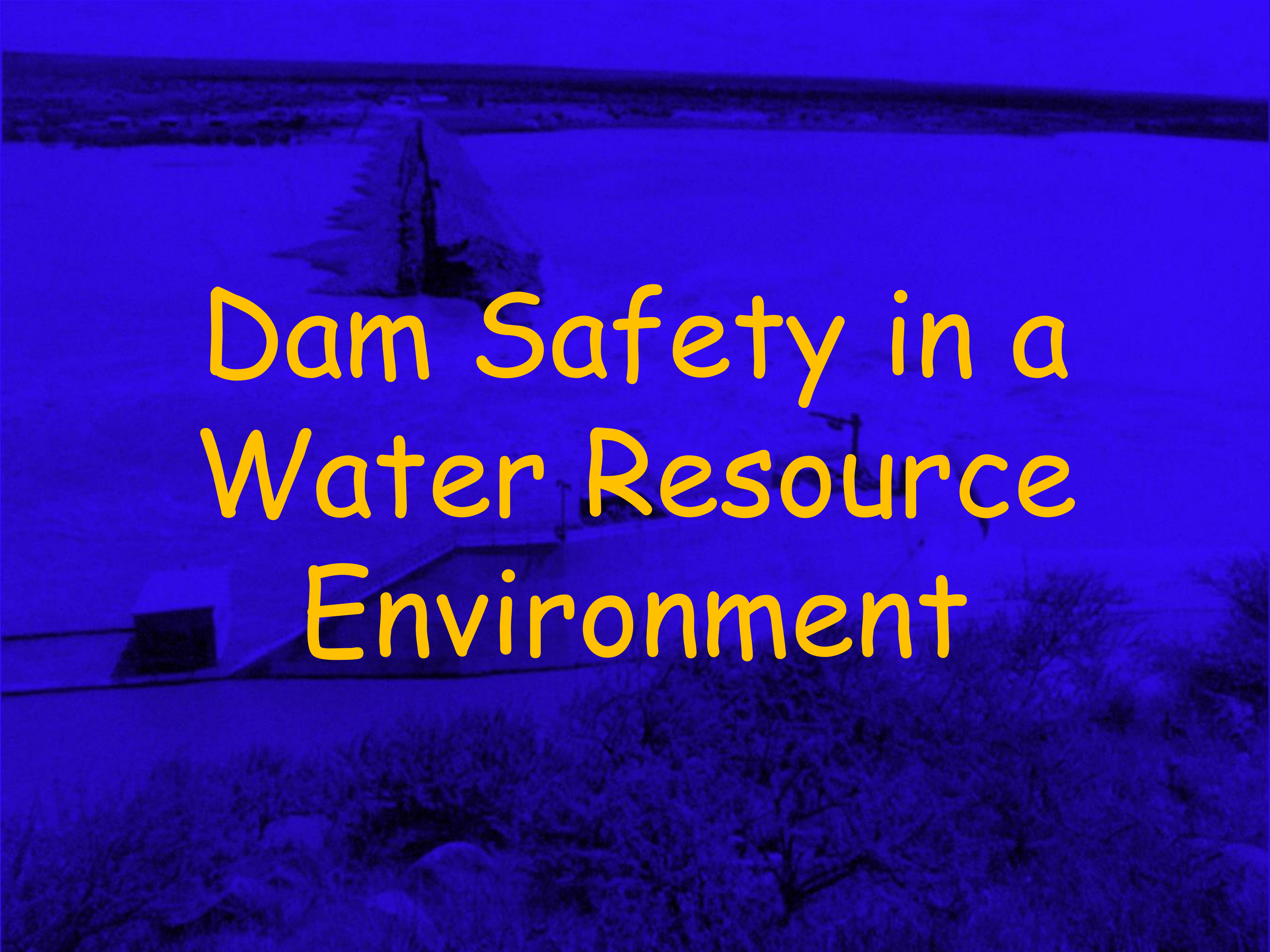


Dam Safety in a Water Resource Environment

What is "Dam Safety"?

- A hassle to do an inspection once in a while
- Something that is somebody else's responsibility
- It has no influence on water resource management so we don't need to give any due attention
- When doing water resources management only optimise from water resources perspective


PEZULA


Baldwin Hills

Definition of Dam Safety

- Dam safety is concerned with two closely related but different aspects:
  - The safety of the dam and appurtenant structures; and
  - The safety of the population, property & the environment in the vicinity of or downstream from the dam
- It spans the whole life cycle from planning to decommissioning
- It is an unfortunate fact that periodically dams do fail, sometimes causing extreme damage and loss of life downstream

Dams Safety

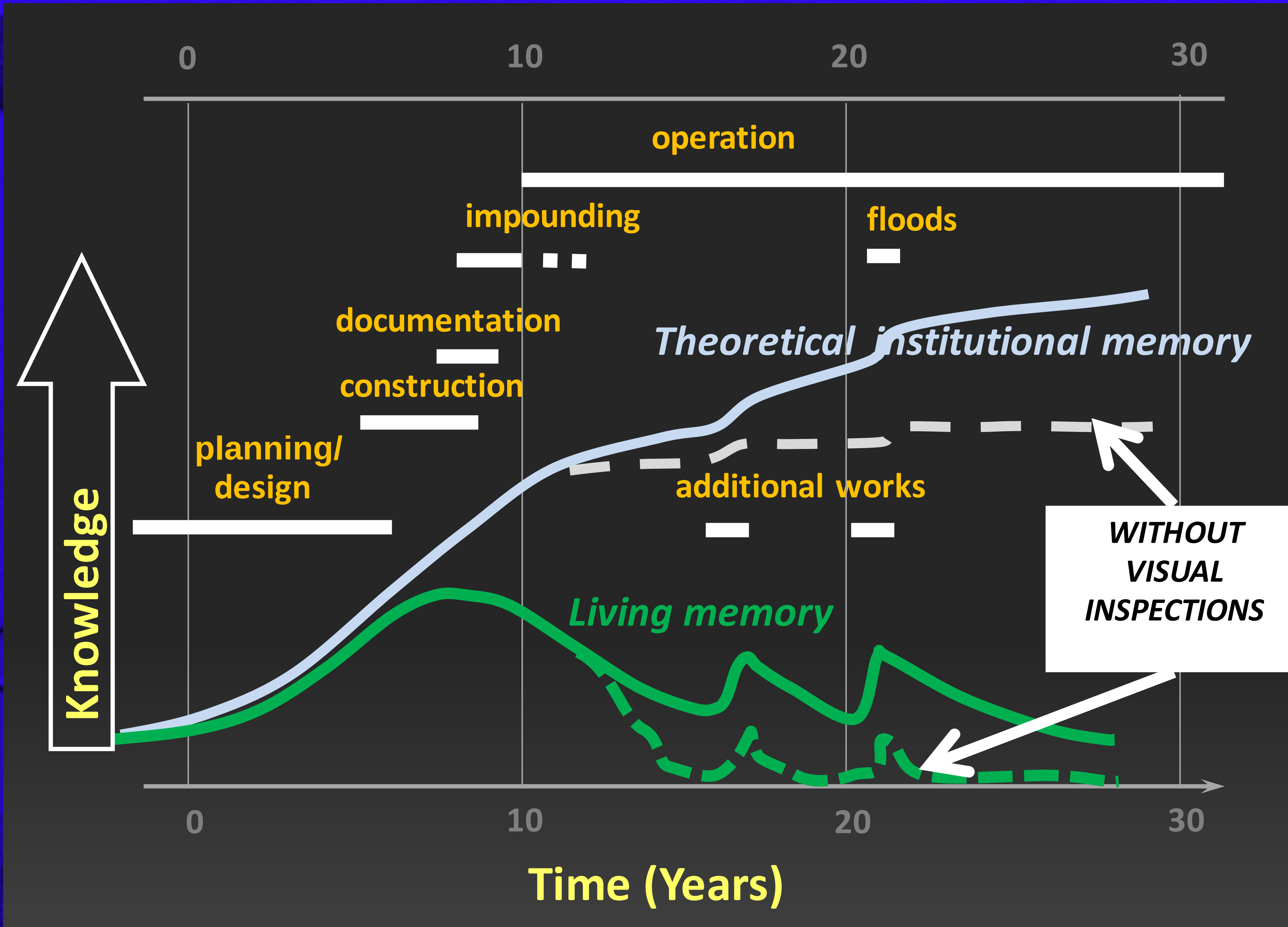
- Dams provide enormous benefits to society world wide
- However, the vital services that they provide can also be accompanied by serious hazards
- During the 1950's and 1960's there was growing international concern about the safety of dams

Safety Concerns Generally

- Originally dams were built in remote areas far removed from population centers
- This has changed in recent years
- As more and more people move in to vulnerable areas downstream of dams, concern about potential failure of dams becomes increasingly important

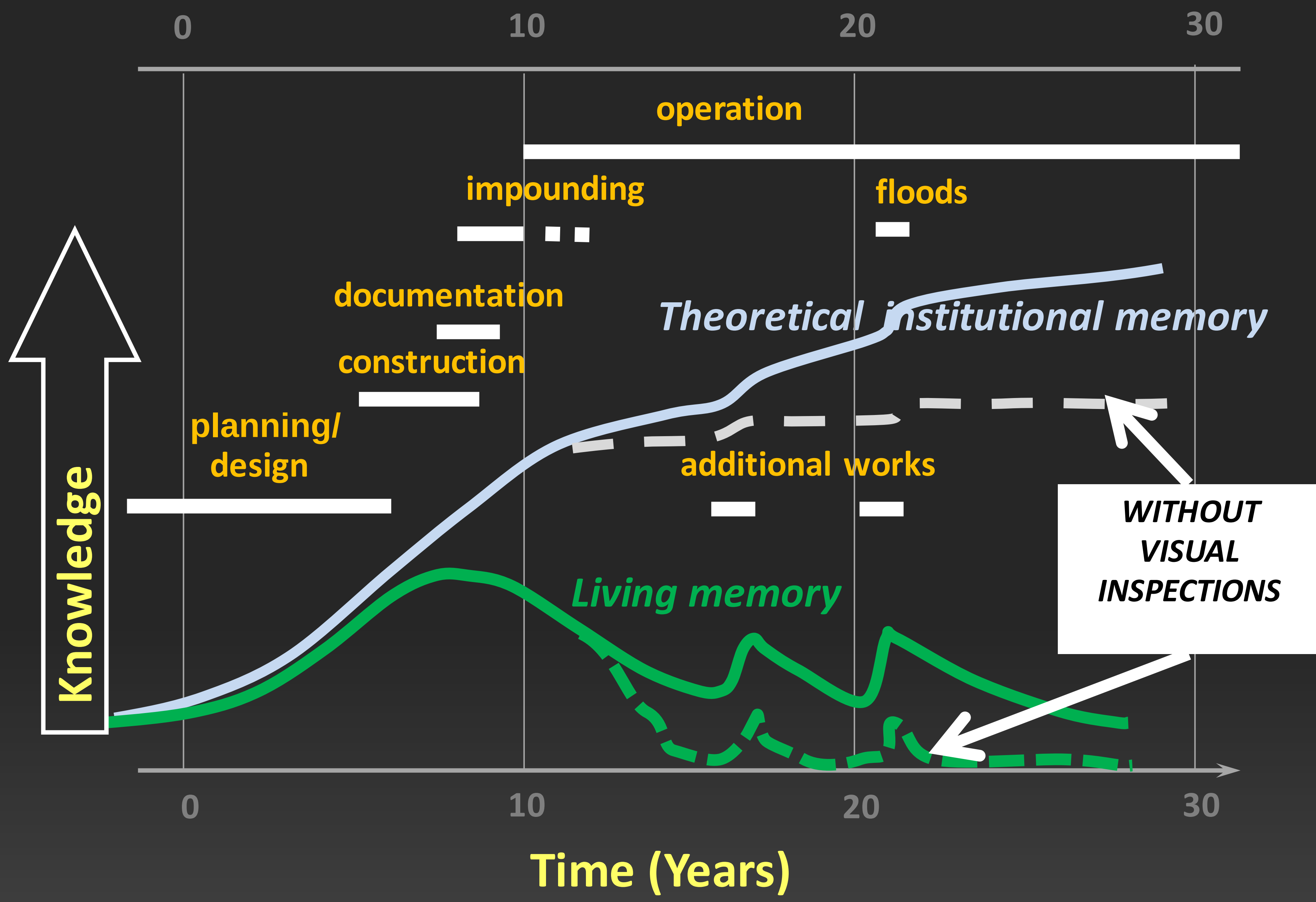
The Need for Considering Risk

- Engineering planning/design = process of making complicated decisions using all available data
- Because the data are always limited by time, budget or physical constraints, these decisions have to be made under uncertainty
- Dealing with uncertainty is such an intrinsic part of their work that many managers, planners and designers do not give this conscious consideration
- Some overlook the fact that the main part of their work is risk management


0
10
20
30
operation
impounding
floods
documentation
Theoretical institutional memory
construction
planning/
design
additional works
WITHOUT
VISUAL
INSPECTIONS
Knowledge
Living memory
0
10
20
30
Time (Years)

WHAT IS THE LIFESPAN OF A DAM?


THE CORPORATION OF THE CITY OF CAPE TOWN
THIS THE LAST STONE OF THE DAM WAS LAID BY
HIS WORSHIP THE MAYOR
SIR JOHN WOODHEAD J.P.
ON
THE FIRST DAY OF MAY 1897
BEING THE YEAR OF THE DIAMOND JUBILEE OF
HER MOST GRACIOUS MAJESTY QUEEN VICTORIA


0
10
20
30
operation
impounding
floods
documentation
Theoretical institutional memory
construction
planning/
design
additional works
Knowledge
WITHOUT
VISUAL
INSPECTIONS
Living memory
0
10
20
30
Time (Years)

Key objectives

- Public & environment shall be protected from effects of dam failure = risks as low as reasonably practicable
- Due diligence exercised at all stages of dam's life cycle
- Dam safety management system implemented
- Include the management of environmental and socio-economic issues

Key objectives

- Dam Safety effort = potential consequences of dam failure
- Decisions be based on risk posed – life cycle
- Dam Safety = life cycle
- Document O&M (incl. surveillance)
- Operate, maintain & surveillance of dam = documented procedures
- Flow control equipment tested & capable of operation
- Regular safety review
- Use of qualified engineer/person/team

Key objectives

- Dam safe to handle loads
- Define components
- Identify hazards – internal & external
- PFMs identified
- Effective emergency management process documented & implemented & tested regularly

Dam safety consideration summary

1) Dam Safety Management: Responsibility & accountability of dam owner, regulatory authorities, dams engineers and operators
2) Risk Informed Decision Making: Establishes the design basis and level of care
3) Planning: Factors to be addressed in project planning
4) Investigations: Includes feasibility stages of investigations and design
5) Design: Concepts, hydrological, geological factors and stability
6) Construction: Construction contract management quality control
7) Commissioning: Safety issues in first filling and project commissioning
8) Records: Design and construction
9) Operations and Maintenance: Procedures for reservoir filling and operating strategies
10) Surveillance: Inspections, monitoring, assessment and reports
11) Safety Reviews: Potential failure modes analysis (PFMA), risk analysis
12) Dam Safety Emergency Planning: Preparedness and Response
13) Remedial Actions: Decision making and implementation
14) Environmental Issues: Factors affecting dam safety
15) Trans-boundary Considerations: Factors affecting dam safety


Dam Safety Regulation in
South Africa: 32 years down
the line

History

- Early attempts in 1970s unsuccessful – very little political support
- Visit to US, UK & Europe ⇨ in 1984 & promulgation of regulations in 1986
- Formation of regulator (Dam Safety Office) in 1986
- New Constitution in 1996
  - Human centred but also protection of environment
- New National Water Act 1998 – included environmental impact
- Update of regulations in 2012 - included environmental impact

NO LARGE DAM HAS FAILED THAT WAS DESIGNED OR BUILT UNDER DAM SAFETY LEGISLATION

Classification

- Size (height)

Size class	Maximum wall height (m) (from the river bed level to the highest point of the dam)
Small	< 12 m
Medium	≥ 12 m but < 30 m
Large	≥ 30 m

Classification

- Hazard potential

Hazard potential rating	Potential loss of life	Potential economic loss	Potential adverse impact on resource quality
Low	None	Minimal	Low
Significant	≤ 10	Significant	Significant
High	> 10	Great	Severe

Classification

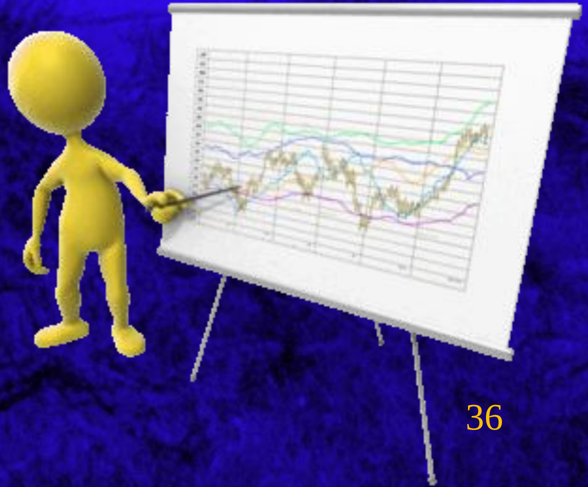
- Category classification

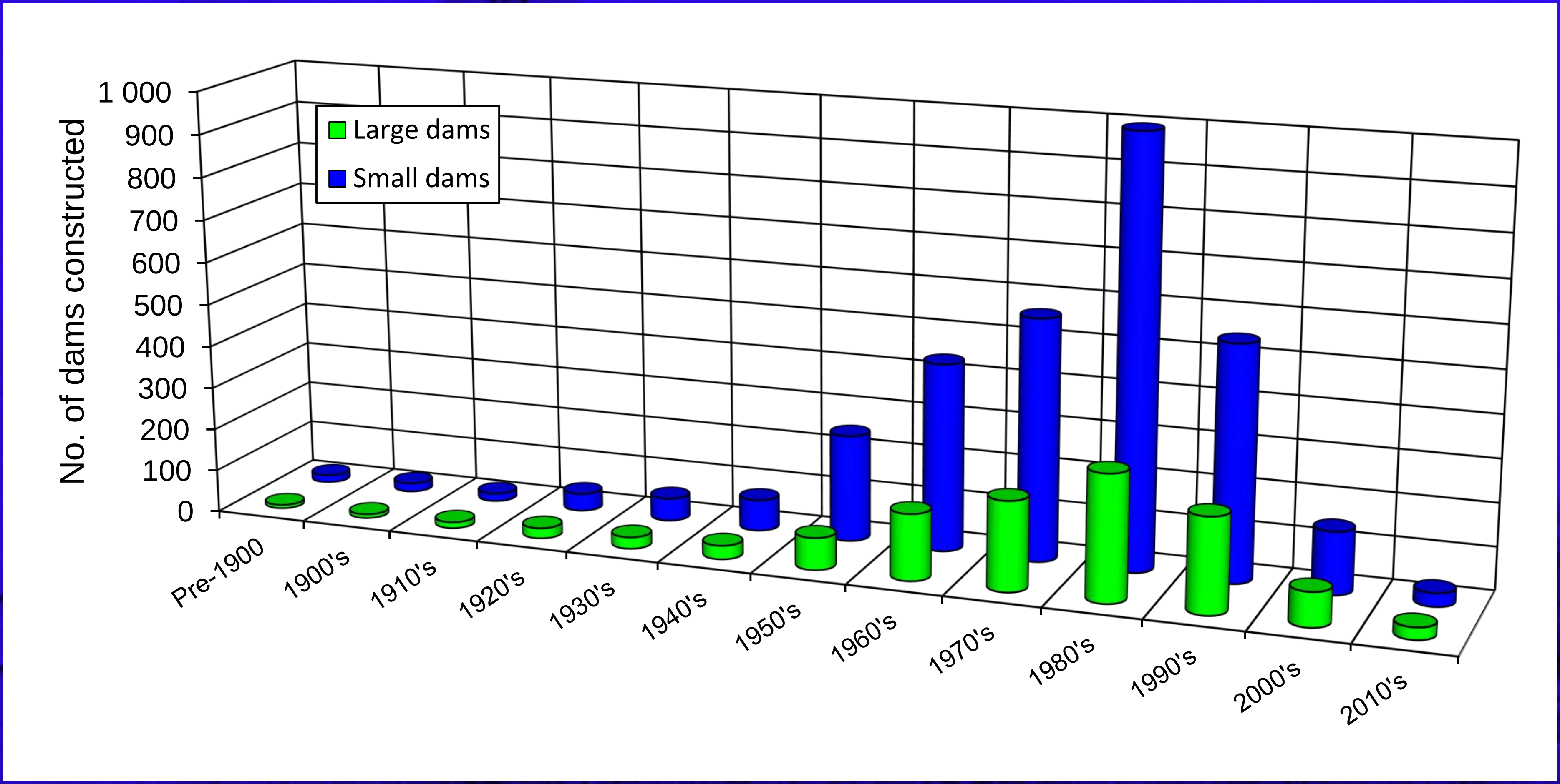
Size class	Hazard potential rating		
	Low	Significant	High
Small	Category 1	Category 2	Category 2
Medium	Category 2	Category 2	Category 3
Large	Category 3	Category 3	Category 3

Some important concepts

- Regulator = Dam Safety Office = important archive of existing info
- Use of Approved Professional Person (qualifications & experience)
  - Category 2 = APP
  - Category 3 = APP & professional team
  - APP approved each time for each task @ dam including construction
- Updates in 2012:
  - Consider impact on environment
  - Freeboard survey during each safety evaluation (previously based on existing info)
- Reporting of failures/incidents to the regulator
- Dirty water regulations
- Water use

