TECHNICAL RECOMMENDATIONS FOR HIGHWAYS

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GUIDELINES FOR THE HYDRAULIC DESIGN AND MAINTENANCE OF RIVER CROSSINGS

VOLUME VI : RISK ANALYSIS OF RIVER CROSSING FAILURE

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PREFACE

At the rate at which new information is generated and made available it is becoming increasingly difficult for the practising civil engineer to decide on the appropriate norms and analytical methods to be used in designs. Although there will always be cases necessitating a comprehensive independent literature study to ascertain the best suited norms and methods to achieve a sound solution, it is recognised that they tend to be the exception rather than the rule. The designer cannot be expected to undertake such detailed studies for each case as this would become impractical. Consequently the need for practical guidelines.

The main aims of these guidelines are to make recommendations on methods of calculation, design norms as well as legal and other issues which need to be taken into consideration in the pursuit of providing safe, economical and viable river crossings. The intention is not to stifle original thinking and new development, and thus designers are expected to deviate from the general recommendations where optimum solutions clearly fall outside the general applicable norms. The guidelines are furthermore intended to serve as a basis for governing bodies to formulate their policies on design standards with due consideration of legal and other risks.

These guidelines comprise seven volumes each dealing with a particular subject or related subjects.

SYNOPSIS

During the 1970s and 1980s a number of major floods caused serious damage to the road and rail infrastructure in southern Africa. These events prompted the development of a methodology to assess the risk of failure of river crossings and of management strategies to reduce the risk to "acceptable" levels.

This volume deals with risk analysis of river crossings systems and provides a procedure that can easily be applied in practice to these systems and takes into account maintenance prioritization, evaluation of alternatives and risk management.

Whilst this document should not be considered as an exclusive methodology, it can be used to view holistically the risk of river crossing failure for use in maintenance prioritization, evaluation of alternatives and risk management.

Keywords : Risk analysis, river bridges, risk estimation, risk management, bridge failure.

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Volume VI, 1994. Committee of State Road Authorities, South Africa.

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By

G W Annandale

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1. INTRODUCTION

The need to provide safe and economically functional river crossing systems at all times, especially during extreme flood events, lead to the desire to review current design standards and develop new guidelines for design of river crossing systems in the Republic of South Africa. This guideline deals with Risk Analysis of river crossing systems and forms part of a series of guidelines addressing various other aspects.

The goal of this guideline is to provide a risk analysis procedure which can easily be applied in practice to manage river crossing systems. Risk analysis entails risk assessment and risk management. Risk assessment consists of hazard assessment, risk determination, and risk characterization. Once the risk has been characterized, appropriate risk management strategies are developed and implemented to minimize public exposure to hazards.

Risk analysis is required to ensure that individual river crossings and river crossing systems are safe for use by the public.

The need for a consistent, holistic approach to evaluate the safety of river crossings and river crossing systems is emphasized by an analysis of river crossing failure statistics collected in the United States of America, New Zealand and the Republic of South Africa. A summary of the findings of this analysis, presented in Figure 1.1 in the form of pie-charts, indicate that the major distress modes leading to river crossing failure are related to the hydraulic behaviour of the facility. Scour, overtopping, embankment erosion (approach failure) and debris accumulation accounts for 80 to 85 percent of the distress modes leading to river crossing failure. The relative frequencies of structural inadequacy in river crossing failure is only 15 to 20 percent.