DAM STATISTICS



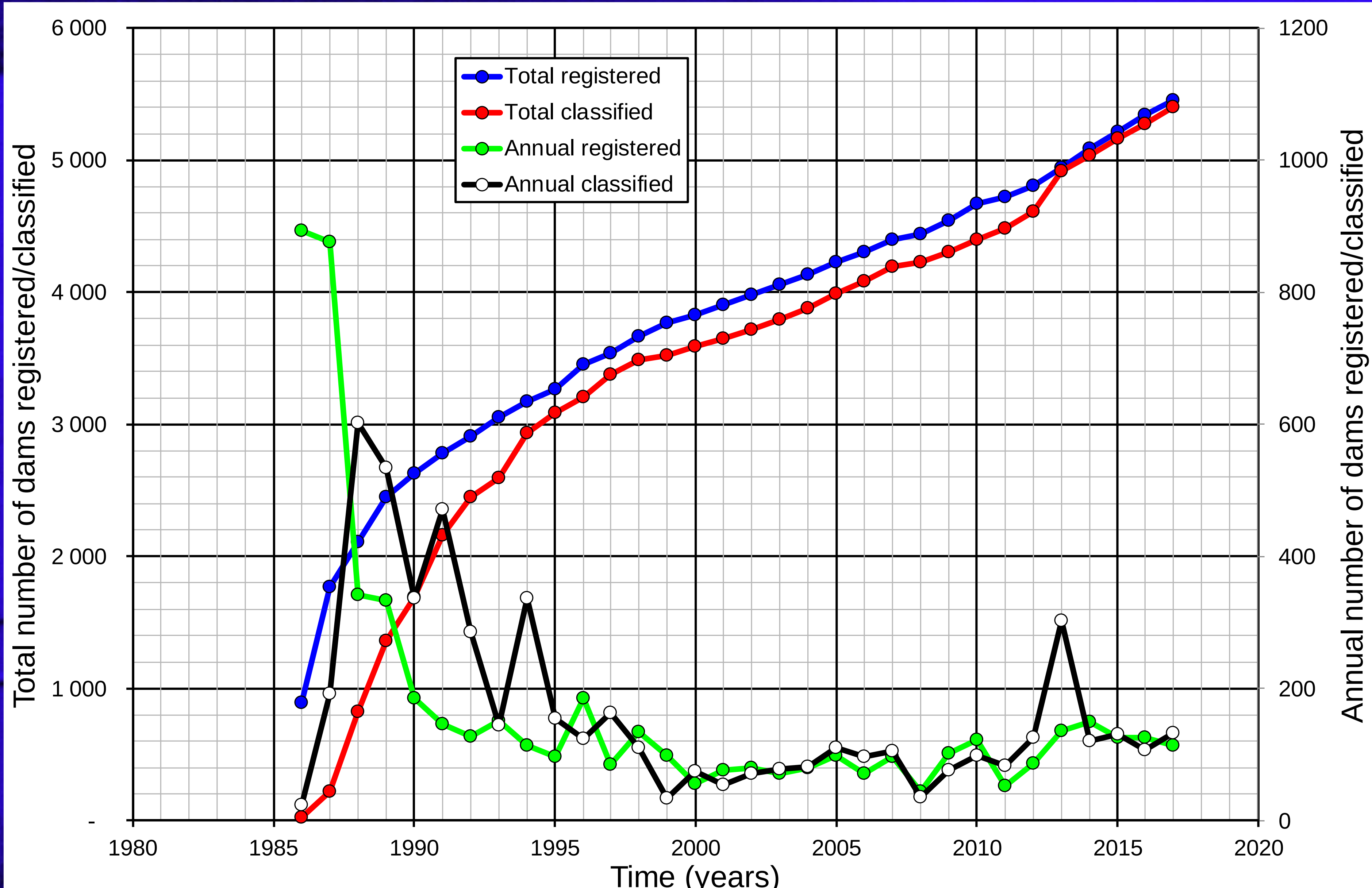


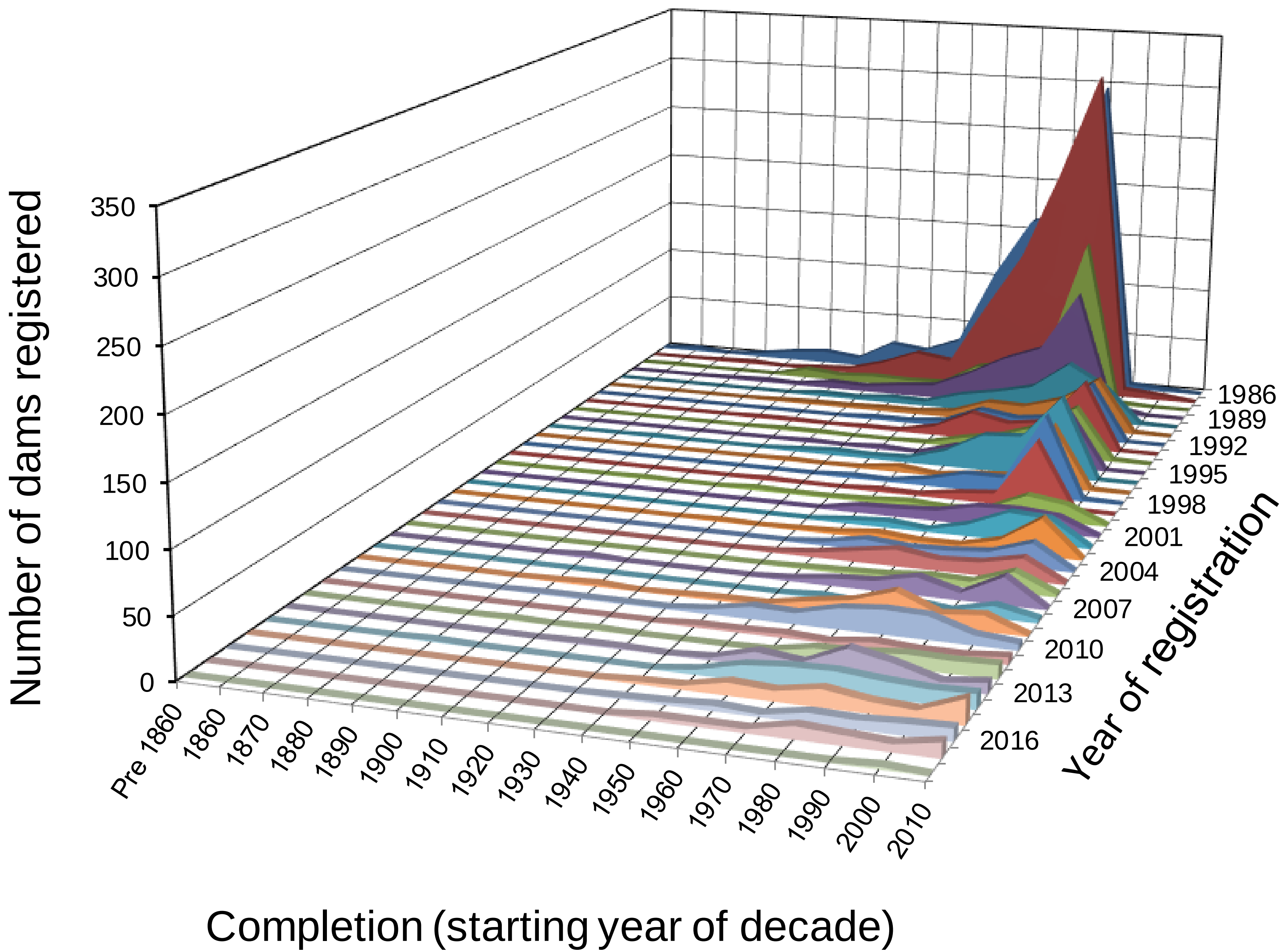
No. of dams constructed
1 000
900
800
700
600
500
400
300
200
100
0
Large dams
Small dams
Pre-1900
1900's
1910's
1920's
1930's
1940's
1950's
1960's
1970's
1980's
1990's
2000's
2010's

Dam statistics

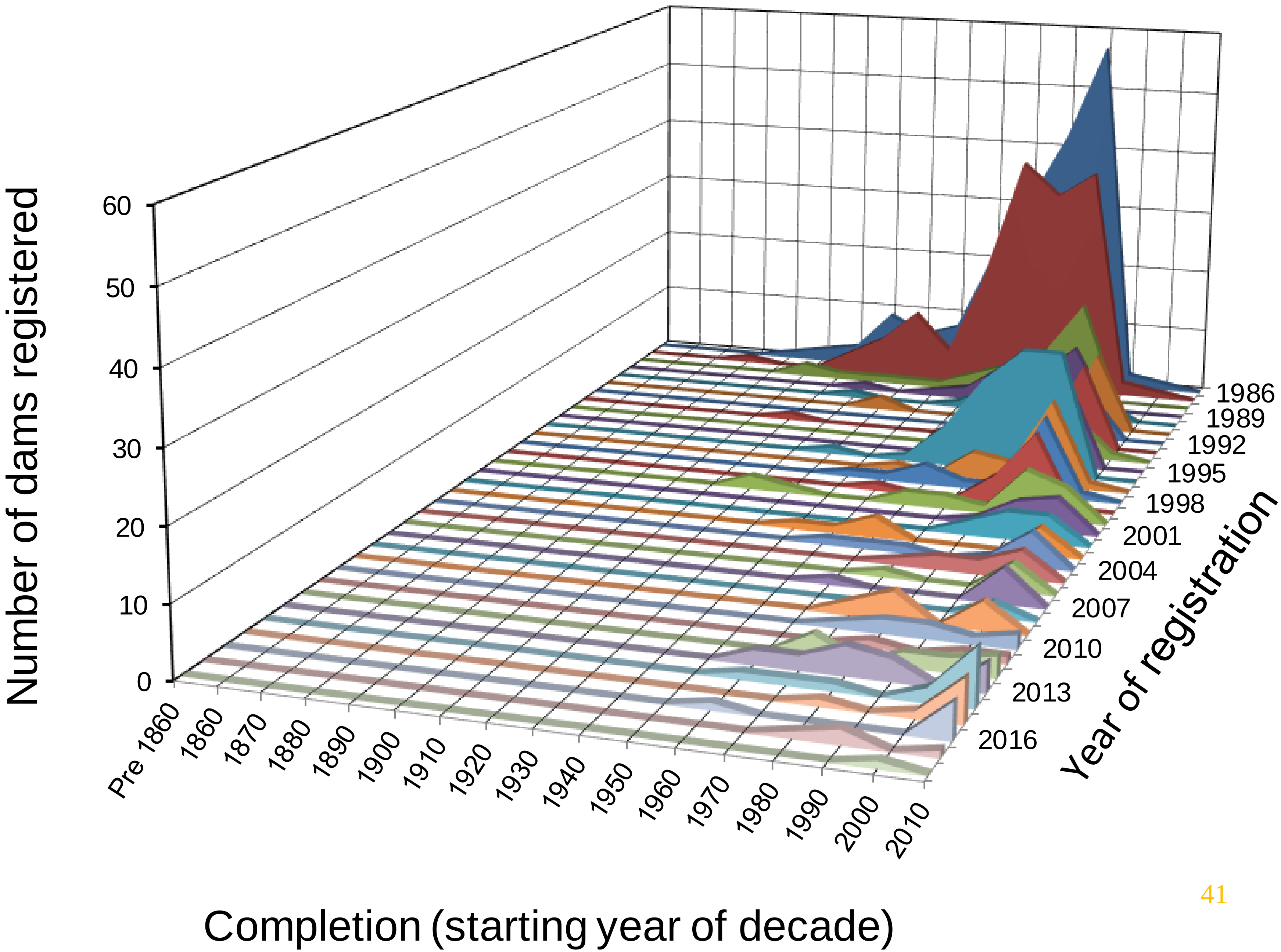
- Registered (Feb 2018)
  - Total = 5 462
  - Small dams = 4 616
  - Large dams = 846

  - Category 1 = 57.8%
  - Category 2 = 36.6%
  - Category 3 = 5.5%

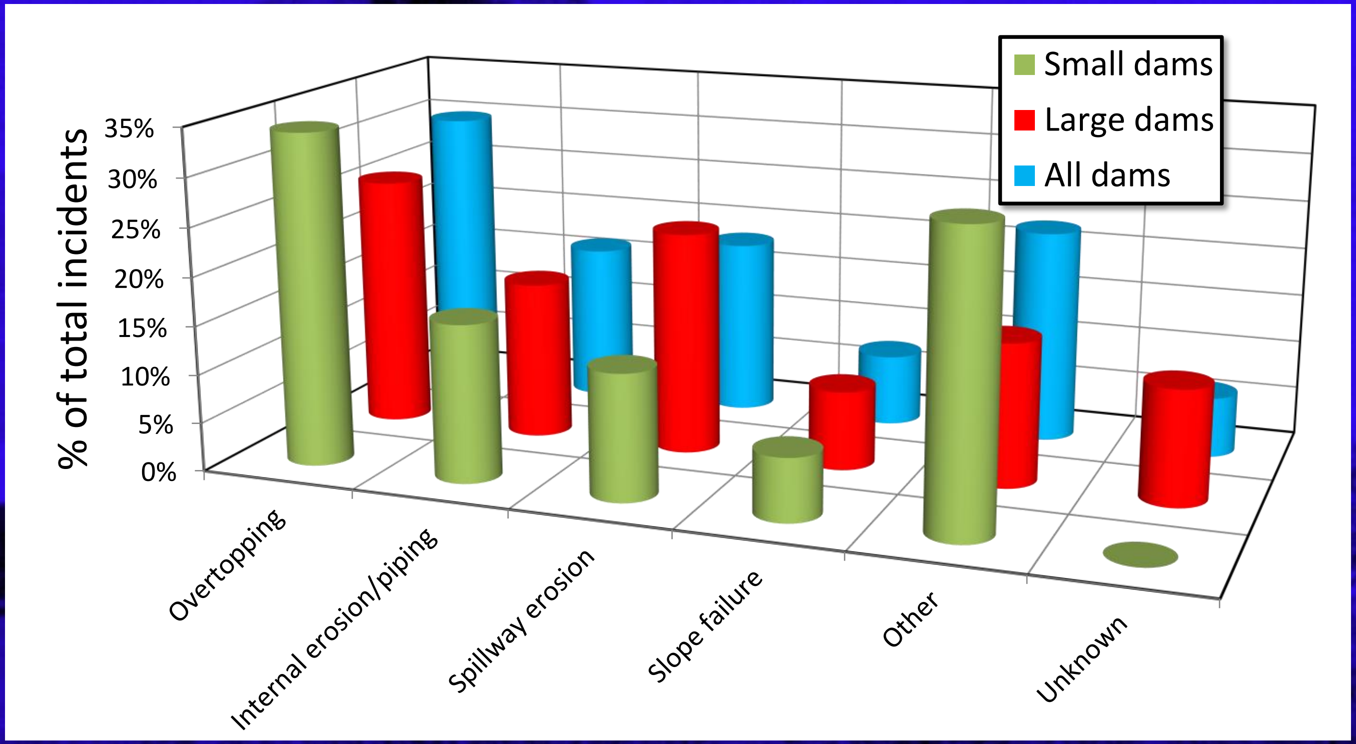

Total registered
Total classified
Annual registered
Annual classified
Total number of dams registered/classified
Annual number of dams registered/classified
Time (years)
6 000
5 000
4 000
3 000
2 000
1 000
-
1200
1000
800
600
400
200
0
1980
1985
1990
1995
2000
2005
2010
2015
2020



Number of dams registered
350
300
250
200
150
100
50
0
Pre 1860
1860
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
1986
1989
1992
1995
1998
2001
2004
2007
2010
2013
2016
Year of registration
Completion (starting year of decade)


Number of dams registered
0
10
20
30
40
50
60
Pre 1860
1860
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Year of registration
1986
1989
1992
1995
1998
2001
2004
2007
2010
2013
2016
Completion (starting year of decade)

IT TAKES TIME TO SUCCESSFULLY IMPLEMENT DAM SAFETY REGULATION



Small dams
Large dams
All dams
% of total incidents
35%
30%
25%
20%
15%
10%
5%
0%
Overtopping
Internal erosion/piping
Spillway erosion
Slope failure
Other
Unknown

Dam safety without failure mechanisms?

Failure mechanisms without understanding dam materials?

Essential also in planning process

Failure mechanisms

- Internal erosion
- Structural
- Hydrologic
- Hydraulic
- Seismic
- Operational
- Other

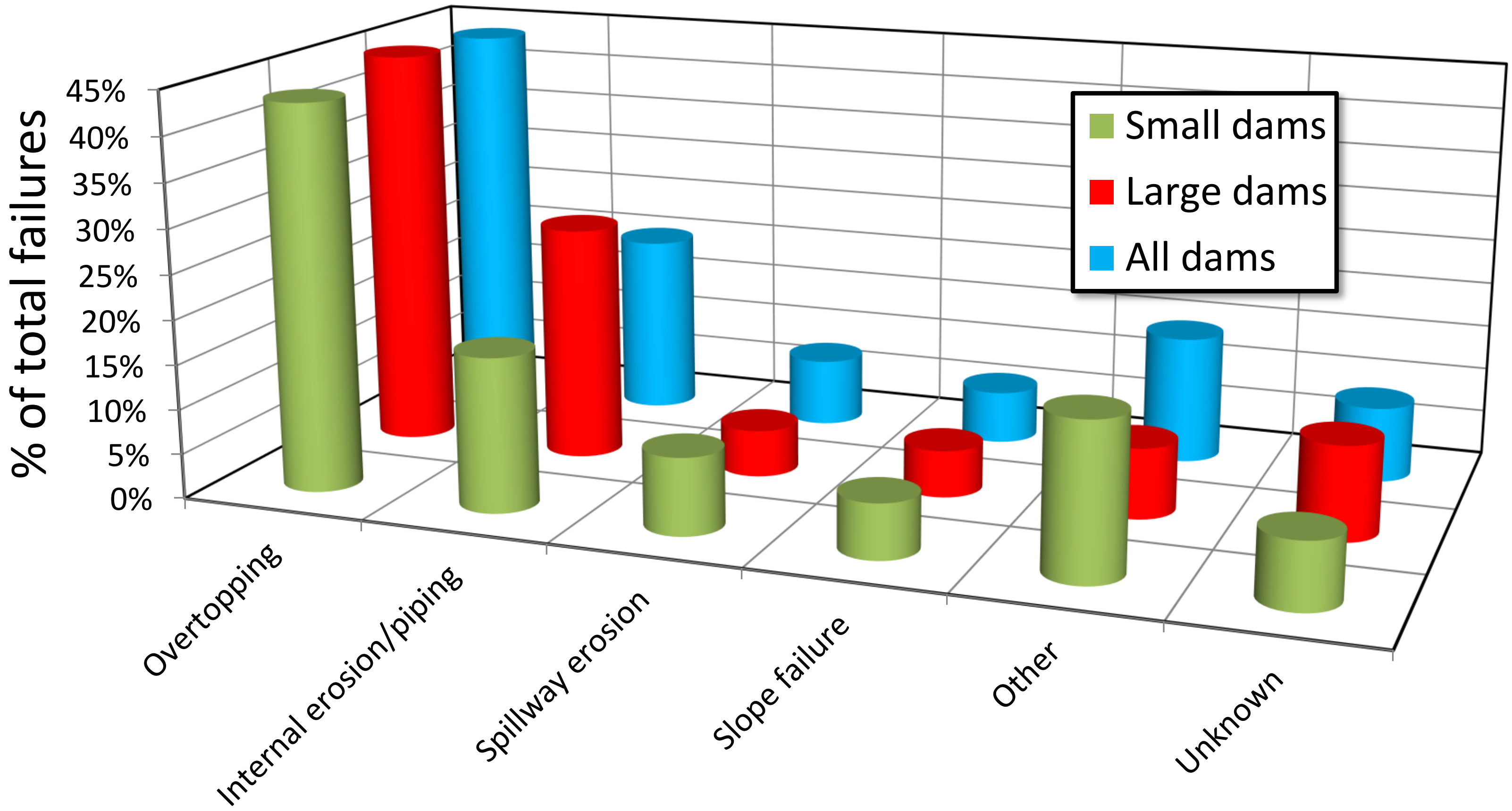
Failure mechanisms

- Internal erosion
- Structural
  - Concrete gravity dams failures
  - Concrete arch dam failures
  - Concrete buttress dam failures
- Hydrologic
  - Overtopping
- Hydraulic
  - Failure due to erosion of rock
  - Failure due to overtopping of spillway walls and stilling basins
  - Stagnation Pressure Failure of Spillway Chutes
  - Cavitation Damage Induced Failure of Spillways
- Seismic
  - Failure of embankment dams during to seismic loads
  - Seismic failure of retaining walls
- Operational
- Other
  - Landslide failures and incidents
  - Trunnion Friction Radial Gate Failure
  - Drum Gate Failures

Overtopping


Overtopping failure = spillway
capacity is NOT sufficient

South Africa - 2016



ONLY EMBANKMENT FAILURES

Nzhelele Dam, South Africa, 2014

Nzhelele Dam, South Africa, 2000

Construction issues

- Make sure dam is built to designed levels
- Spillway built to the correct dimensions
- PROPER As-Built drawings

Spitskop Dam, South Africa 1988

Bellair Dam, South Africa 2003

Risk of gated spillways

Gated spillway requirements

- Proper design
- Proper operation
  - Human inputs
  - Mechanical/electrical efficiency
- Proper maintenance
- Risk much higher than uncontrolled spillway

- Non compliance ⇨ incident or failure


Hardap Dam


Copyright 2006 Geology.com

Hardap Dam

- Asphalt concrete faced rockfill embankments with centrally located controlled ogee concrete gravity spillway: 35.9 m high
- Completed in 1963
- 4 radial gates: 11.1 m high x 11.6 m wide

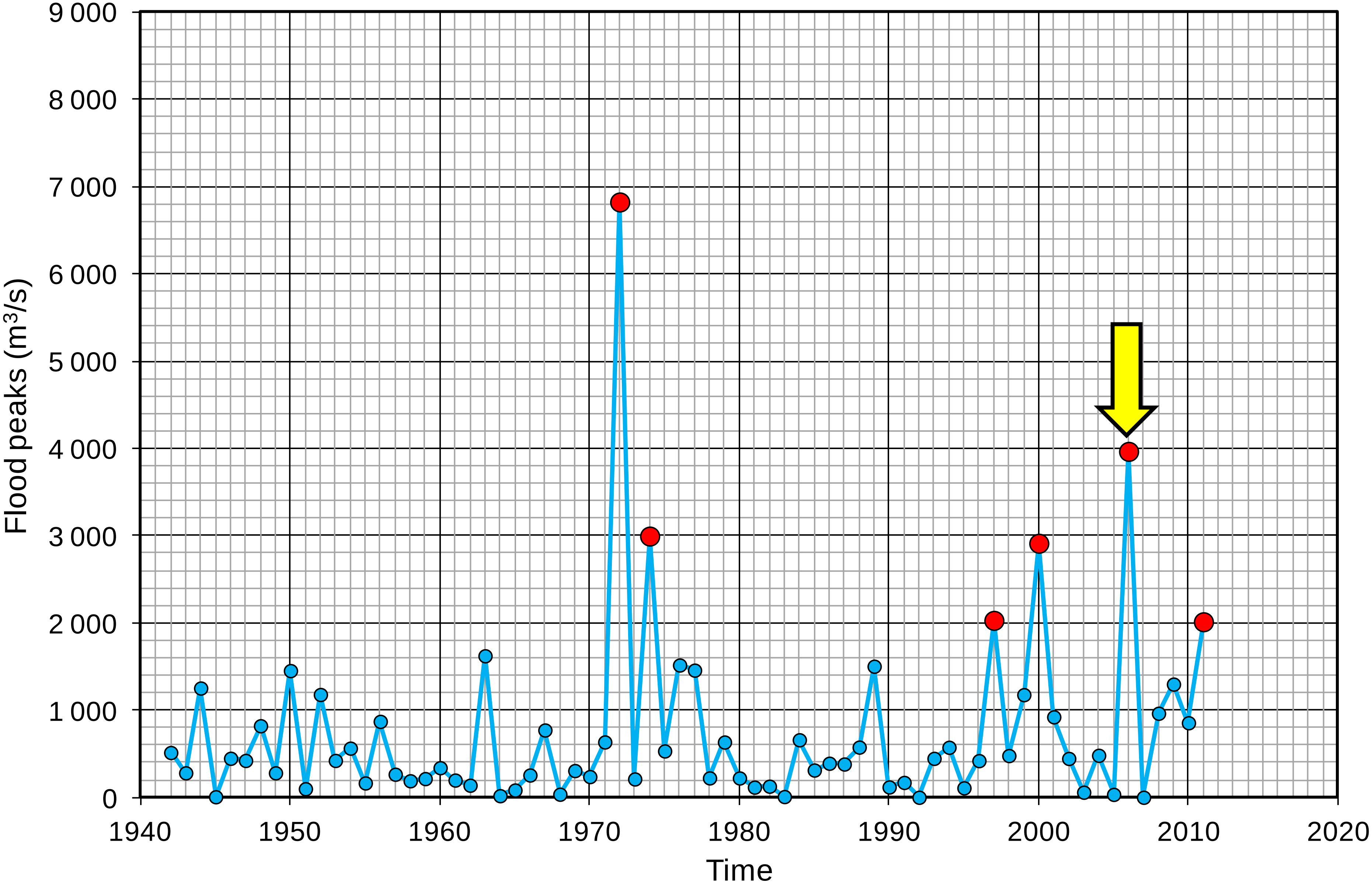
Radial gate power sources

- National grid
- Standby generator

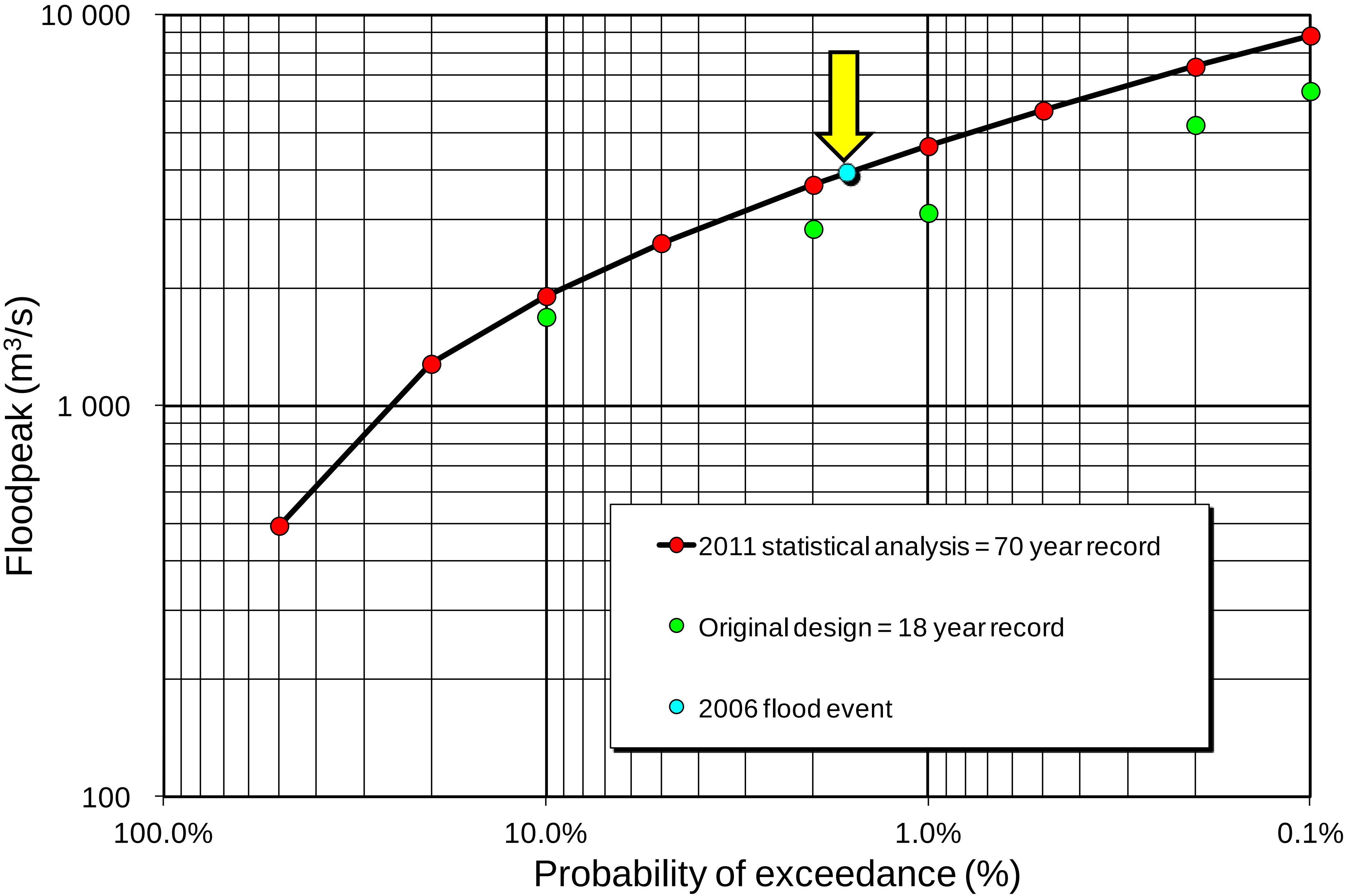
Radial gate power sources

- National grid
- Standby generator
- Small mobile generator operated at gates

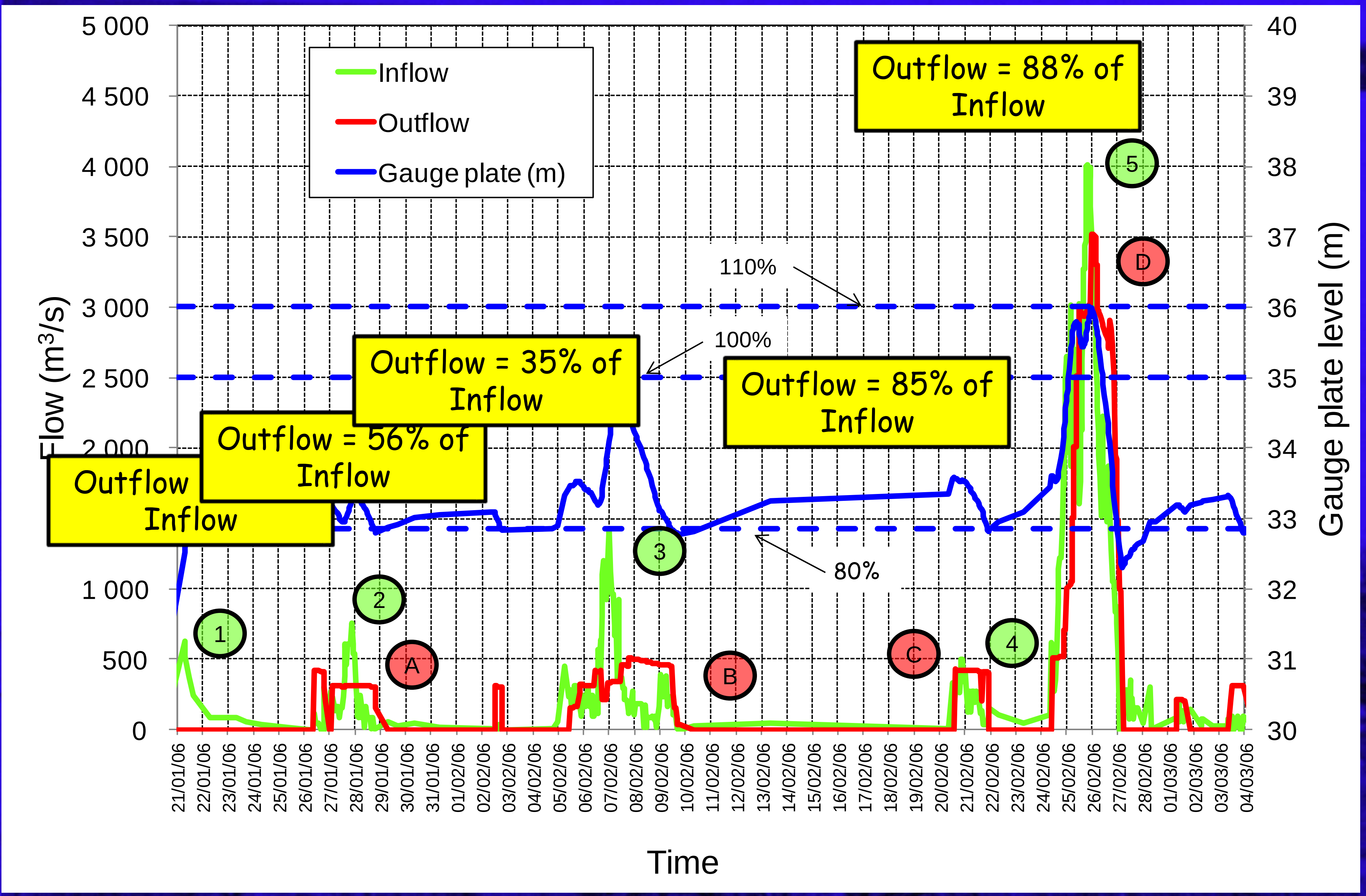

February 2006



9 000
8 000
7 000
6 000
5 000
4 000
3 000
2 000
1 000
0
Flood peaks (m3/s)
1940
1950
1960
1970
1980
1990
2000
2010
2020
Time



10 000
1 000
100
Floodpeak (m3/s)
100.0%
10.0%
1.0%
0.1%
Probability of exceedance (%)
2011 statistical analysis = 70 year record
Original design = 18 year record
2006 flood event



Inflow
Outflow
Gauge plate (m)
Outflow = 88% of Inflow
Outflow = 35% of Inflow
Outflow = 56% of Inflow
Outflow = 85% of Inflow
Outflow Inflow
110%
100%
80%
1
2
3
4
5
A
B
C
D
Flow (m3/s)
Gauge plate level (m)
Time
5 000
4 500
4 000
3 500
3 000
2 500
2 000
1 000
500
0
40
39
38
37
36
35
34
33
32
31
30
21/01/06
22/01/06
23/01/06
24/01/06
25/01/06
26/01/06
27/01/06
28/01/06
29/01/06
30/01/06
31/01/06
01/02/06
02/02/06
03/02/06
04/02/06
05/02/06
06/02/06
07/02/06
08/02/06
09/02/06
10/02/06
11/02/06
12/02/06
13/02/06
14/02/06
15/02/06
16/02/06
17/02/06
18/02/06
19/02/06
20/02/06
21/02/06
22/02/06
23/02/06
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27/02/06
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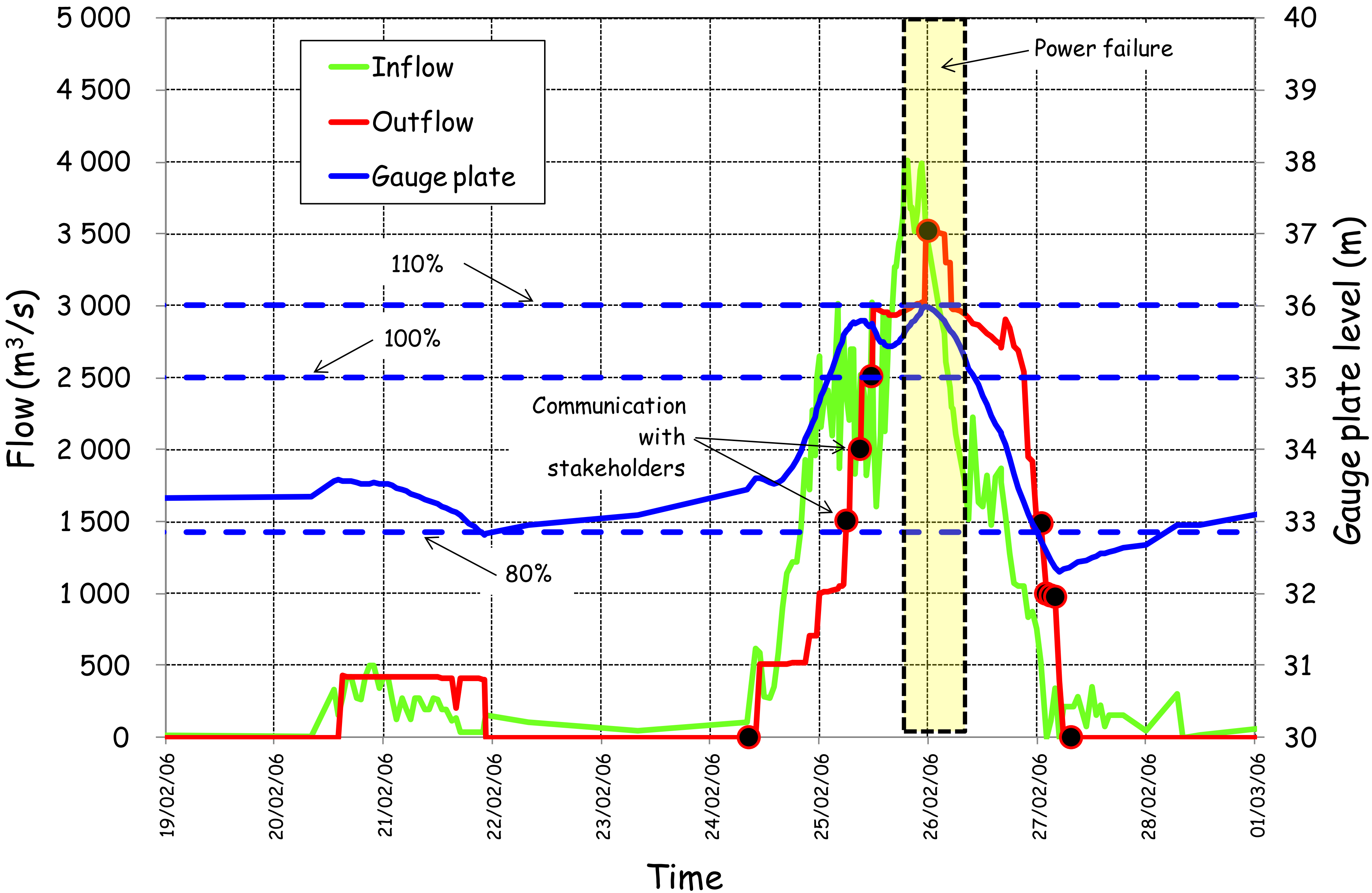
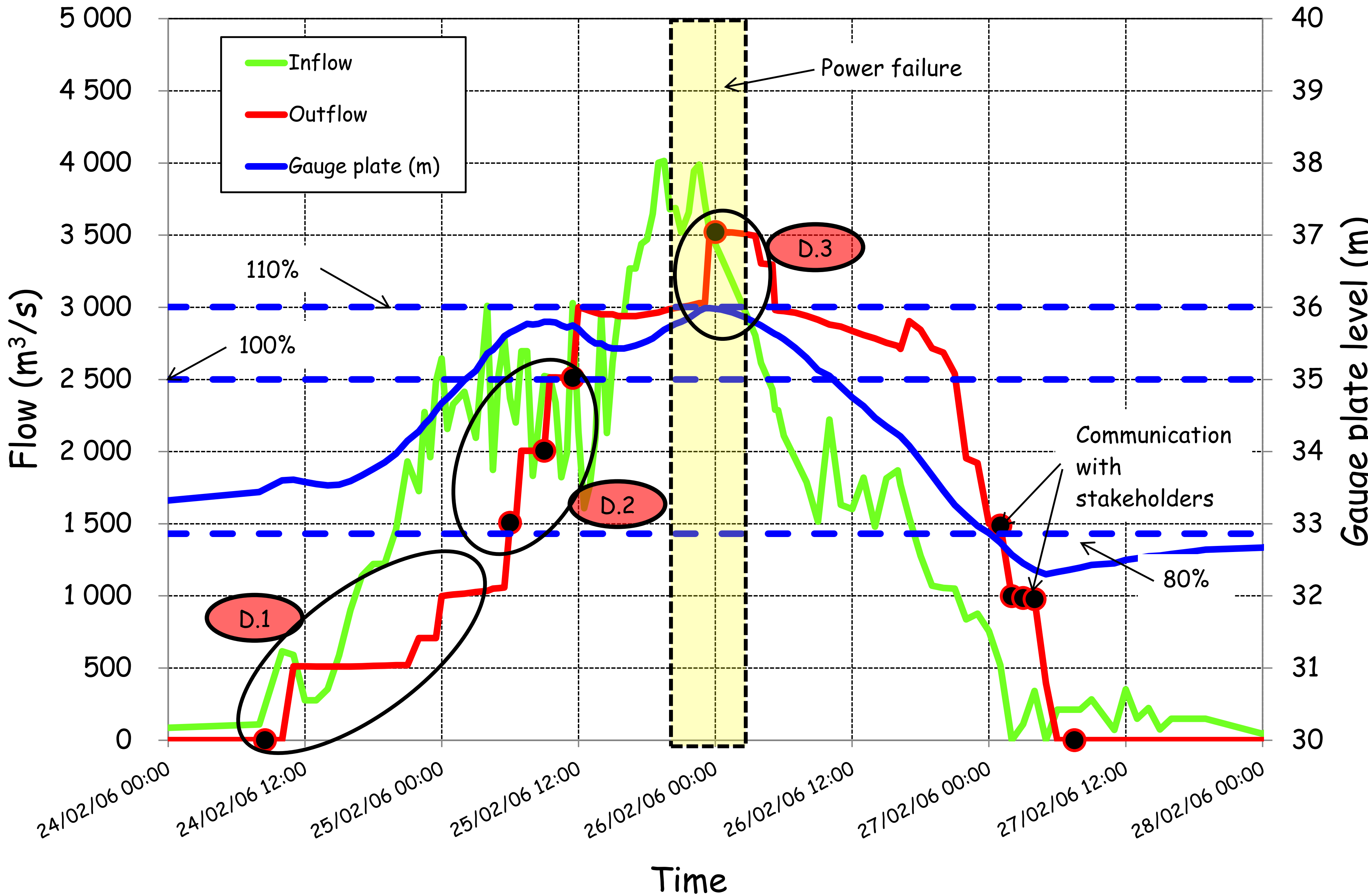
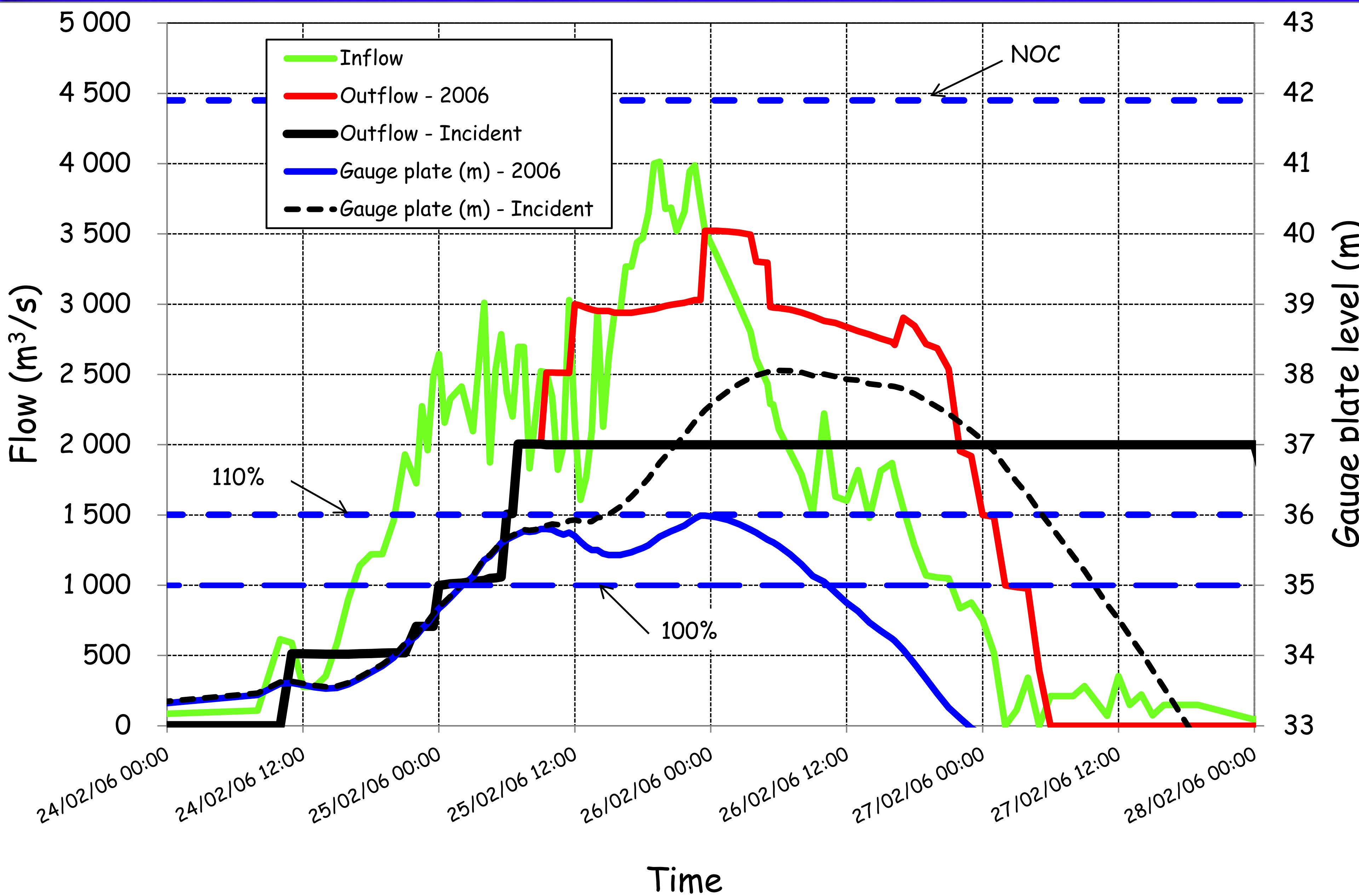
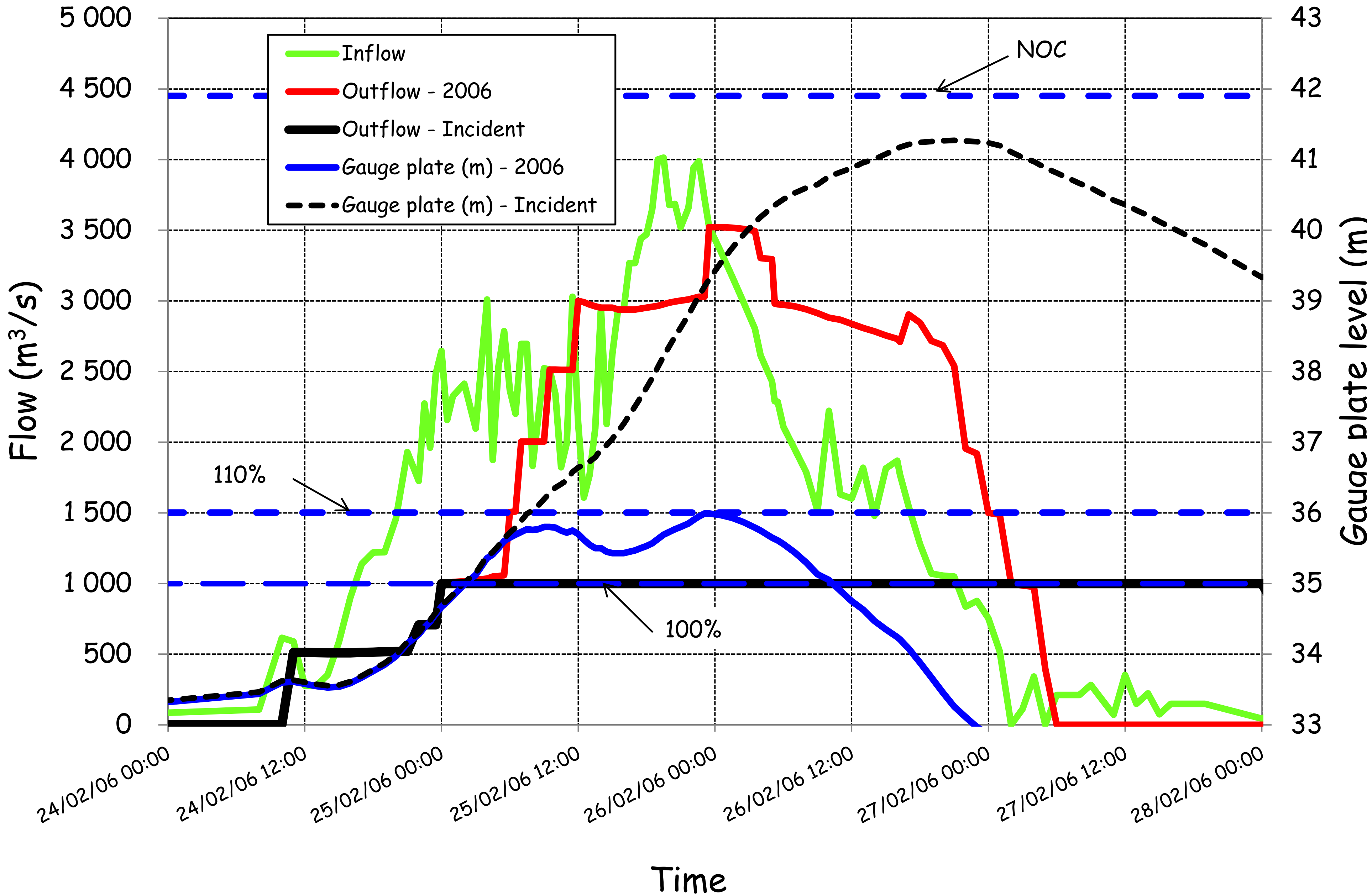
01/03/06
02/03/06
03/03/06
04/03/06