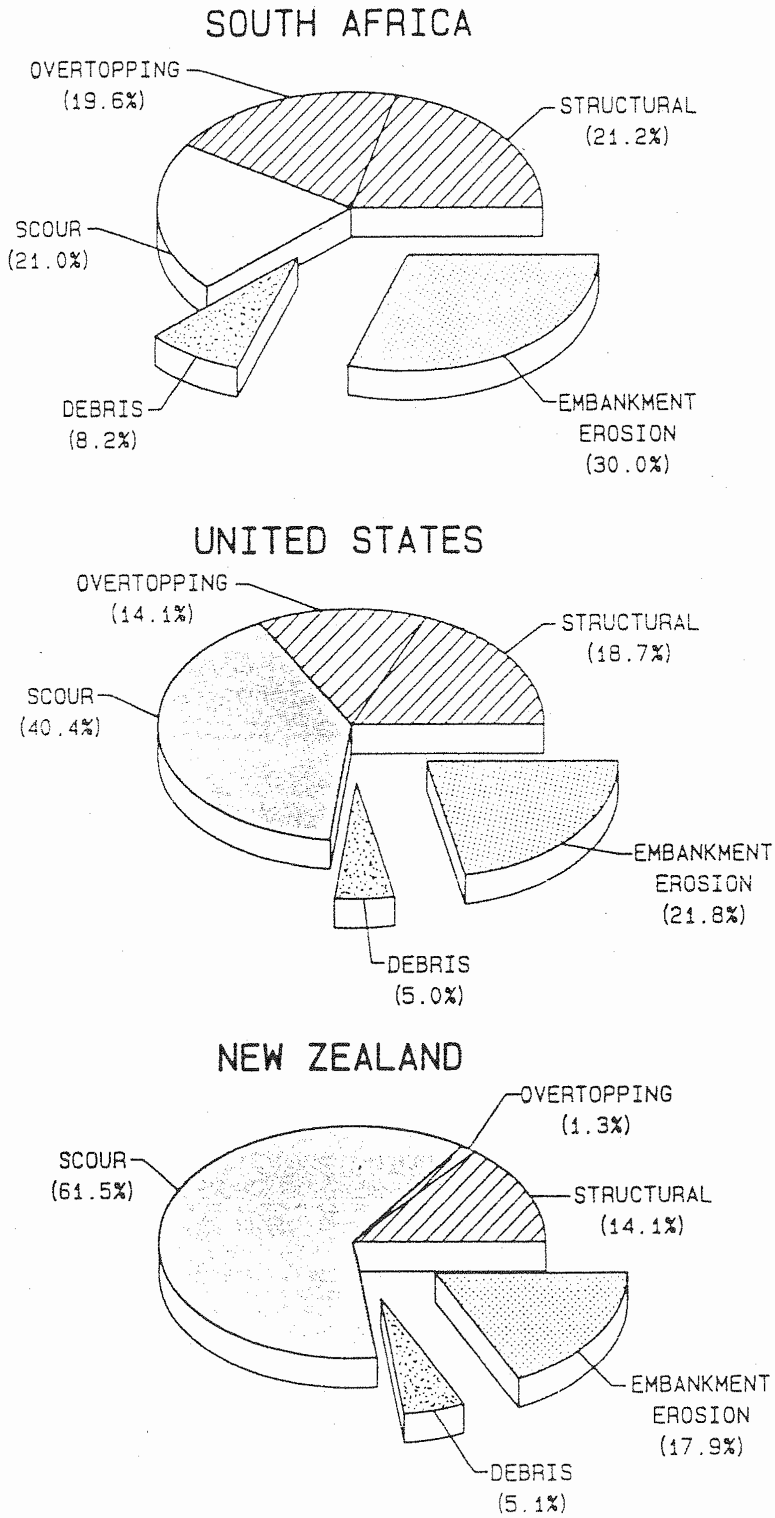

FIGURE 1.1 : DISTRESS MODES LEADING TO RIVER CROSSING FAILURE

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2. SCOPE

Risk analysis, entailing risk assessment and risk management, often provides important decision making information. Risk assessment consists of hazard assessment, an estimate of risk and characterization thereof, whereas risk management consists of actions which can be implemented to manage or reduce the risk to "acceptable" levels.

Risk should not be confused with the probability of failure of a system. Probability of failure is a numerical expression of the likelihood that a system would fail, and only forms part of the determination of risk. Risk, in engineering terms, is usually expressed as the product of probability of failure and consequences. Risk analysis requires a definition of river crossing failure. In general, a river crossing is deemed to have failed if either the ultimate or serviceability limit states or both have been exceeded. The five major distress modes which lead to river crossing failure are structural failure, embankment erosion (approach failure), debris accumulation, scour, and overtopping (Figure 1.1). These distress modes are all considered in the analysis of risk of river crossing failure.

Figure 2.1 presents the outline of the risk analysis procedure which is followed in this guideline. The method consists of two levels of risk assessment and a risk management procedure. The Level I Risk Assessment entails hazard assessment, exposure identification, consequence assessment, and risk characterization. The Level II procedure consists of the standard approach of hazard assessment, risk estimation and risk characterization. However, the Level I procedure is simpler than the Level II procedure, allowing the practicing engineer to assess the risk of failure of a river crossing by making use of the standardized procedure presented in this guideline. The Level I procedure also guides the engineer in making a decision as to whether more comprehensive risk assessment is required. If required, a more involved procedure, could include the use of Fault and Event Trees to calculate risk. The Level II risk characterization also requires more expertise than the Level I characterization.

Once the risk of river crossing failure has been assessed, whether conducted at Levels I or II, the findings are used to develop Risk Management procedures. Risk management basically consists of devising and implementing management strategies to reduce risk, with regular re-assessment as to whether the risk of river crossing failure requires re-evaluation. If conditions have changed and the decision is taken to re-evaluate risk, a further decision as to whether Level I or Level II assessment is required guides the engineer to one or the other (see Figure 2.1).