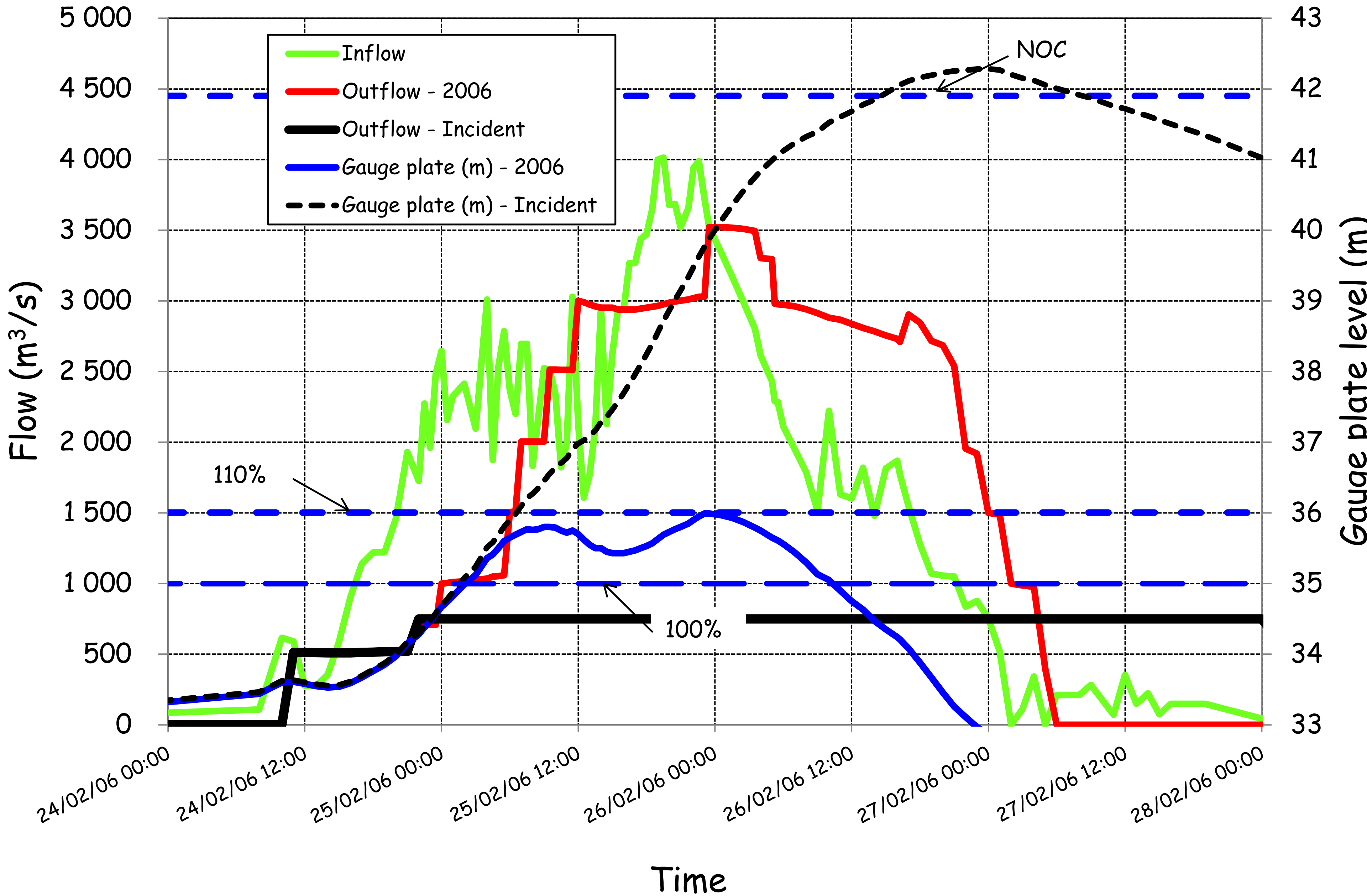
Inflow
Outflow
Gauge plate
Power failure
110%
100%
80%
Communication with stakeholders
Flow (m³/s)
Gauge plate level (m)
Time
5 000
4 500
4 000
3 500
3 000
2 500
2 000
1 500
1 000
500
0
40
39
38
37
36
35
34
33
32
31
30
19/02/06
20/02/06
21/02/06
22/02/06
23/02/06
24/02/06
25/02/06
26/02/06
27/02/06
28/02/06
01/03/06


Inflow
Outflow
Gauge plate (m)
Power failure
110%
100%
D.1
D.2
D.3
Communication with stakeholders
80%
Flow (m3/s)
Gauge plate level (m)
Time
5 000
4 500
4 000
3 500
3 000
2 500
2 000
1 500
1 000
500
0
40
39
38
37
36
35
34
33
32
31
30
24/02/06 00:00
24/02/06 12:00
25/02/06 00:00
25/02/06 12:00
26/02/06 00:00
26/02/06 12:00
27/02/06 00:00
27/02/06 12:00
28/02/06 00:00


5 000
4 500
4 000
3 500
3 000
2 500
2 000
1 500
1 000
500
0
Flow (m³/s)
43
42
41
40
39
38
37
36
35
34
33
Gauge plate level (m)
Inflow
Outflow - 2006
Outflow - Incident
Gauge plate (m) - 2006
Gauge plate (m) - Incident
NOC
110%
100%
24/02/06 00:00
24/02/06 12:00
25/02/06 00:00
25/02/06 12:00
26/02/06 00:00
26/02/06 12:00
27/02/06 00:00
27/02/06 12:00
28/02/06 00:00
Time



Inflow
Outflow - 2006
Outflow - Incident
Gauge plate (m) - 2006
Gauge plate (m) - Incident
NOC
110%
100%
Flow (m³/s)
Gauge plate level (m)
Time
5 000
4 500
4 000
3 500
3 000
2 500
2 000
1 500
1 000
500
0
43
42
41
40
39
38
37
36
35
34
33
24/02/06 00:00
24/02/06 12:00
25/02/06 00:00
25/02/06 12:00
26/02/06 00:00
26/02/06 12:00
27/02/06 00:00
27/02/06 12:00
28/02/06 00:00



Inflow
Outflow - 2006
Outflow - Incident
Gauge plate (m) - 2006
Gauge plate (m) - Incident
NOC
110%
100%
Flow (m^3/s)
Gauge plate level (m)
Time
5 000
4 500
4 000
3 500
3 000
2 500
2 000
1 500
1 000
500
0
43
42
41
40
39
38
37
36
35
34
33
24/02/06 00:00
24/02/06 12:00
25/02/06 00:00
25/02/06 12:00
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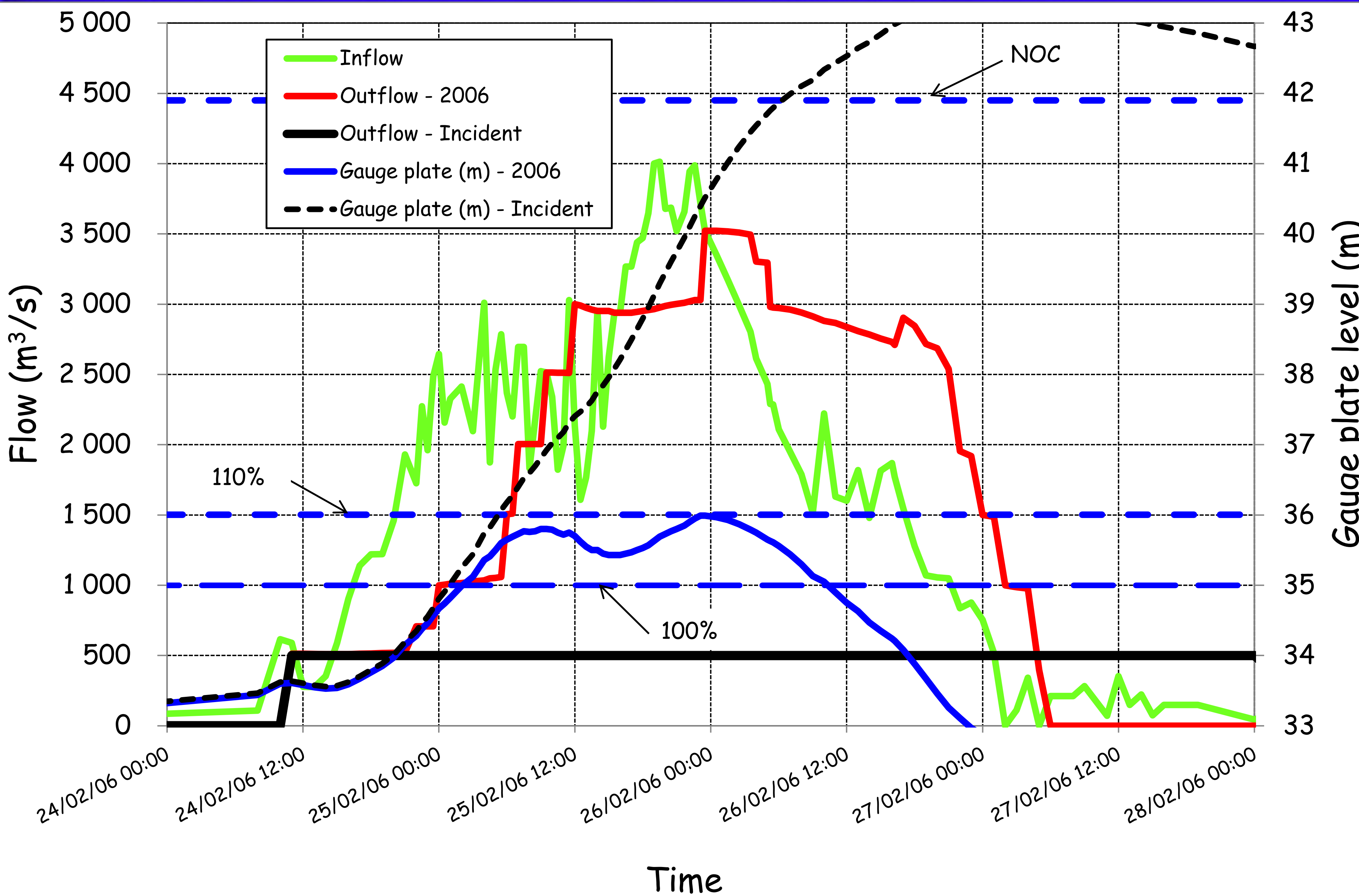
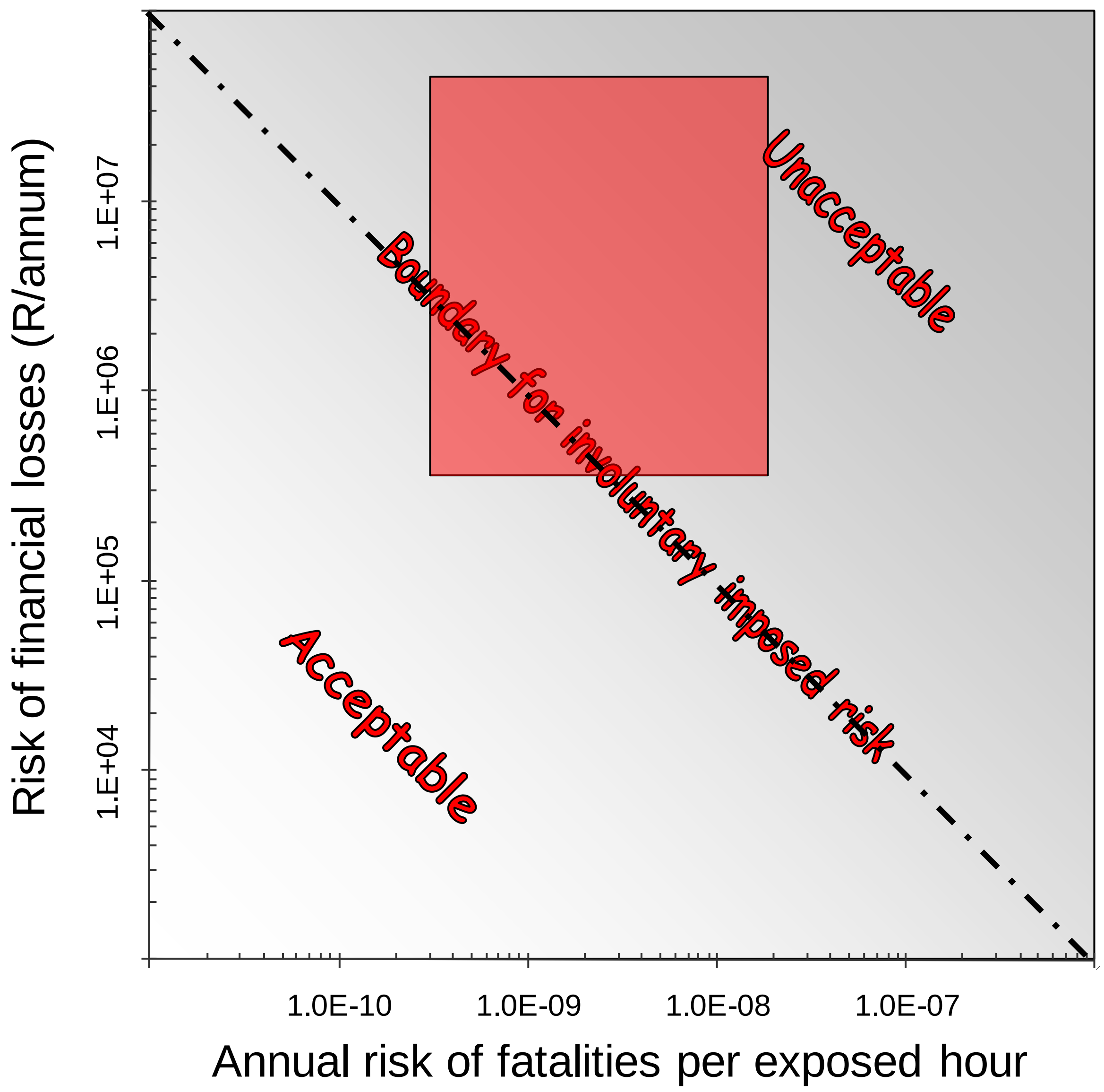
26/02/06 12:00
27/02/06 00:00
27/02/06 12:00
28/02/06 00:00