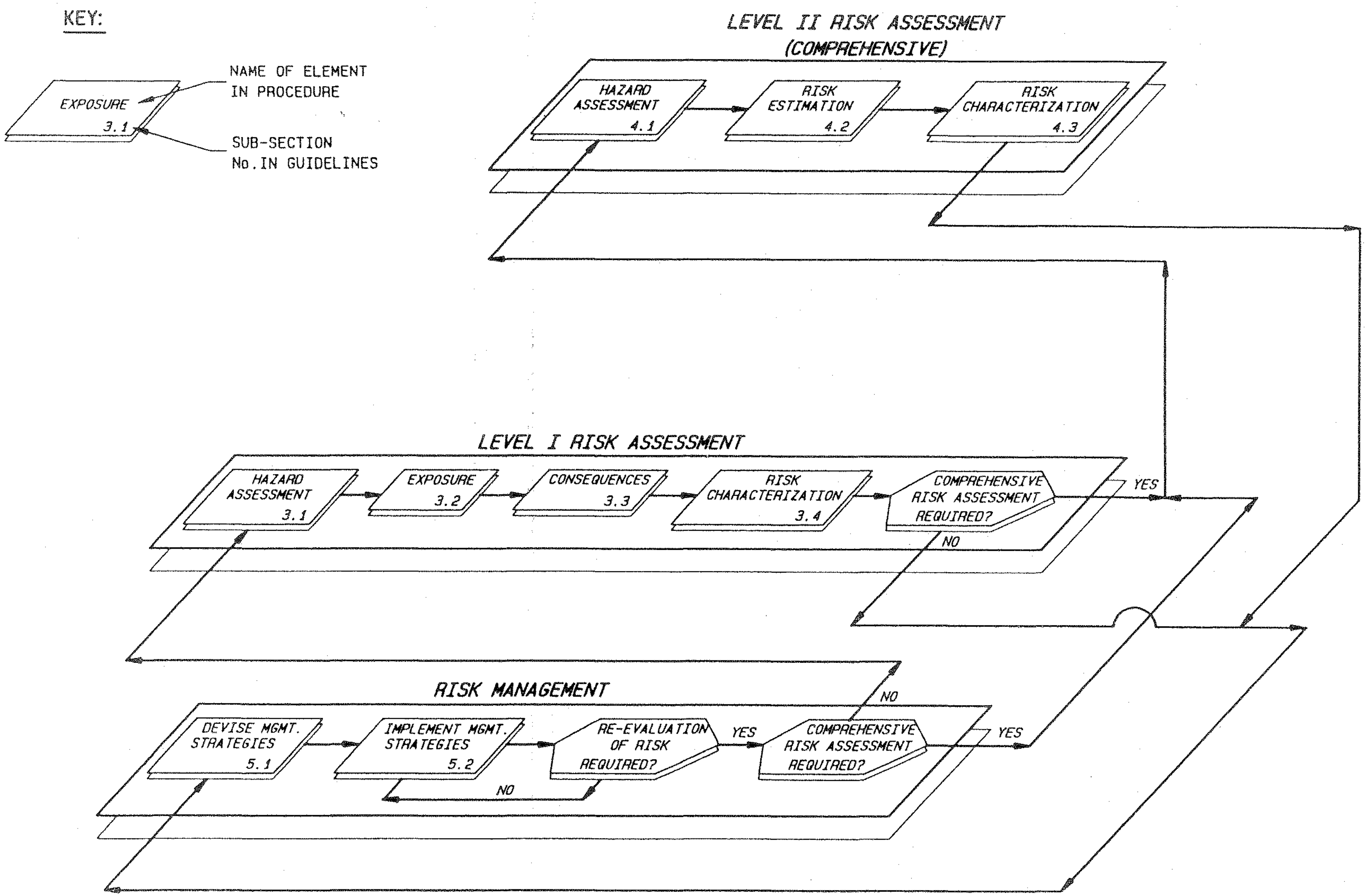

FIGURE 2.1 : RISK ANALYSIS OF RIVER CROSSING FAILURE

3. LEVEL I RISK ASSESSMENT

The Level I risk assessment procedure is discussed by following the outline in Figure 2.1. The discussion commences with hazard assessment and describes a consistent procedure for rating hazards. By making use of this information and identifying the entities which are exposed to the hazards, it is possible to assess consequences. The consequence assessment of river crossing failure entails an estimate of the number of human lives exposed to danger, and an estimate of potential losses (expressed in monetary terms). The risk is then characterized by combining this information with a preliminary estimate of the probability of failure of the river crossing. Risk is characterized as low, medium, high or unacceptable, and combined with the hazard rating to decide whether advanced risk assessment is required, whether risk management procedures should be implemented, or whether occasional maintenance will suffice. The procedure is presented by discussing pertinent issues and demonstrating its application by means of examples. Practical application of the procedure is facilitated by providing standardized forms in Section 3.5. An example of a typical Level I risk assessment investigation for a river crossing over the Caledon River is presented in Appendix 7.2.

3.1 Hazard assessment

Hazards are defined as sources of potential danger.

In the case of river crossing failure, the hazards associated with the occurrence of extreme floods play a dominant role, and can be divided into the following categories:

- River instability,
- Potential for morphological change due to extraneous factors,
- Fluvial hydraulics in the immediate vicinity of the river crossing, and
- Structural integrity of the river crossing.

The objective of the Level I hazard assessment is to identify and rate the hazards imposing on the river crossing under investigation. This can be done by utilizing the outline presented in Figure 3.1, which shows that the Level I investigation consists of three phases. The investigation commences with data collection and evaluation, whereafter the Level I identification of hazards is carried out and the hazard assessment rating finally determined.

The Level I work can, more often than not, be conducted as a desk study. However, field work will be required if insufficient information is available for the Level I assessment, and/or when the conclusion to the Level I risk analysis points to the need for more comprehensive risk analysis (Level II).