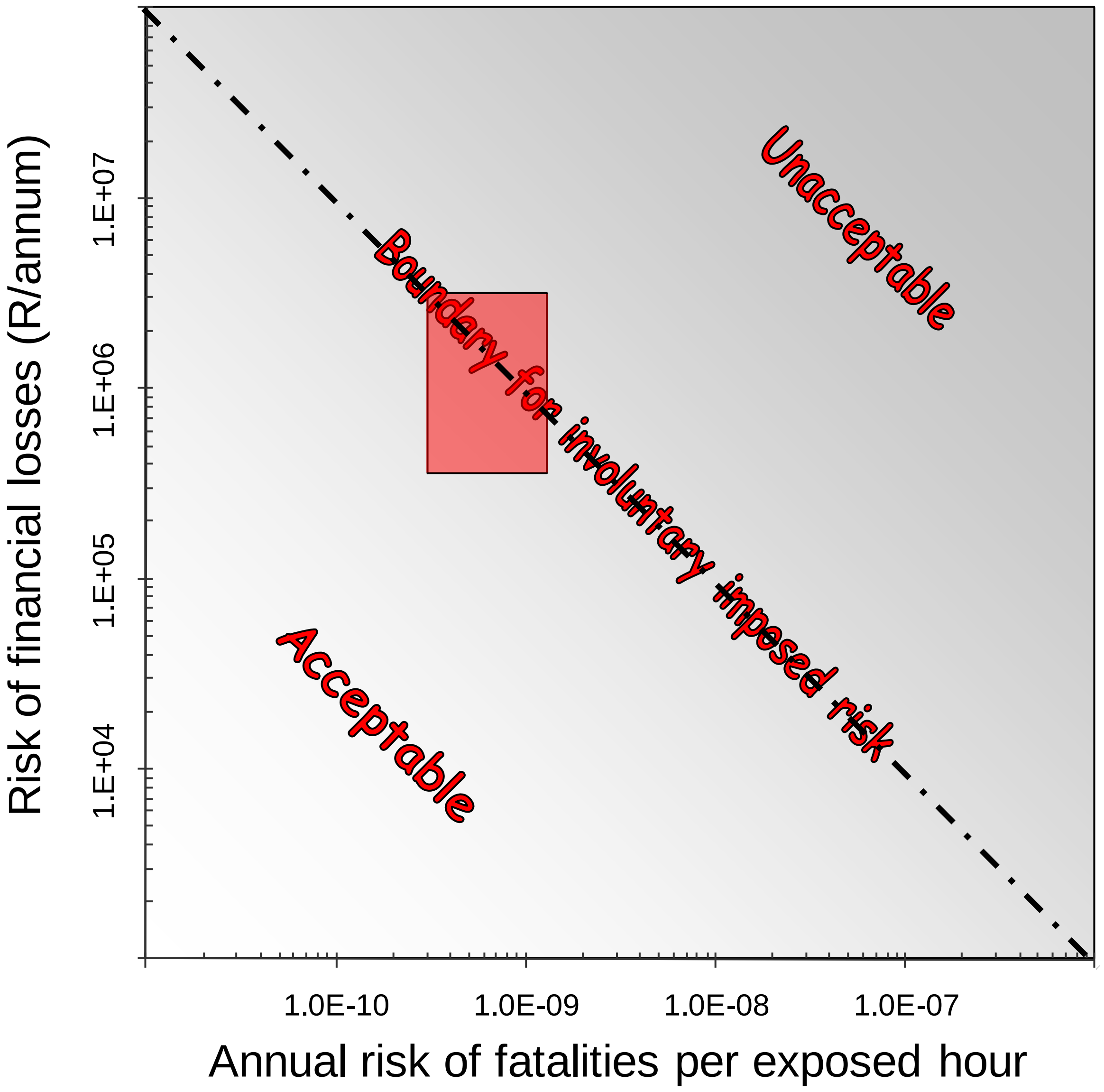

Inflow
Outflow - 2006
Outflow - Incident
Gauge plate (m) - 2006
Gauge plate (m) - Incident
NOC
110%
100%
Flow (m³/s)
Gauge plate level (m)
Time
5 000
4 500
4 000
3 500
3 000
2 500
2 000
1 500
1 000
500
0
43
42
41
40
39
38
37
36
35
34
33
24/02/06 00:00
24/02/06 12:00
25/02/06 00:00
25/02/06 12:00
26/02/06 00:00
26/02/06 12:00
27/02/06 00:00
27/02/06 12:00
28/02/06 00:00


Human impact on risk

Risk level


Unacceptable
Boundary for involuntary imposed risk
Acceptable
Risk of financial losses (R/annum)
1.E+07
1.E+06
1.E+05
1.E+04
1.0E-10
1.0E-09
1.0E-08
1.0E-07
Annual risk of fatalities per exposed hour

Risk level

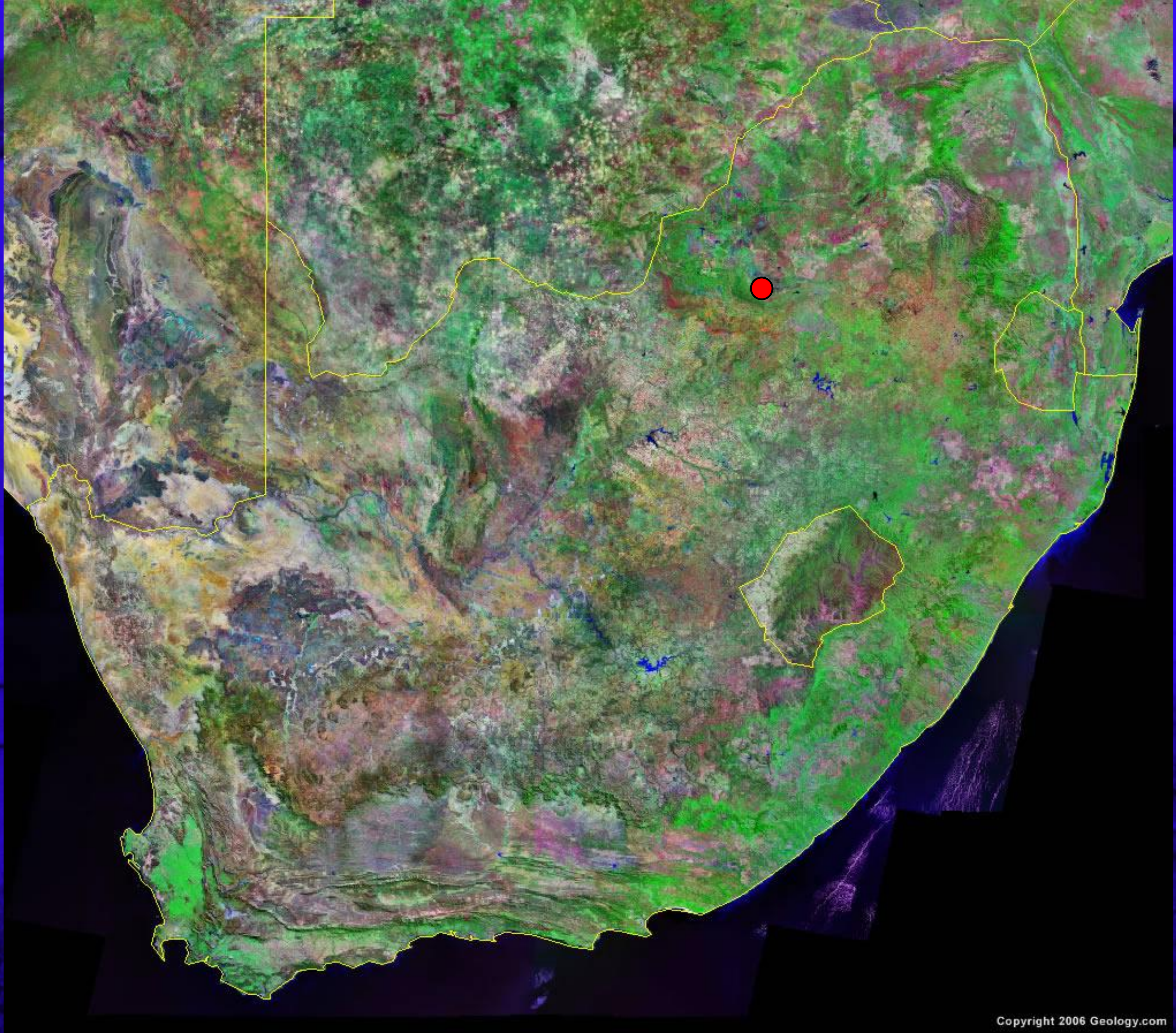


Unacceptable
Boundary for involuntary imposed risk
Acceptable
1.E+07
1.E+06
1.E+05
1.E+04
Risk of financial losses (R/annum)
1.0E-10
1.0E-09
1.0E-08
1.0E-07
Annual risk of fatalities per exposed hour

Conclusions

- Importance of:
  - On site, properly trained and well informed personnel
  - Redundancy


Bospoort Dam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8/4/2004
Image © 2013 DigitalGlobe
249 m
2004
Imagery Date: 8/4/2004 25°33'42.78" S 27°20'52.78" E elev 1085 m eye alt 2.16 km
Google earth


2006 8 16

Bospoort Dam

- Concrete gravity: 23 m high
- 3 embankments
- Completed in 1933 as buttress concrete gravity
- 1953: Raised into concrete gravity
- 1969: Raised with 12 radial crest gates + anchored by post tensioned anchors

Radial gate power sources

- National grid
- Small mobile generator operated at gates

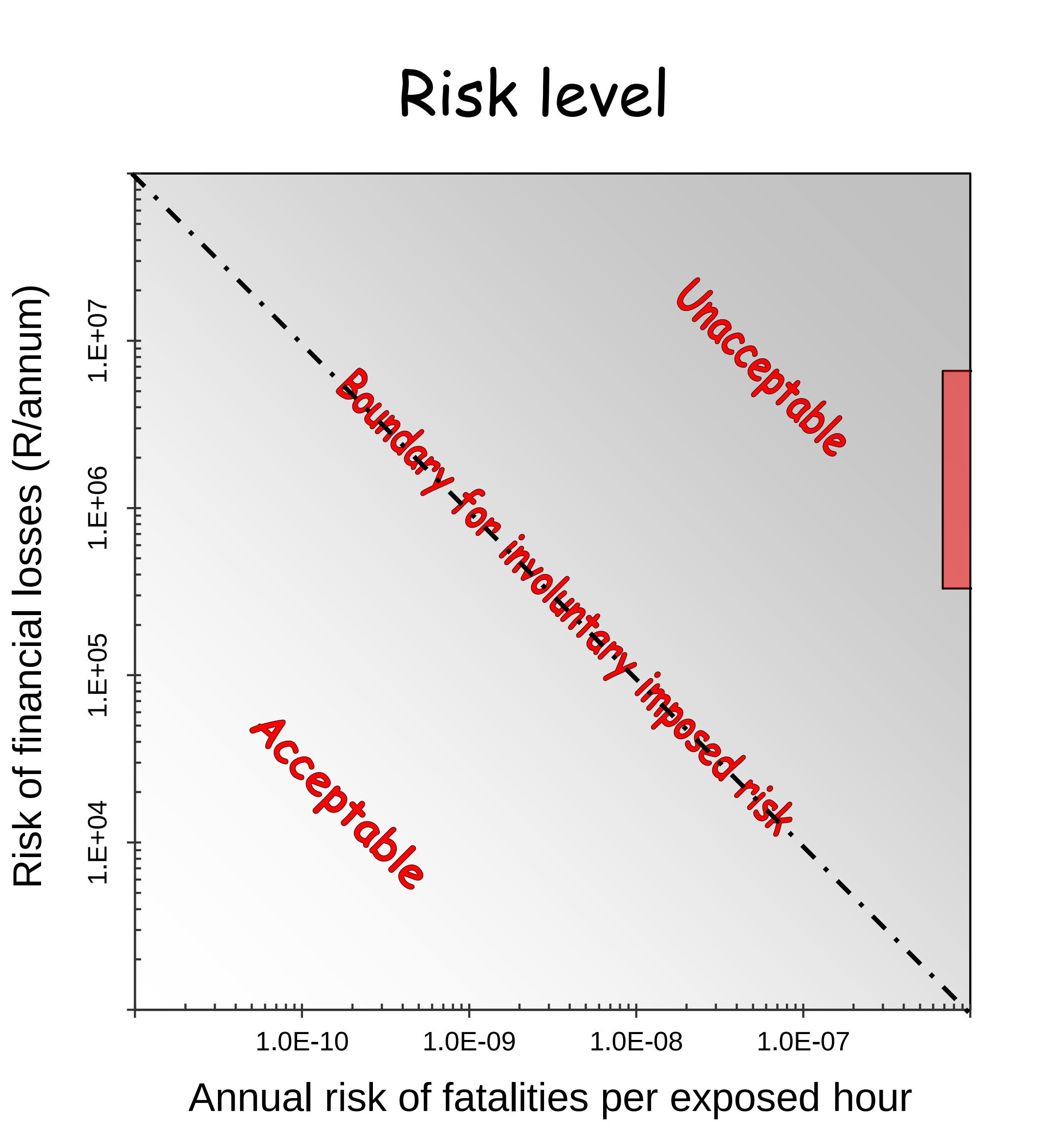

December 2004


HONDA

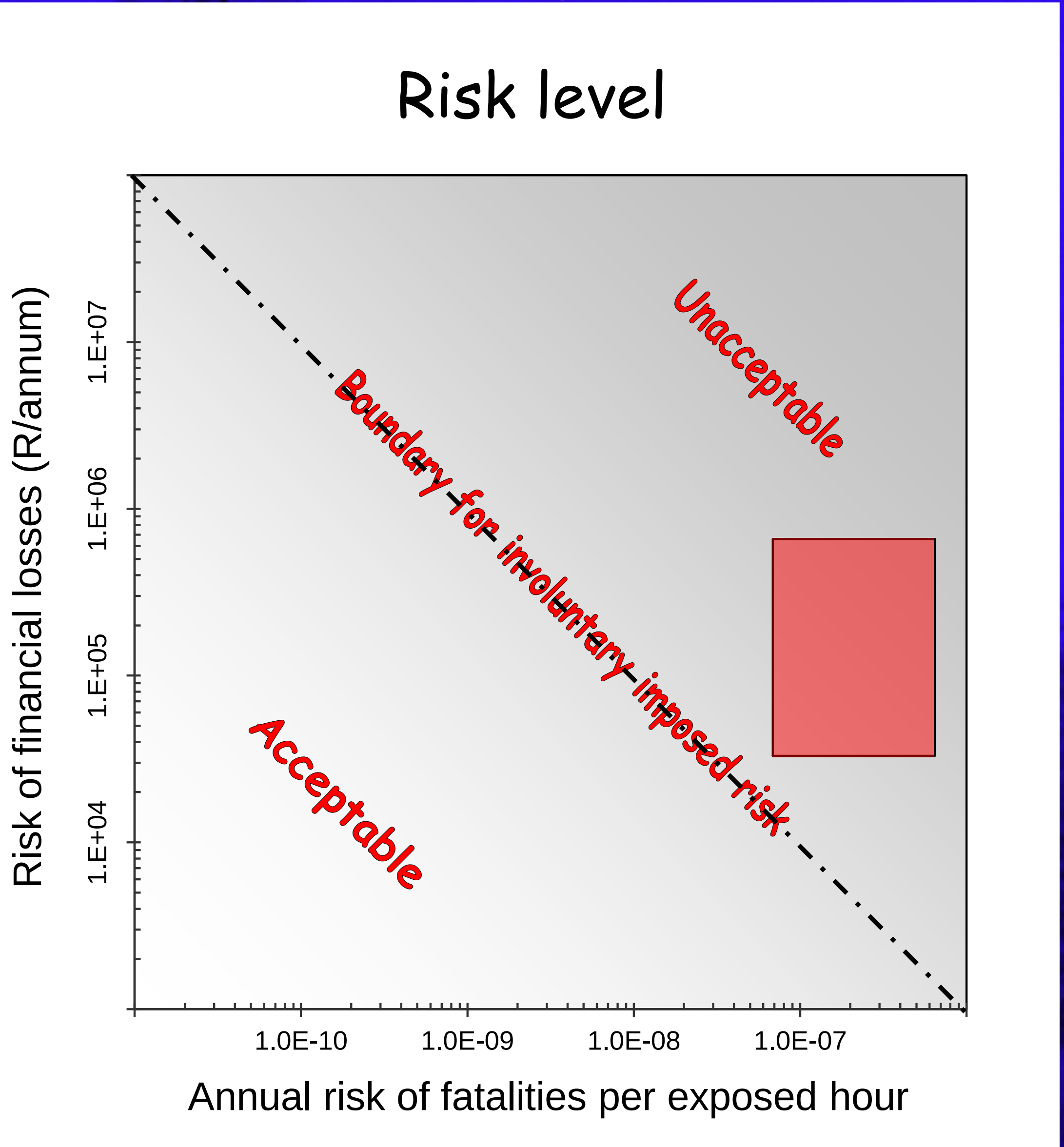
Issues

- Operator not stationed @ dam (30 km away)
- Power cable stolen
- Backup generator not functioning
- 5 out of 12 gates' cables completely corroded
- Water spilling over gates

2004


Risk level
Unacceptable
Boundary for involuntary imposed risk
Acceptable
Risk of financial losses (R/annum)
1.E+07
1.E+06
1.E+05
1.E+04
1.0E-10
1.0E-09
1.0E-08
1.0E-07
Annual risk of fatalities per exposed hour

Normal operation




8/4/2004
Image © 2013 DigitalGlobe
249 m
2004
Imagery Date: 8/4/2004 25°33'42.78" S 27°20'52.78" E elev 1085 m eye alt 2.16 km
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10/7/2012
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10/7/2012
Image © 2013 DigitalGlobe
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10/7/2012
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2004
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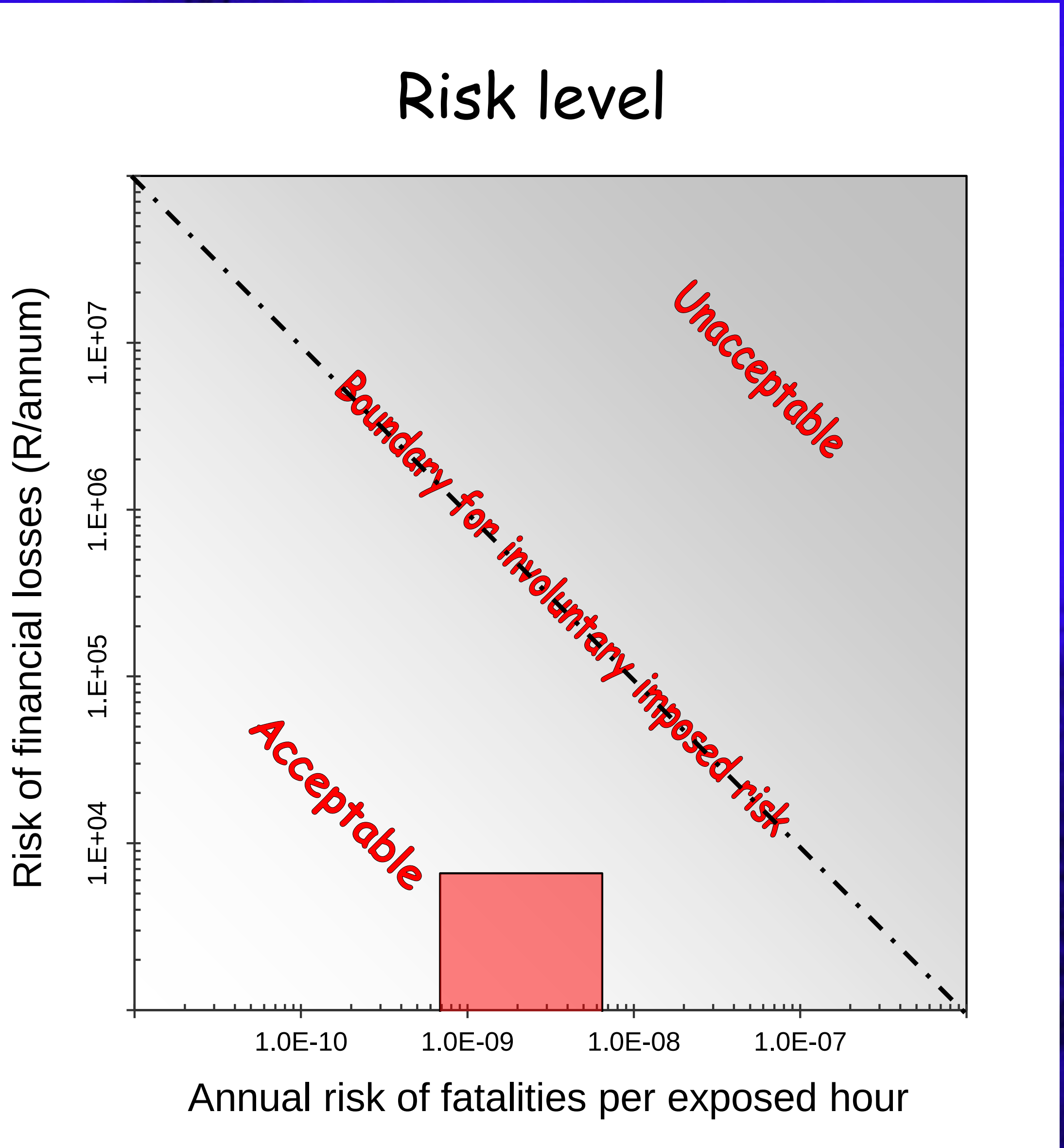
25°33'42.78" S 27°20'52.78" E elev 1085 m
eye alt 2.16 km
Google earth

Rehabilitated



Conclusions

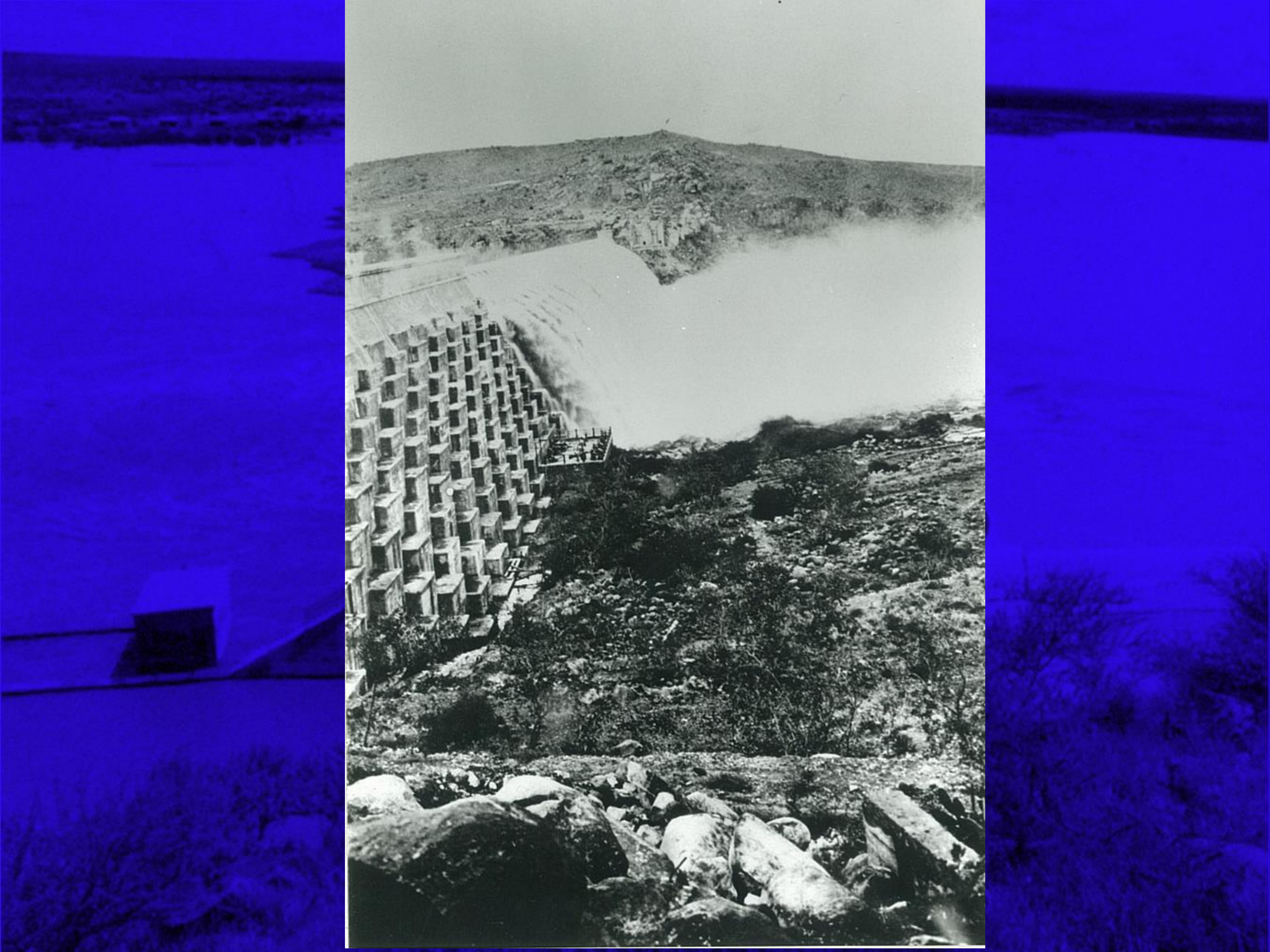
- Failure waiting to happen
- Lack of:
  - On site personnel
  - Redundancy
  - Maintenance

Lake Arthur Dam

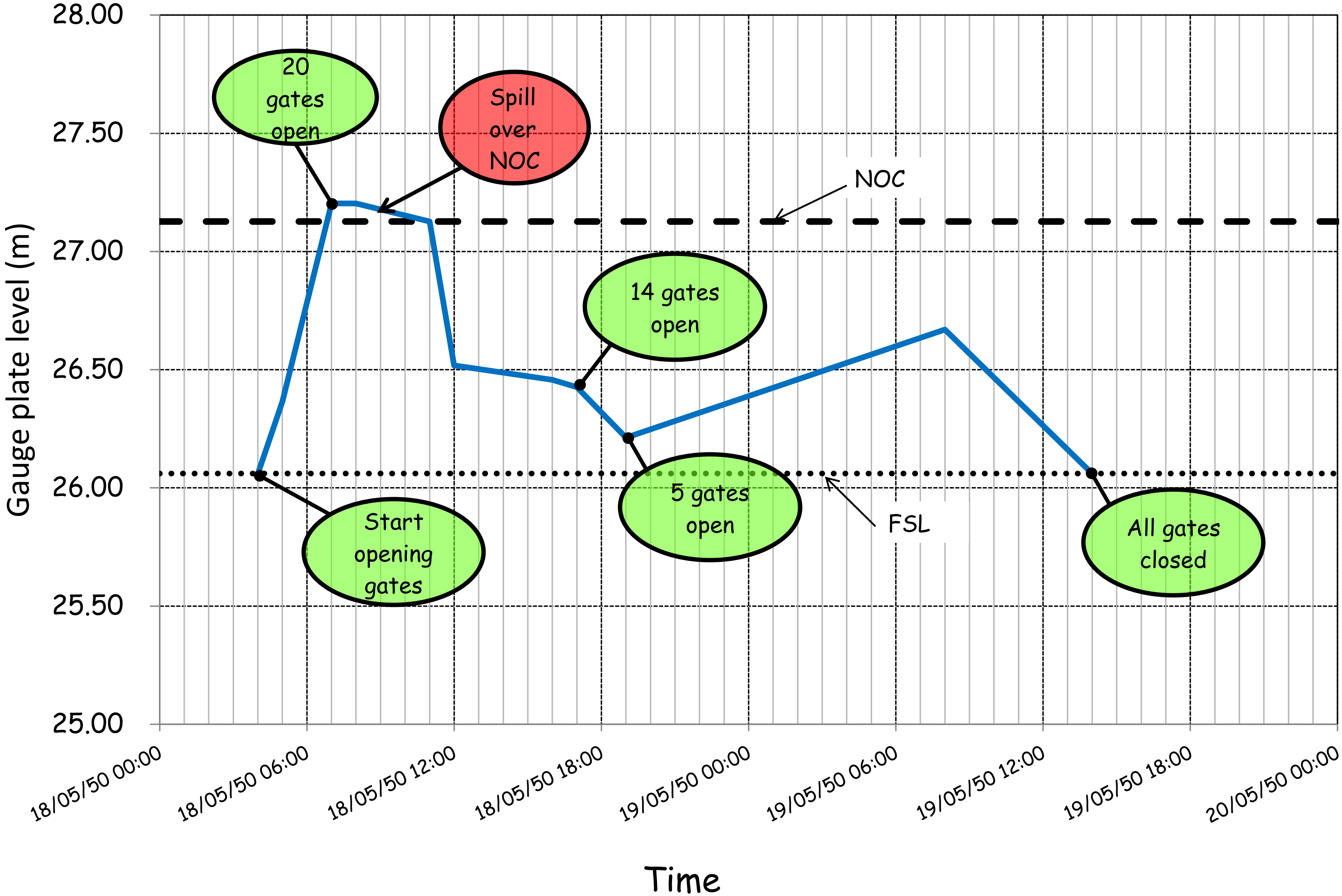

Copyright 2006 Geology.com

Lake Arthur Dam

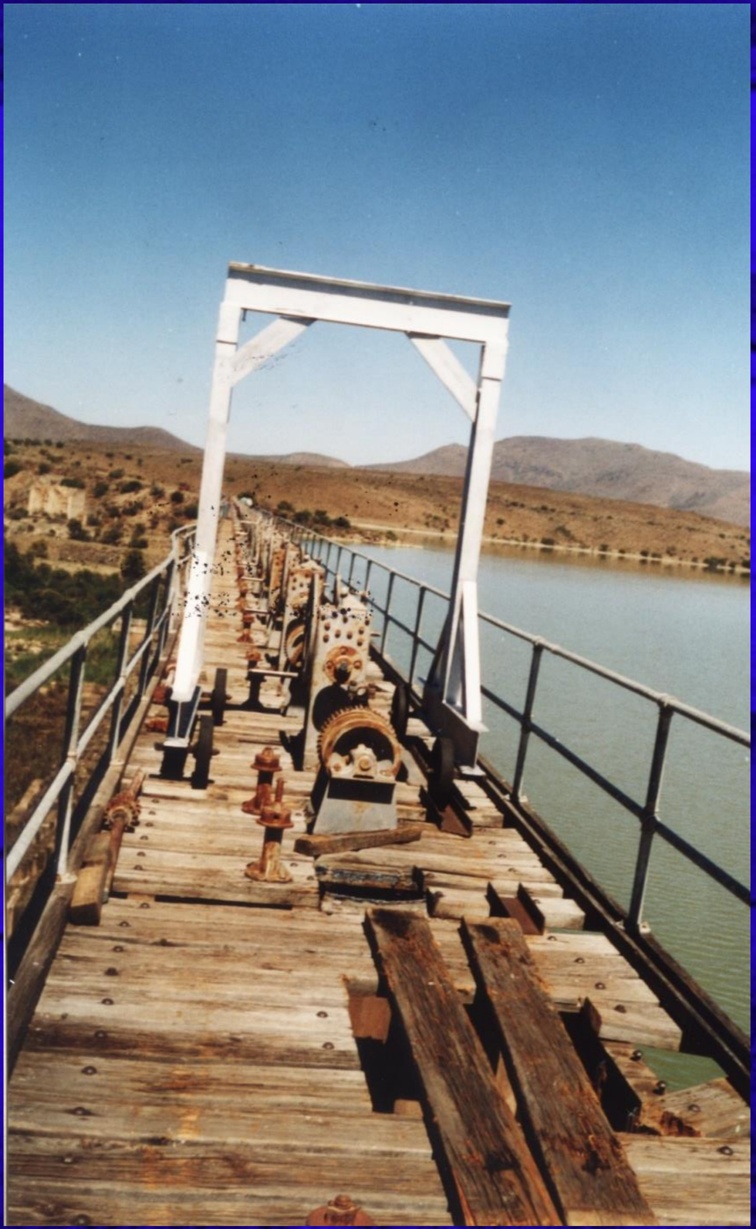
- Concrete gravity: 33.7 m high
- Completed in 1924
- 1939: 66 roller (sluice) gates on spillway crest – lifted by manually operated winch
- 1945: Gates extended by 0.9 m
- 2003: Gates removed




May 1950



Gauge plate level (m)
28.00
27.50
27.00
26.50
26.00
25.50
25.00
20 gates open
Spill over NOC
NOC
14 gates open
5 gates open
FSL
Start opening gates
All gates closed
18/05/50 00:00
18/05/50 06:00
18/05/50 12:00
18/05/50 18:00
19/05/50 00:00
19/05/50 06:00
19/05/50 12:00
19/05/50 18:00
20/05/50 00:00
Time



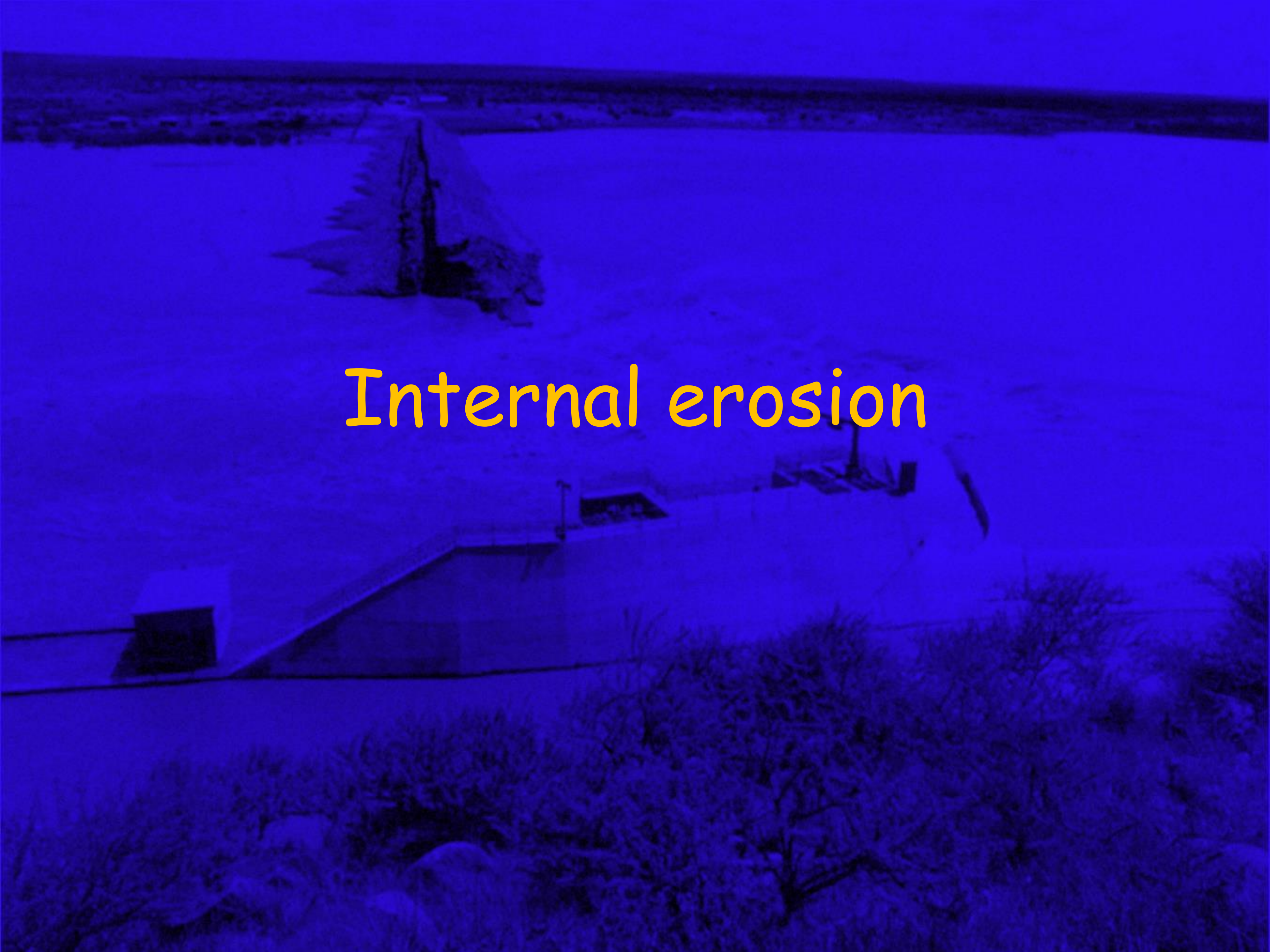
Conclusions

- Fatal flaw in design – opening speed
- Lack of:
  - On site personnel
  - Redundancy
  - Maintenance

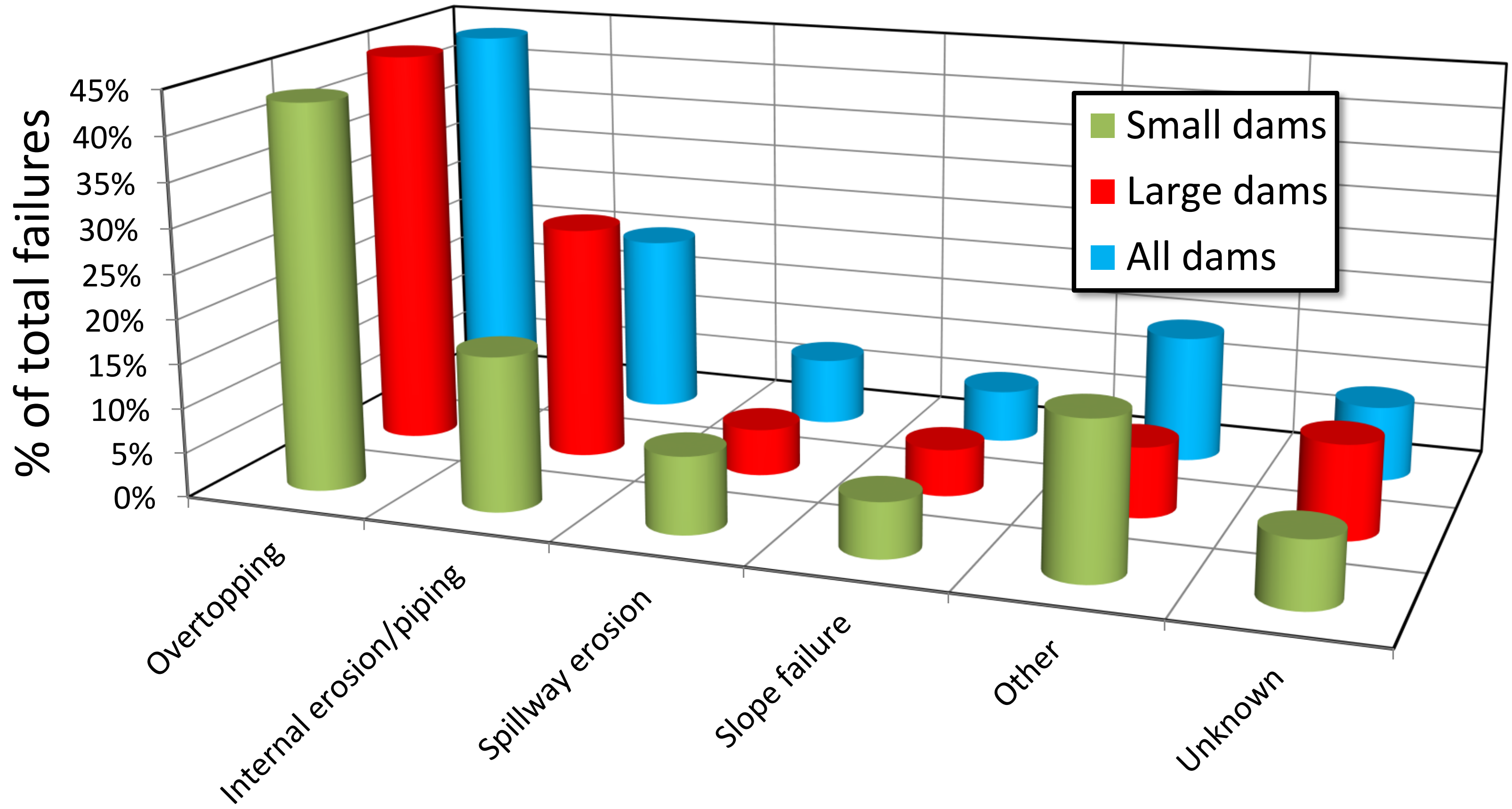
The bottom line

- Planning decisions = increased risk compared to uncontrolled spillways
- Increased risk by:
  - Inefficient design
  - Lack of proper operation and maintenance
  - The human factor