3.1.1 Data collection and evaluation

The data which should be collected are:

- Aerial photographs of the river and river crossing,
- Maps of the catchment,
- Survey of the river crossing site,
- Hydrological and hydrometeorological data,

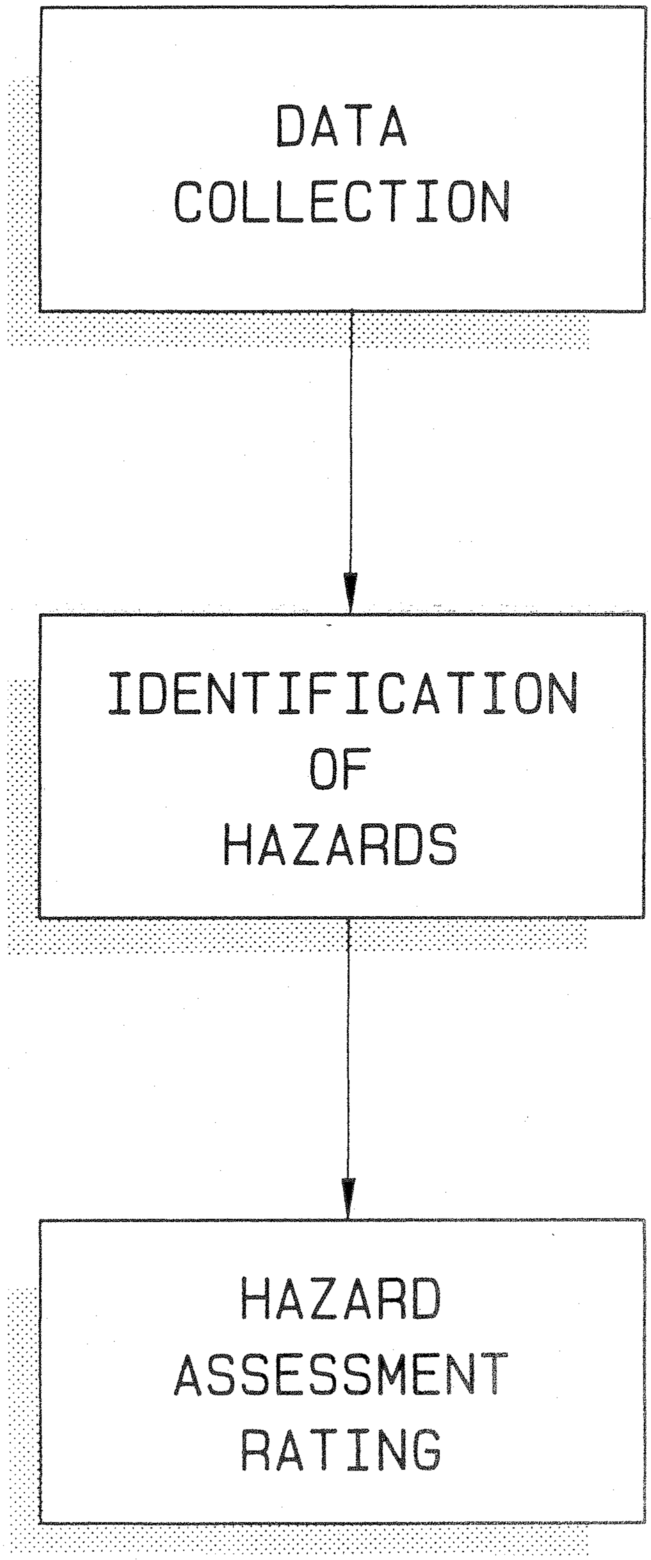

FIGURE 3.1 : LEVEL I HAZARD ASSESSMENT

- Land use plans,
- Vegetation maps,
- Design and maintenance reports,
- Design and construction drawings of the river crossing, and
- Geological information of both the river crossing site and catchment.

It is advisable to collect historic maps and aerial photographs of the river. This allows an investigation of the stability characteristics of the river.

Once collected, the data should be evaluated for completeness, consistency and accuracy.

3.1.2 Identification of hazards

The Level I hazard identification is conducted by considering hydrology, river/stream stability, potential for morphological change due to extraneous factors, fluvial hydraulics and structural integrity of the river crossing. This subsection only briefly discusses the factors which should be considered, whereas the most important part of the hazard assessment procedure, viz the hazard assessment rating, is presented in Section 3.1.3.

(i) Hydrology

The important aspects are catchment characteristics, and meteorological and flood data. The catchment characteristics which should be determined are size, land-use, topography, vegetation, soil types, geology, and river and stream types. This information is required to conduct the hydrological analysis, assess the erodibility of the streams and rivers, estimate the possibility of debris accumulation, estimate the stability characteristics of rivers and streams, and the potential for morphological change.

A hydrological analysis is also undertaken to determine the flood peak/recurrence interval relationship by making use of flood data and/or hydrological models and meteorological data. This information is required to determine the frequency of occurrence of significant floods, which can be used to estimate the Level I probability of failure (see Section 3.3.1).

(ii) River and stream stability characteristics

This part of the investigation deals with issues related to the river channel, such as sediment load characteristics (relative magnitude, bedload/suspended load ratio, sediment size), bank stability, stream power, slope, width/depth ratio, and channel pattern.