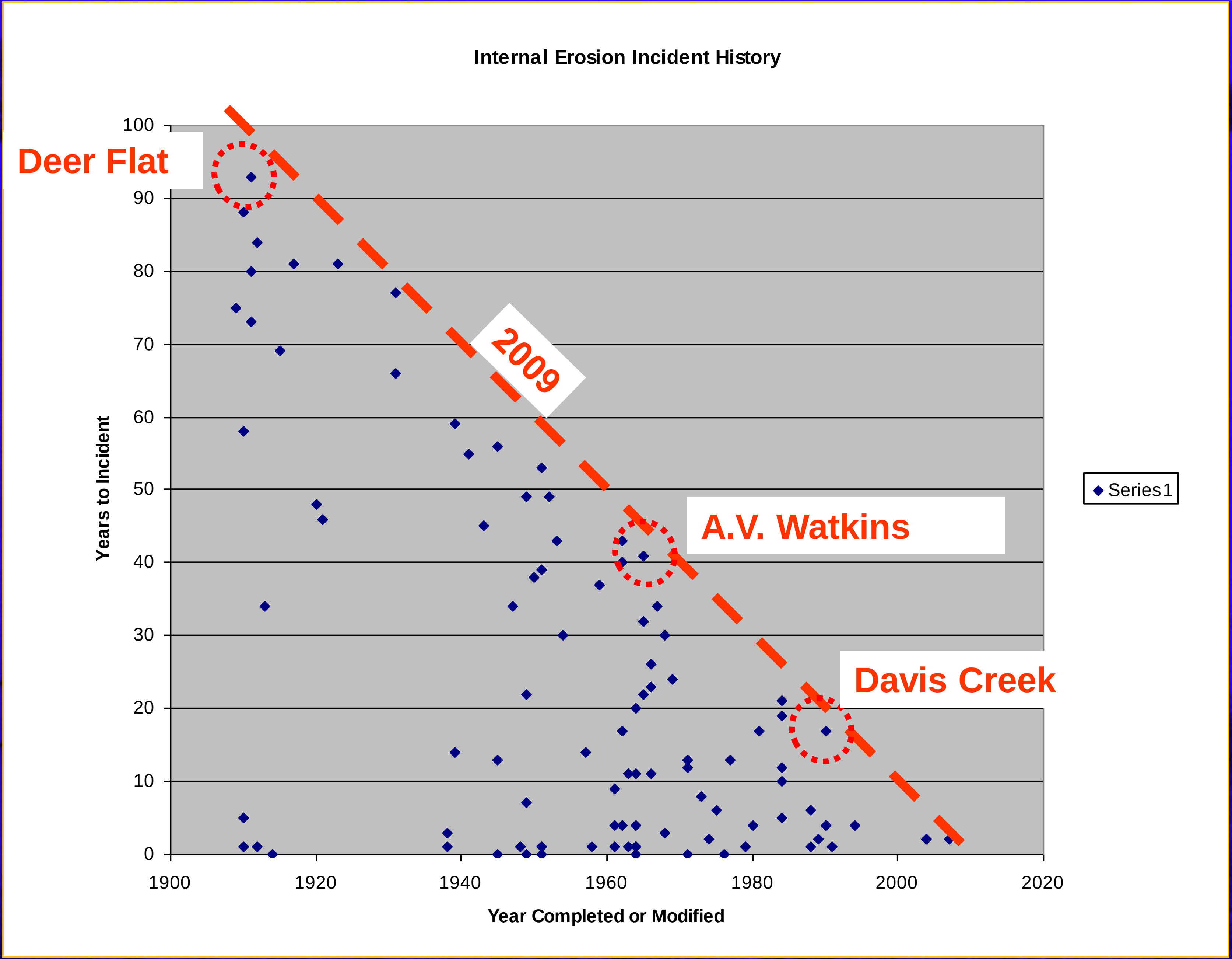
⇨ Incident


Internal erosion

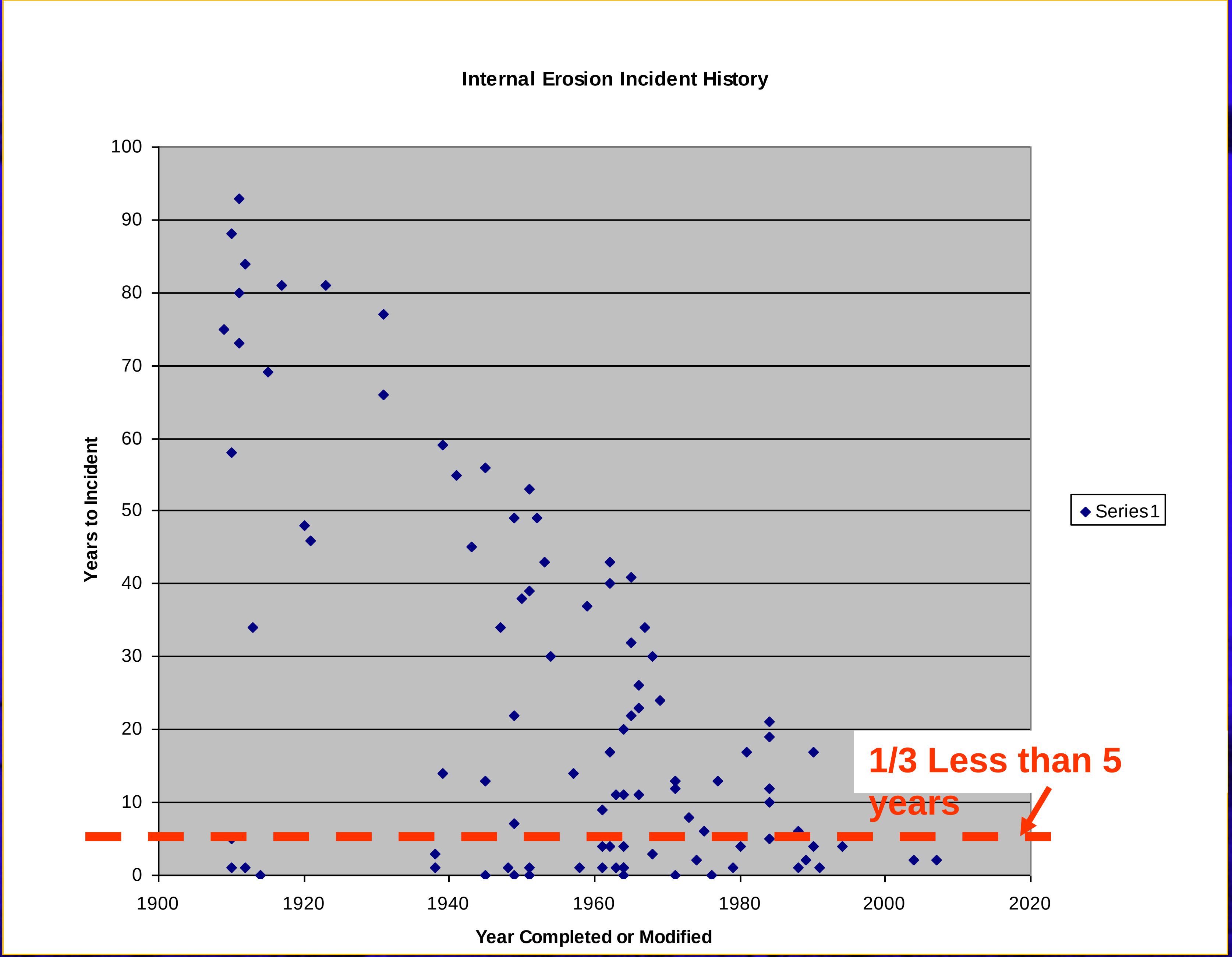
South Africa - 2016



ONLY EMBANKMENT FAILURES



Internal Erosion Incident History
Deer Flat
2009
A.V. Watkins
Davis Creek
Years to Incident
Year Completed or Modified
Series1
0
10
20
30
40
50
60
70
80
90
100
1900
1920
1940
1960
1980
2000
2020


Internal Erosion Incident History
Years to Incident
100
90
80
70
60
50
40
30
20
10
0
1900
1920
1940
1960
1980
2000
2020
Year Completed or Modified
Series1
1/3 Less than 5 years

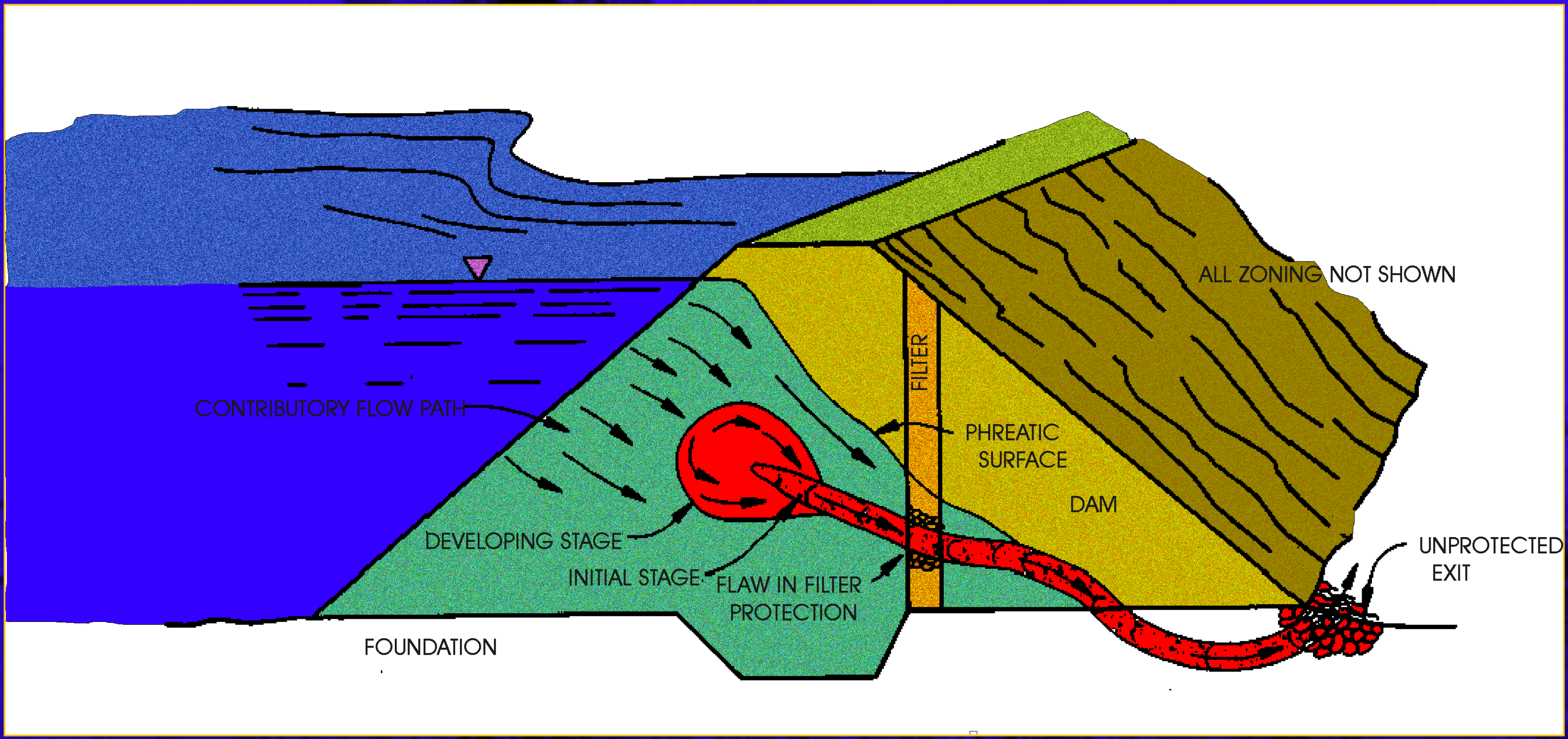
Internal Erosion Failure mechanisms

- Because internal erosion can occur during “normal” operations, it may pose higher risks to a dam than hydrologic (flood) and seismic (earthquake) loadings.
- “Piping” is a special type of internal erosion

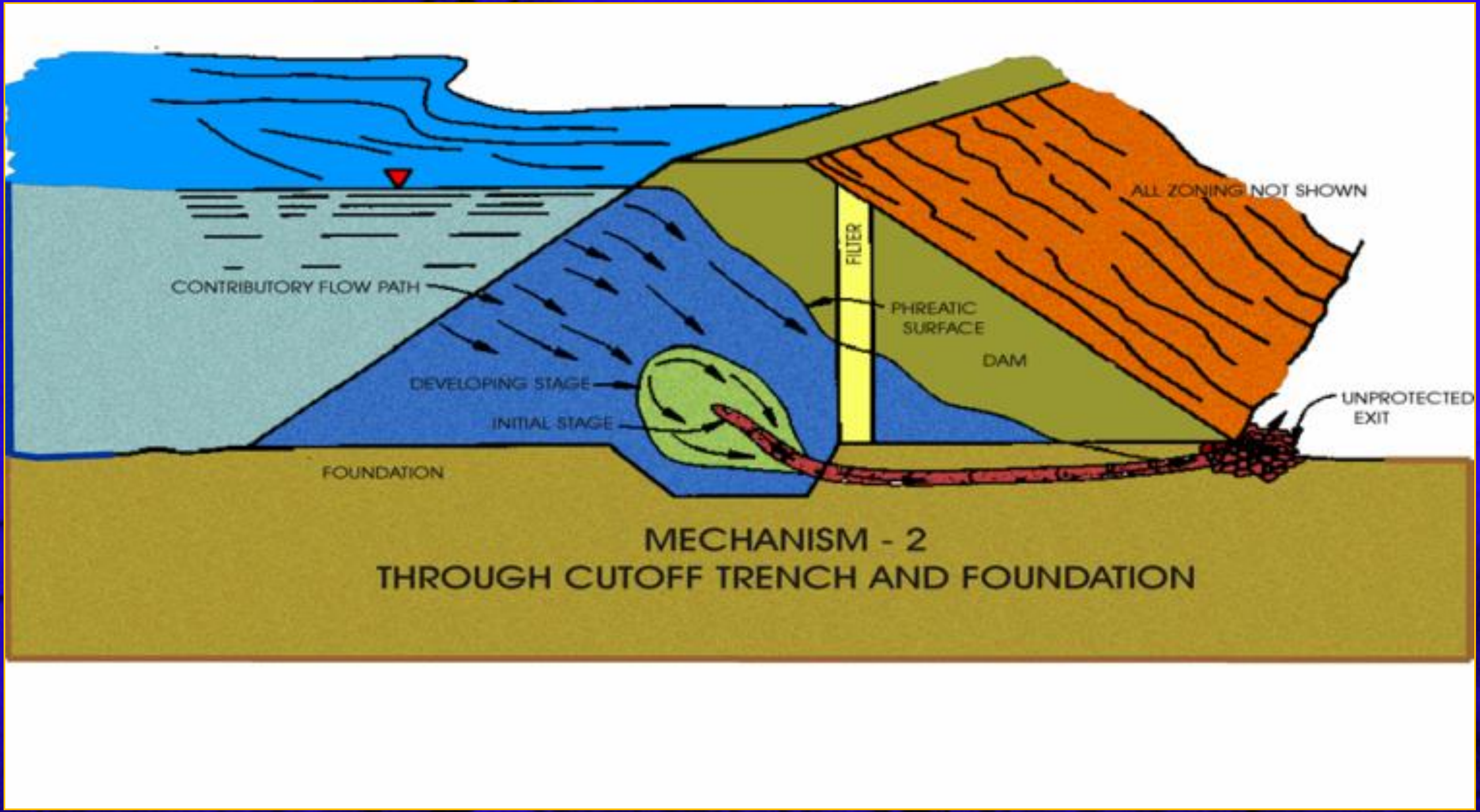
Definitions

- Internal erosion occurs when soil particles within an embankment dam or its foundation are carried downstream by seepage flow.
- Internal erosion can initiate by:
  - Concentrated leak erosion
  - Backward erosion
  - Internal instability
  - Soil contact erosion

Erosion through the embankment

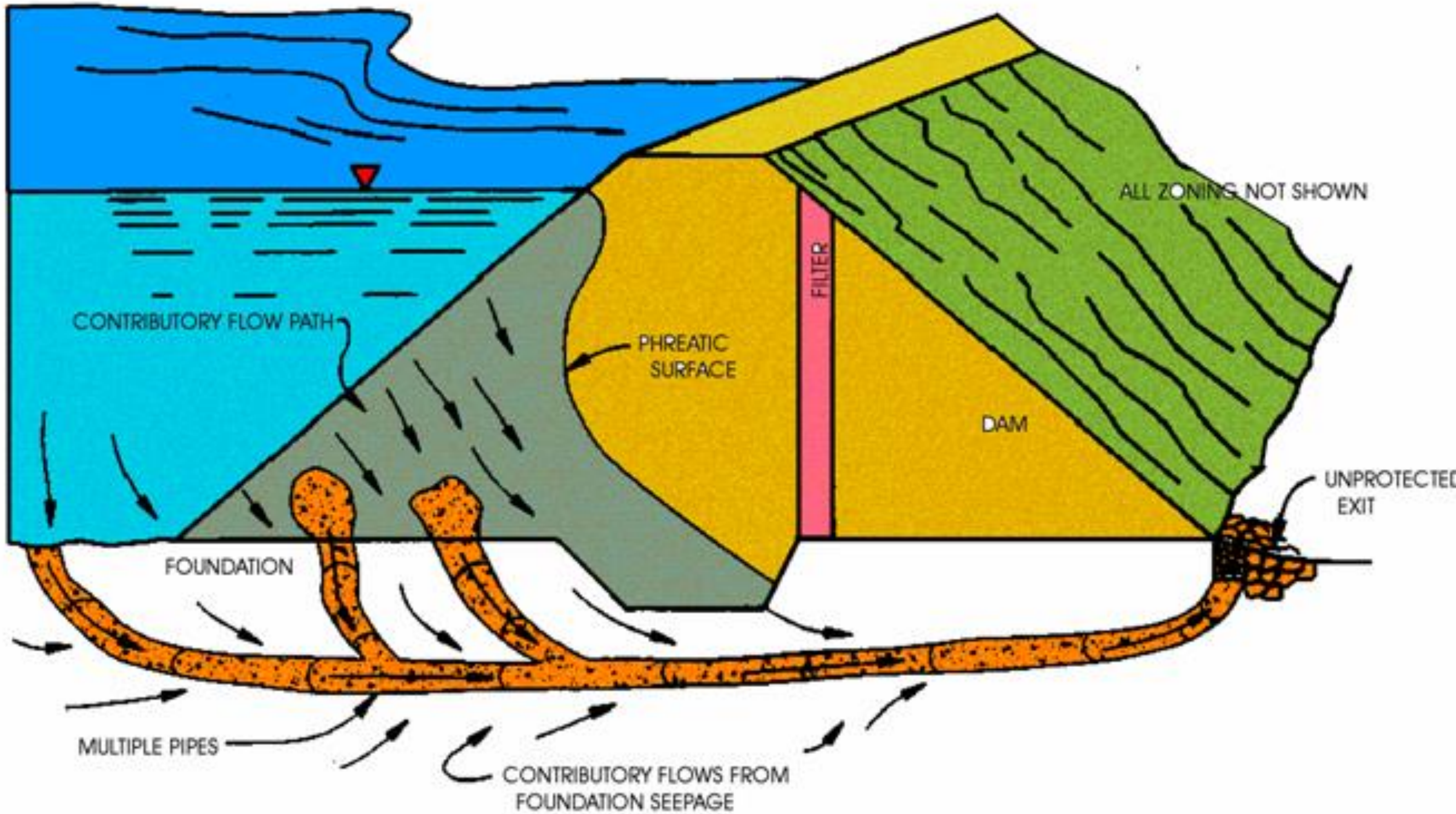


Erosion of the embankment along and into the foundation



Erosion in/through the foundation

Responsible for about 2/3 of USBR Incidents



Google earth
Image © 2015 DigitalGlobe
300 m
N

Zoeknog dam failure introduction

Background

Owner:
Lebowa Homeland Government
Construction embankment:
In-house Lebowa Homeland Government
Construction concrete
Grinaker
Design and site supervision:
Eksteen,van der Walt and Nissen

Basic Statistics

Height: 40 m
US slope: 2,5:1 upper part
4,0:1 lower down
DS slope: 2,0:1
Central clay core: 0,8:1
Chimney drain: Sand with Geo-textile upstream Blanket drain: Geotextile, sand, gravel and geotextile
Geology: Weathered granites

In hindsight

Dispersiveness tests only done prior to construction and not during construction
AASHTO specifications resulted in drier than optimum PROCTER moisture content
Homogeneous constructed
Blanket drain: 38mm aggregate sandwiched between geotextiles

Zoeknog dam failure timeline

In hindsight (2)

Piezometers installed by Fil Filmalter (Kop-Kop) Latter discovered that blanket drain (left of outlet tunnel) not on founding level but 5m higher (indicated as founding level on drawings

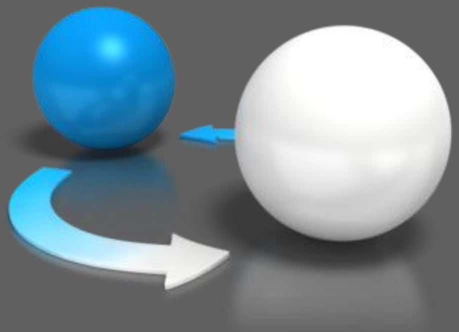
Several warnings on OMC: Filmalter and DWA officials, (unofficially) pointed dubious OMC out

Piezometer warning:

Impoundment started towards end of 1992

Filmalter warned that one of the piezometers installed on the left-hand side of the outlet work is recording high pressures

Piezometer warning ignored 10 Jan 1993



Zoeknog dam failure timeline

Jan 25 1993:
Dam failure early morning hours
Soon after midnight guard heard water running …
Progressed from piping to dam empty in 6 hours.
No lives lost

Feb 2 & 4
Dam safety
First investigations:

Feb 12
Another investigation

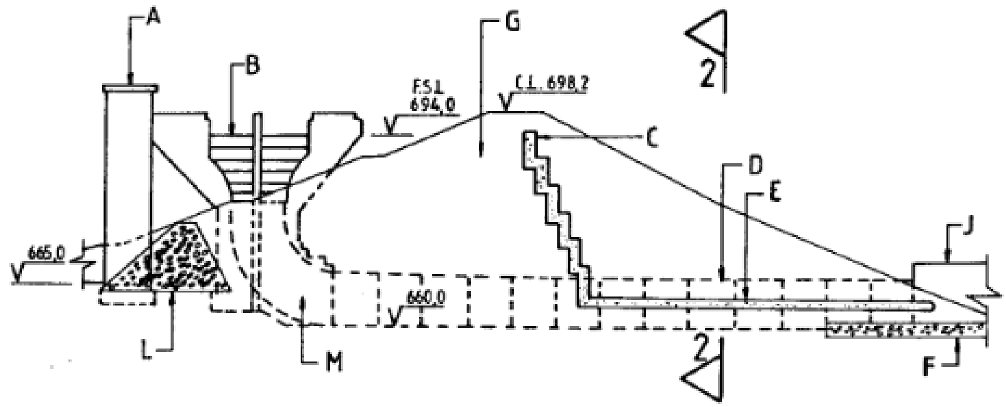


Fig. 1 (1-1)

Cross section of embankment adjacent to conduit

NOTATION

- A- INTAKE TOWER
- B- MORNING GLORY SPILLWAY
- C- CHIMNEY DRAIN
- D- CONDUIT
- E- BLANKET DRAIN
- F- STONE DRAIN
- G- EMBANKMENT FILL
- H- FOUNDATION LEVEL
- I- TRENCH FILLING
- J- TRAINING WALL
- K- ROCK EXCAVATION FACE
- L- ROCKFILL CONE
- M- SPILLWAY SHAFT

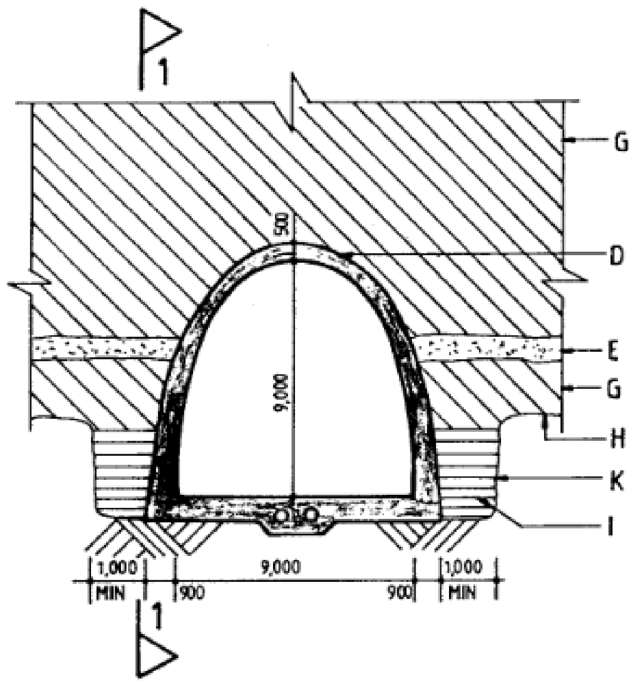


Fig. 2 (2-2)

Zoeknog Dam

- Importance of a diligent and experienced instrumentation installer
- Ignore monitoring results @ your own peril
  - Site supervision staff ignored potential failure mode indicated by piezometer results - was considered as a sensor failure

WALLY HOLMES DAM

Failure due to internal erosion caused by poor compaction.

WALLY HOLMES DAM

Note size of "pipe or tunnel" compared to height of the interested observer

Structural failures

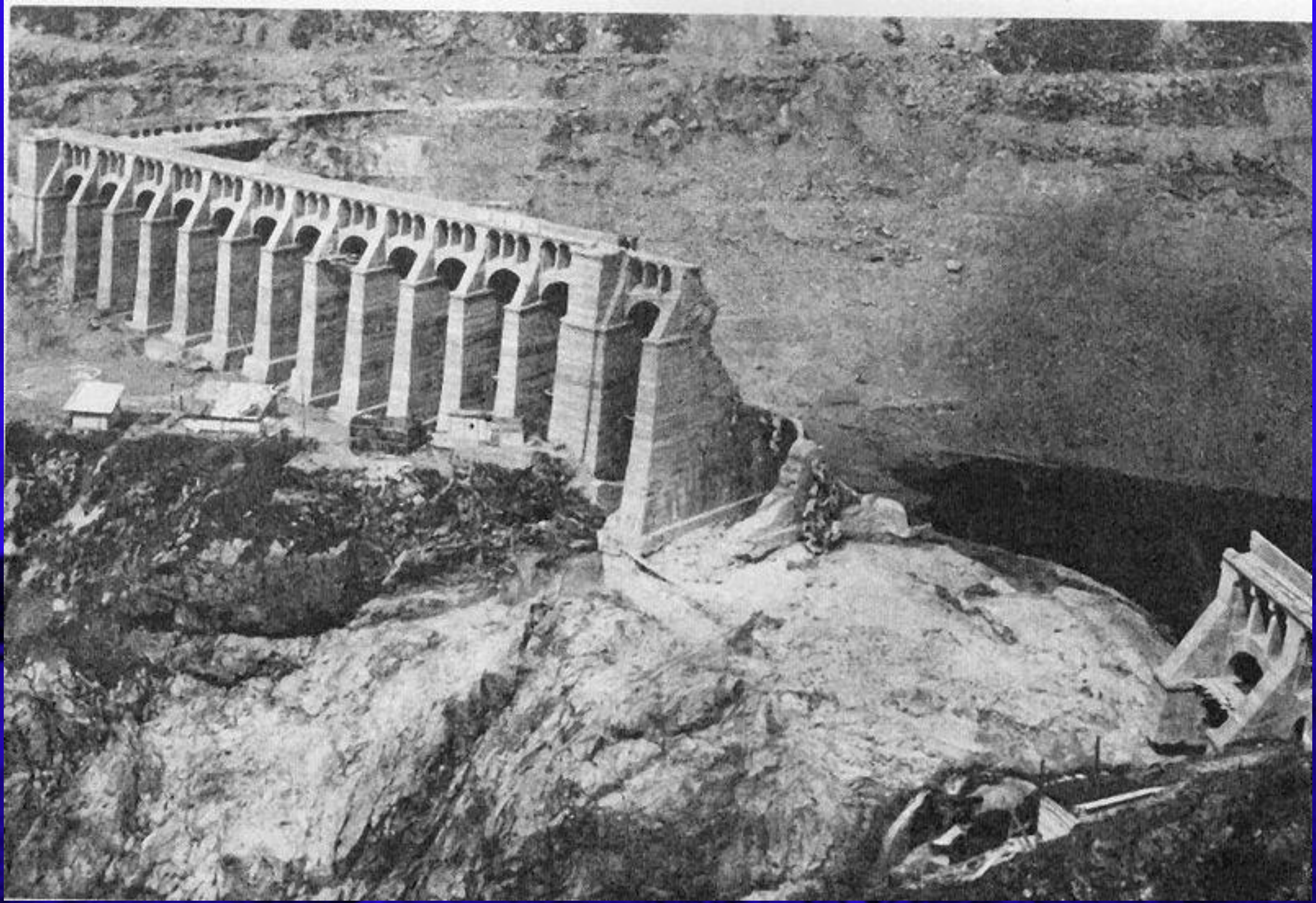
- Concrete gravity dams failures
  - St Francis Dam, USA
  - Camara Dam, Brazil
- Concrete buttress dam failures
  - Gleno Dam, Italy
- Concrete arch dam failures
  - Malpasset Dam, France

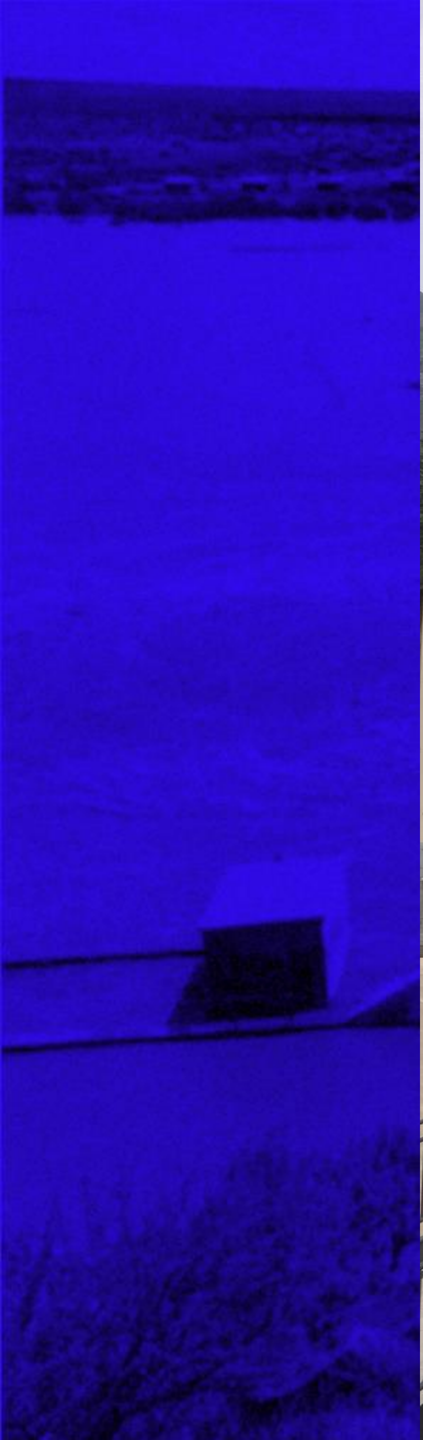
Gleno Dam, Italy

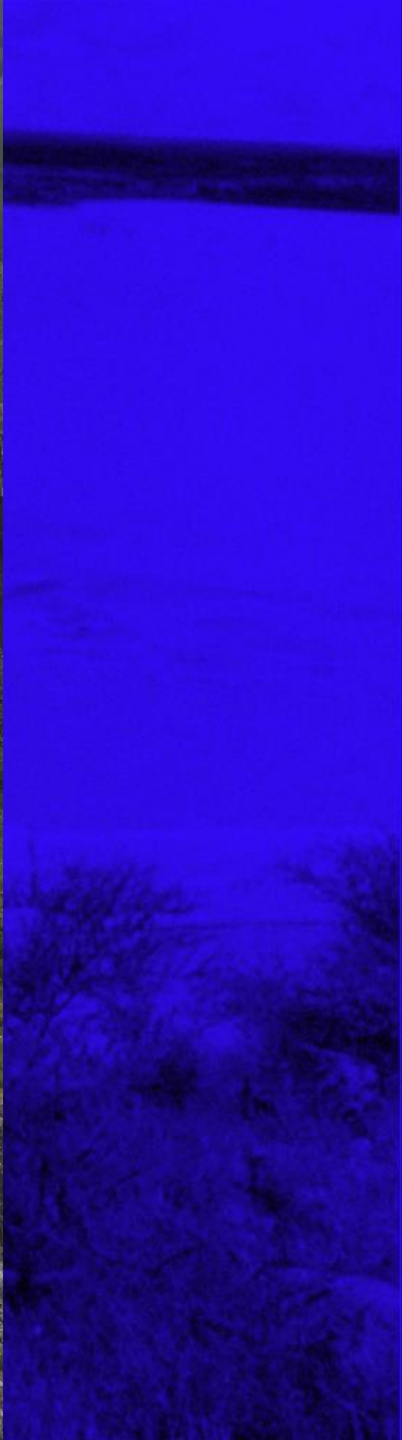
Gleno Dam, Italy

- 50 m high multiple concrete arch dam 213 m long
- Masonry gravity plug built in deep central valley gorge (use lime mortar instead of cement mortar)
- Original concrete gravity
- Changed to multiple arch but not approved
- 1923:
  - Failure of one of the buttresses leading to multiple arch failure
  - 356 fatalities

Gleno Dam, Italy







Gleno Dam, Italy

- Change in design
- Iffy concrete quality
- Inappropriate material
  - Lime mortar for masonry section
- Settlement of masonry plug?

Hydraulic

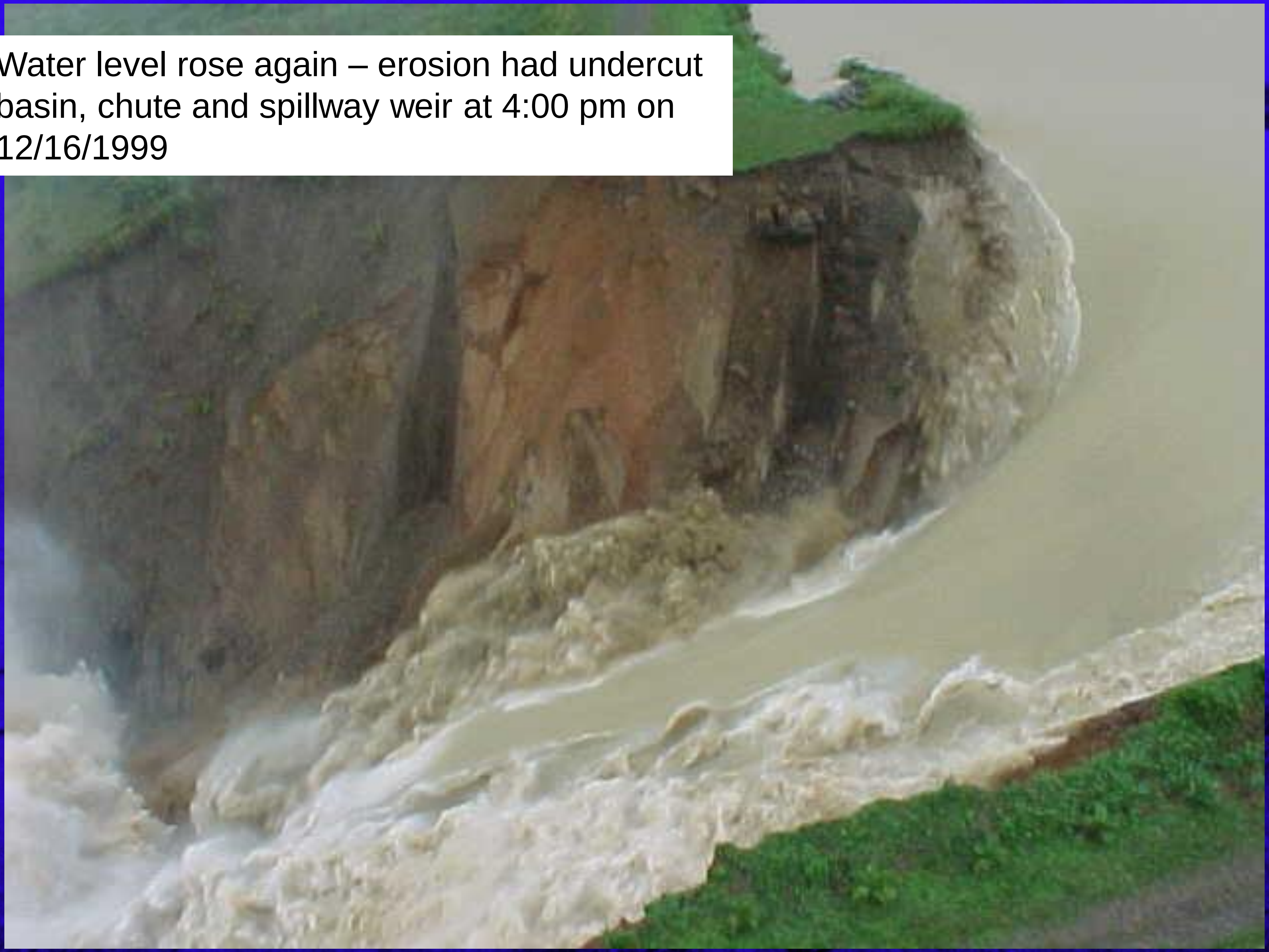
- Failure due to erosion of rock
  - Kariba Dam, Zambia/Zimbabwe
- Failure due to overtopping of spillway walls and stilling basins
  - El Guapo Dam, Venezuela
- Stagnation Pressure Failure of Spillway Chutes
- Cavitation Damage Induced Failure of Spillways

El Guapo Dam, Venezuela


Flow outside the spillway chute
Walls Began to overflow at 1:15 am on 12/16/1999

Water level behind dam decreased at 9:00 am on 12/16/1999

Water level rose again – erosion had undercut basin, chute and spillway weir at 4:00 pm on 12/16/1999



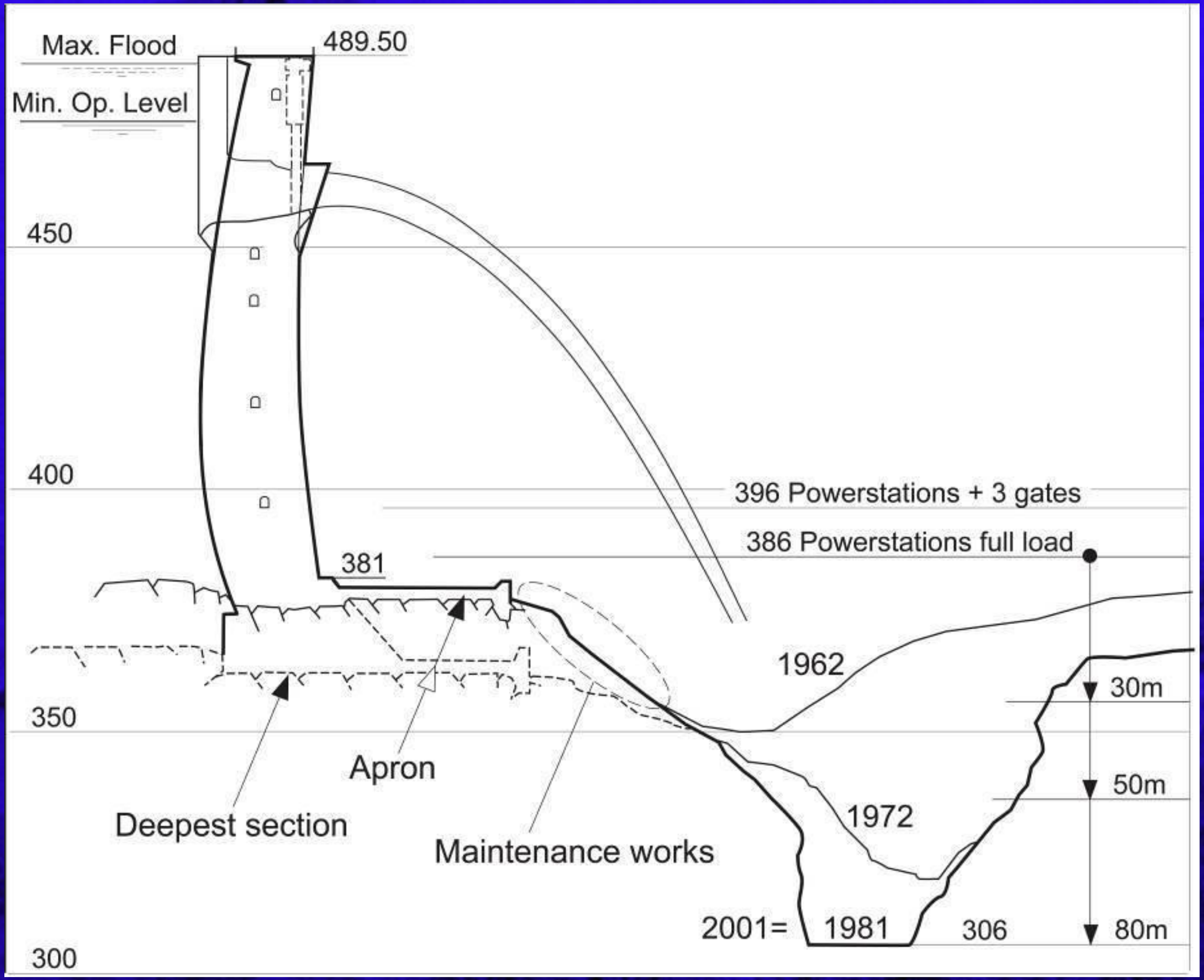
Approach channel collapsed at 5:00 pm on 12/16/1999

Flood wave reached 1st village at 6:00 pm on 12/16/1999 – reservoir lowered 30 meters in 40 minutes

El Guapo Dam, Venezuela

- Built 1975 to 1980
- No proper hydrologic studies - based on similar basin
- Spillway system
  - Original uncontrolled ogee with downstream chute
  - Tunnel spillway added after chute wall overtopping during construction
- Failure in 1999

Kariba Dam, Zambia/Zimbabwe



Kariba Dam, Zambia/Zimbabwe

- 128 m high concrete arch
- Built between 1956 & 1959
- World's largest artificial lake
- Gated spillway sill = 33 m below crest
- Spillway use created 80 m deep eroded plunge pool over 20 years
- Geological feature (discontinuity) in the river section that was not picked up during planning and design
- Plans are abreast to deal with the issue

Oroville Dam

Oroville Dam

Operational failures

- Taum Sauk Dam, USA

Landslide failures

- Vajont Dam, Italy

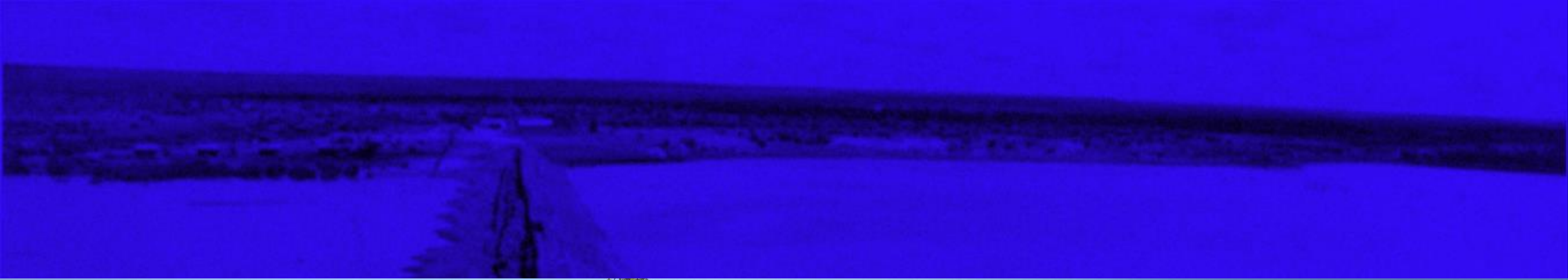
Vajont Dam, Italy

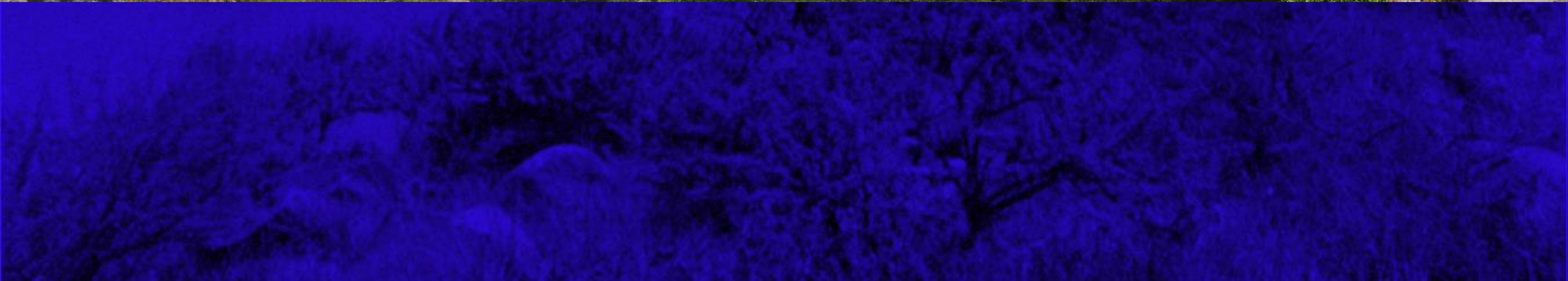
Vajont Dam, Italy

- 265 m high concrete arch dam
- Completed in 1960
- Left side reservoir foundation = steep slopes in bedded limestone with clay interbeds
- 1 month after completion & after heavy rain = first landslide = 700 000 m^3 & 2 m wave
- Exploratory adits, piezometers & level of reservoir adjusted to limit slide movement
- 1963
  - Massive slide of 267 million m^3
  - 100 m high over dam wall
  - 2 600 fatalities
  - Arch survived

Vajont Dam, Italy

Vajont Dam, Italy





Vajont Dam, Italy

- Dam abondoned
- Low strength clay layers between limestone beds
- Reservoir geology not fully understood

Folsom Dam

Shih-Kang Dam

Questions, Comments, or Discussion

Thank you for your attention.