This information provides significant clues as to the stability characteristics of a river or stream as demonstrated by Schumm and Meyer (1979). Schumm and Meyer (1979) proposed a useful graphic relationship which can be applied to classify the stability characteristics of river systems (Figure 3.2). Schumm's original figure does not contain the anabranched river (Channel Type 6), which is added to Figure 3.2. This figure succinctly illustrates the relationship between channel pattern, sediment load type and characteristics, flow velocity, stream power and relative stability of a river. As an example, one can consider the stability of a naturally straight stream (not modified to be straight). Although streams of this type are very rare, a naturally straight stream with a small, suspended load, flat channel slope, low width

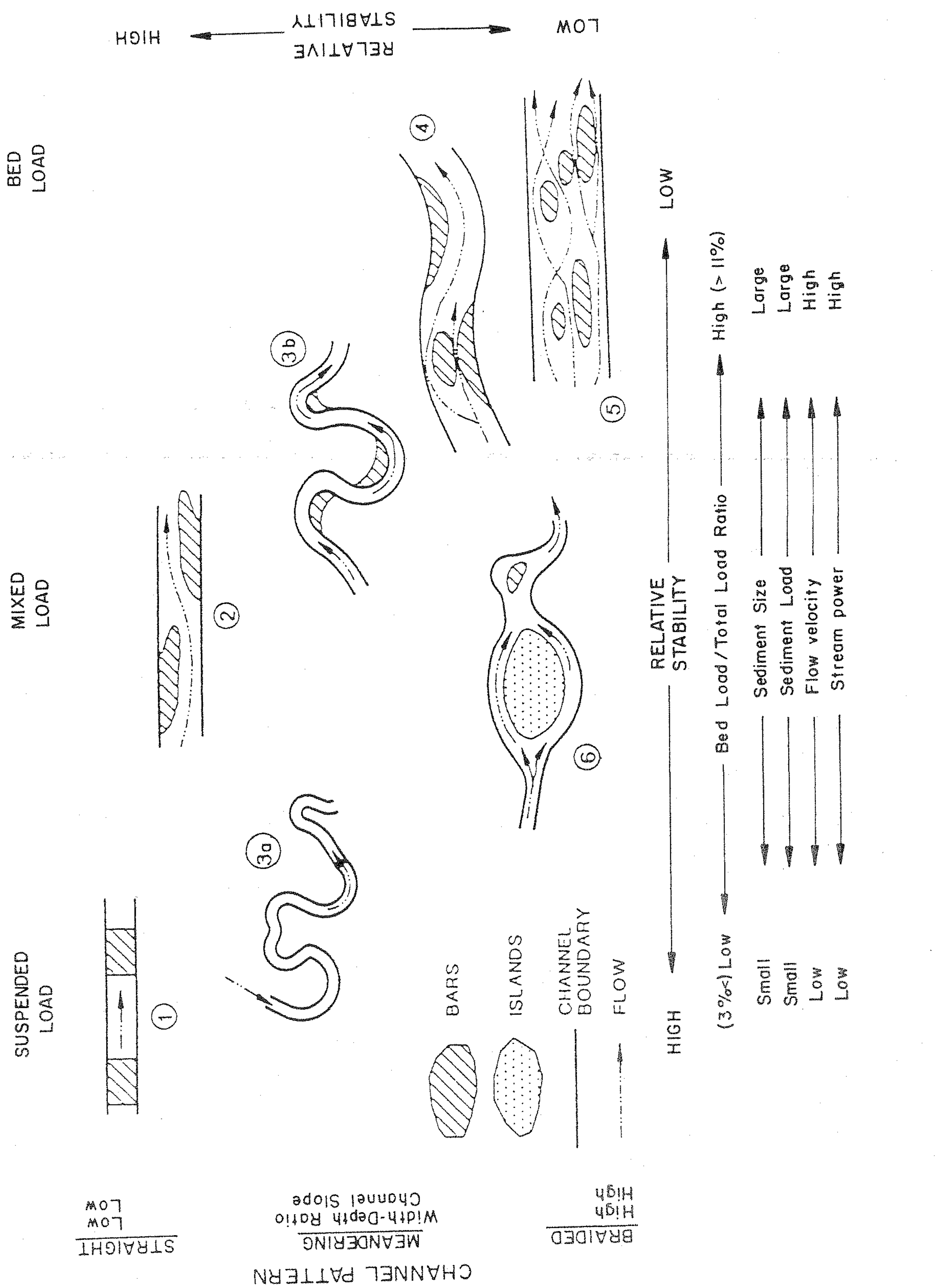

FIGURE 3.2 : STABILITY AND CLASSIFICATION OF RIVER CHANNELS

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to depth ratio and low stream power will be more stable than a meandering stream with a high, mixed sediment load, low bank stability, high stream power, steep slope, high width to depth ratio and coarse sediment (Channel Type 4). The use of this information is illustrated in Section 3.1.3.

(iii) Potential for morphological change due to extraneous factors

Extraneous factors, such as sand or gravel extraction from a river bed or sediment deposition in a reservoir downstream of a river crossing, may induce morphological changes which can be hazardous to the safety of river crossings. Morphological change, as defined herein, occurs as erosion and/or deposition of sediment.

Erosion types are degradation, nickpoint erosion and bank erosion. Nickpoint erosion is erosion which progresses in an upstream direction from a point of disturbance, as may be initiated by sand and/or gravel extraction from a river bed. Degradation is large scale denudation of a river bed (generally resulting in the lowering of long stretches of the riverbed), whereas bank erosion mostly, but not exclusively, occurs on the outside of river bends.

Deposition of sediment can occur as aggradation, down- and backfilling, and berming. Aggradation is the opposite of degradation, leading to a general raising of the river bed profile. Down- and backfilling, the opposite of nickpoint erosion, similarly lead to a raising of the river bed. Backfilling is deposition of sediment in an upstream direction and can occur due to sediment deposition in a reservoir. An example of backfilling exists in the Caledon River, upstream of Walbedacht Dam. The Level I risk assessment of the Jim Fouche bridge over this river, illustrating the impact of backfilling, is presented in Appendix 7.2. Berming is the opposite of bank erosion, and leads to a raising of the river banks above the surrounding floodplains due to deposition of sediment on the banks of a river.

(iv) Fluvial hydraulics

Determination of local effects of fluvial hydraulics in the vicinity of a river crossing entails consideration of the following:

- river crossing location, potential for lateral erosion and approach embankment erosion,
- pier orientation and potential for turbulence generation and local scour,
- river bed material type and the potential for contraction scour (i.e., general scour occurring between the abutments due to contraction of flow),
- potential for debris accumulation, and
- the maximum discharge capacity of the river crossing opening.

Potential for damage, illustrated as a function of river crossing location, is presented in Figure 3.3. This figure, only illustrating three simple situations, implies that potential for damage to river crossings located on straight river reaches is usually low, whereas it can be low to moderate if a river crossing is placed between bends. The potential for damage when a river crossing is located on a river bend is high. The hazards in the latter case are lateral erosion of the river banks and increased erosion potential of the approach embankments.

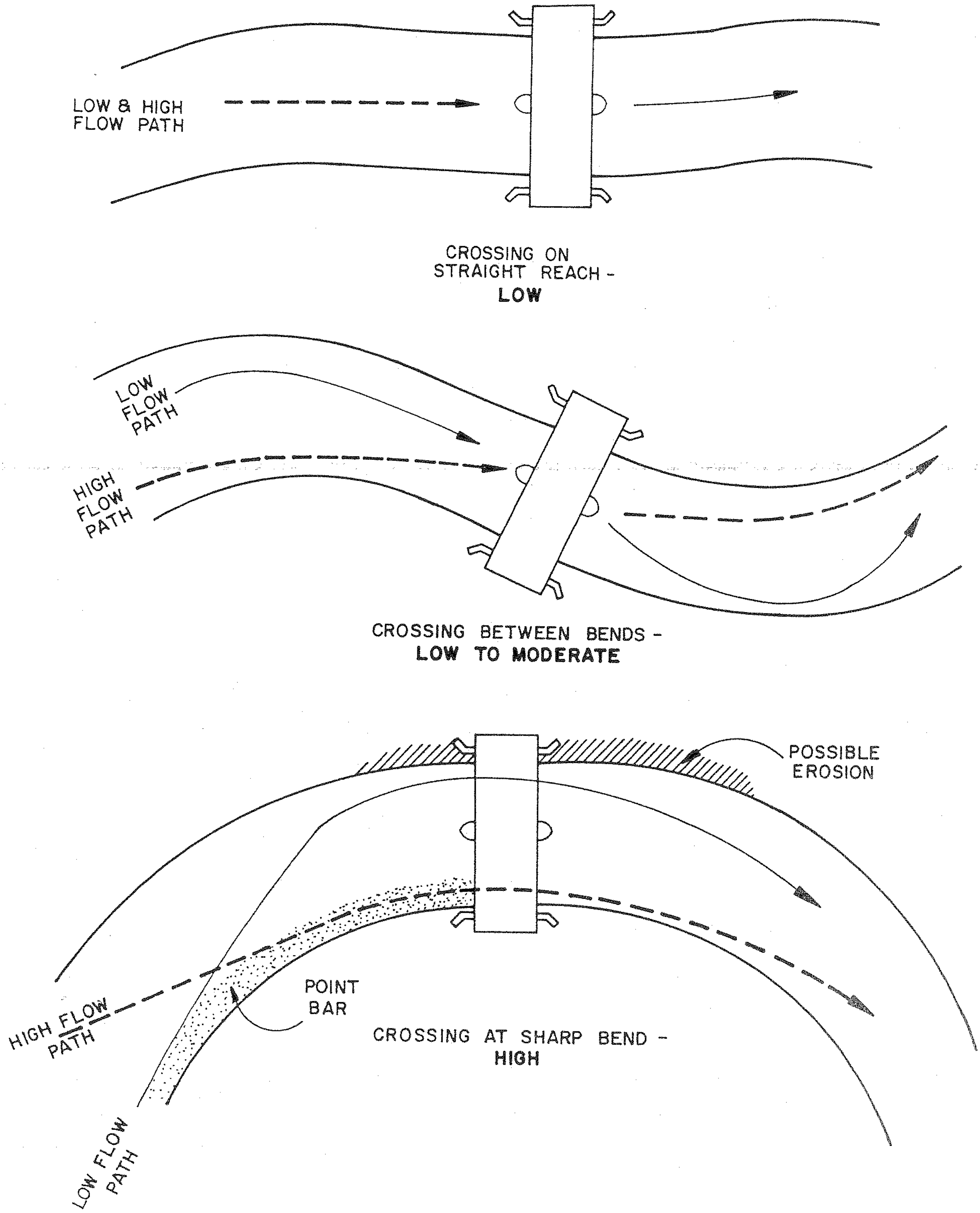

FIGURE 3.3 : RIVER CROSSING LOCATION : POTENTIAL FOR DAMAGE

Pier orientation can play a significant role in increasing the potential for local scour. If the piers of a river crossing are not streamlined and oriented in the direction of streamflow, excessive turbulence which are generated during flood conditions, will severely increase local scour activity.

The potential for debris accumulation can be determined by inspecting bank vegetation and identifying developments along a river which may give rise to debris generation.

An estimate of the maximum discharge capacity of a river crossing opening is important (Figure 1.1 indicates that approximately 20 percent of river crossing failures in South Africa are associated with overtopping). The discharge capacity should be related to flood recurrence interval.

(v) Structural integrity of the river crossing

Structural failure is a distress mode which accounts for approximately 20 percent of river crossing failures in South Africa (Figure 1.1). The structural integrity of the river crossing is therefore important and can be determined by studying design and construction drawings; design, construction and maintenance reports, and/or by conducting field investigations. The objective of the investigation is to establish the integrity of the foundations, piers, abutments, and deck and bearings.

3.1.3 Hazard assessment rating

The hazards identified in Section 3.1.2 are assessed by making use of a rating system, the component values of which can be obtained from Tables 3.1(a), 3.1(b), 3.2 and 3.3. The potential of floods overtopping the river crossing is not considered in the assessment of hazards, but is used in Section 3.3 to estimate probability of failure.

Table 3.1(a) and 3.1(b) deal with river stability and potential for morphological change due to extraneous factors, Table 3.2 contains factors required to assess the impact of fluvial hydraulics; and Table 3.3 accounts for structural integrity. The relative magnitudes of the values of the ratings in these tables reflect the relative importance of the hazards, and is based on river crossing failure research findings from South Africa (see Section 4.2.1), New Zealand (Macky, 1990) and the United States of America (Brice & Blodgett, 1978).

The composite hazard rating (R) is determined by multiplying the individual ratings. The ratings are multiplied in stead of added to prevent any one rating dominating the others (Kirsten, 1982). The composite rating is calculated as follows:

$$R = f_1 * f_2 * f_3 * f_4$$

where

f_1 = one factor from Table 3.1(a)

f_2 = one factor from Table 3.1(b), representing either erosion or deposition

Channel type		Description	Factor
1.	Channel Type 1		
	Sediment load	Small	1,000
	Bed/susp load ratio	Low (suspended load)	
	Bank stability	Cohesive soil, high stability	
	Stream power	Low	
	Slope	Low	
	Width/depth ratio	Low	
	Sediment size	Small	
	Channel pattern	Naturally straight	
2.	Channel Type 2		
	Sediment load	Moderate	2,105
	Bed/susp load ratio	Moderate (mixed load)	
	Bank stability	Moderate to high	
	Stream power	Moderate	
	Slope	Low	
	Width/depth ratio	Low	
	Sediment size	Moderate	
	Channel pattern	Straight with sinuous thalweg	
3.	Channel Type 3a		
	Sediment load	Small to moderate	2,205
	Bed/susp load ratio	Low (suspended load)	
	Bank stability	Moderate	
	Stream power	Low to moderate	
	Slope	Moderate to low	
	Width/depth ratio	Low to moderate	
	Sediment size	Small to moderate	
	Channel pattern	Meandering, high sinuosity	
4.	Channel Type 3b		
	Sediment load	High	2,447
	Bed/susp load ratio	Moderate (mixed load)	
	Bank stability	Low	
	Stream power	Moderate to high	
	Slope	Moderate	
	Width/depth ratio	Moderate	
	Sediment size	Moderate (coarse)	
	Channel pattern	Meandering, wide bends, point bars	

TABLE 3.1(a) : HAZARD ASSESSMENT RATING : RIVER STABILITY BASE FACTOR

TABLE 3.1 (a) Continued

Channel type		Description	Factor
5.	Channel Type 4		
	Sediment load	High	2,893
	Bed/susp load ratio	Moderate to high	
	Bank stability	Low	
	Stream power	High	
	Slope	High	
	Width/depth ratio	High and variable	
	Sediment size	Large (sand, gravel & cobbles)	
	Channel pattern	Meander-braided	
6.	Channel Type 5		
	Sediment load	High	3,162
	Bed/susp load ratio	High	
	Bank stability	Low	
	Stream power	High	
	Slope	High	
	Width/depth ratio	High	
	Sediment size	Large	
	Channel pattern	Bar-braided	
7.	Channel Type 6		
	Sediment load	Moderate to high	3,028
	Bed/susp load ratio	Moderate to high	
	Bank stability	Low to moderate	
	Stream power	Moderate to high	
	Slope	High	
	Width/depth ratio	High to moderate	
	Sediment size	Large to moderate	
	Channel pattern	Anabranched	

Type of morphologic change	Potential for change		
	Low	Moderate	High
Erosion: Degradation Nickpoint migration Bank erosion	1,000 - 2,114	2,115 - 2,892	2,893 - 3,162
Deposition: Aggradation and fill Down- and backfilling Berming	1,000 - 2,114	2,115 - 2,892	2,893 - 3,162

TABLE 3.1(b) : HAZARD ASSESSMENT RATING: POTENTIAL FOR MORPHOLOGICAL CHANGES DUE TO EXTRANEOUS FACTORS

Hydraulic aspect	Potential for damage		
	Low	Moderate	High
River crossing location and potential for lateral scour	2,115 - 2,549	2,550 - 2,757	2,758 - 2,820
Contraction scour	1,057 - 1,274	1,275 - 1,378	1,379 - 1,410
Local scour	1,057 - 1,274	1,275 - 1,378	1,379 - 1,410
Debris accumulation	0,423 - 0,509	0,510 - 0,551	0,552 - 0,564

TABLE 3.2 : HAZARD ASSESSMENT RATING : FLUVIAL HYDRAULICS AT RIVER CROSSING

f_3 = product of all four factors, representing river crossing location, contraction scour, local scour and debris accumulation ratings (Table 3.2)

f_4 = product of all four factors, representing foundations, piers, abutments, and deck and bearings integrity ratings (Table 3.3)

The composite rating thus obtained provides the user with an indication of whether the hazards are significant, moderate or low (Table 3.4).

Component	Integrity		
	Intact	Minor problems	Major problems
Foundations	1,189 - 1,433	1,434 - 1,550	1,551 - 1,586
Piers	1,189 - 1,433	1,434 - 1,550	1,551 - 1,586
Abutments	1,189 - 1,433	1,434 - 1,550	1,551 - 1,586
Deck and bearings	0,595 - 0,716	0,717 - 0,774	0,775 - 0,793

TABLE 3.3 : HAZARD ASSESSMENT RATING: STRUCTURAL INTEGRITY

Category	Significant	Moderate	Low
Composite rating	R > = 70	20 < R < 70	R < = 20

TABLE 3.4 : COMPOSITE HAZARD RATING CLASSIFICATION

Example 3.1

Problem :

A crossing is constructed over a river which is classified as meandering with wide bends and point bars (Channel Type 3b in Figure 3.2). Four aerial photographs, each taken approximately 5 years apart, indicate that sand extraction downstream of the river crossing gives rise to nickpoint erosion which could possibly expose the foundations of the river crossing. The potential for morphological change due to extraneous factors is therefore considered to be high, whereas a study of catchment and river bank vegetation indicates that the potential for debris accumulation is low.

The river crossing is located in a river bend, increasing the potential for lateral erosion under flood conditions. The foundations are located in a sandy river bed, with a high potential for local and general scour.

An investigation of the design, construction and maintenance reports indicate that the structural integrity of the river crossing is excellent. The foundations were designed to cope with the expected local and contraction scour, and the abutments and river bank protection is expected to be able to withstand river bank scour. The structural integrity of the foundations, piers, abutments, and deck and bearings are all classified as intact.

Solution:

The composite hazard rating can be calculated by making use of the following factors, which were obtained from Tables 3.1(a), 3.1(b), 3.2 and 3.3:

Characteristic		**Rating**
River stability - base factor	Table 3.1(a)	2,447
Potential for erosion	Table 3.1(b)	3,162
Potential for deposition	Table 3.1(b)	N/A
River crossing location and potential for lateral erosion	Table 3.2	2,820
Contraction scour	Table 3.2	1,410
Local scour	Table 3.2	1,410
Debris accumulation	Table 3.2	0,509
Foundations - intact (in spite of being threatened by nickpoint erosion)	Table 3.3	1,433
Piers - intact	Table 3.3	1,189
Abutment - intact (in spite of being threatened by nickpoint erosion)	Table 3.3	1,433
Deck and bearings - intact	Table 3.3	0,595

The composite hazard rating is 32.

The hazards to which this river crossing is exposed are considered to be **moderate.** This outcome is largely influenced by the perceived excellent integrity of the river crossing structure, which was apparently designed to cope with the relatively severe site conditions.

Note: In order to be conservative, it is advisable to use the upper value of ratings in a particular category for each hazard. In the case under consideration, lower rating values were used for the piers, deck and bearings as they were considered to be in excellent condition. However, if one would use the higher ratings, the composite rating would change to 47; which is still a **moderate** hazard rating.

3.2 Exposure

Exposure identification entails identification of all elements which are exposed to hazards (either directly or indirectly), estimates of their relative importance and determination of the pathways by which their combined effect will result in failure and consequential losses.

When identifying exposure it is advisable to distinguish between Level I and Level II risk analysis, as the Level II analysis is more comprehensive and requires detailed information. Level I exposure identification consists of merely identifying the elements which may suffer consequential losses due to river crossing failure. Identification of pathways which represent the relationship between elements subject to consequential losses, are not required for this level of analysis but is the subject matter of the Level II analysis.

The elements which are exposed to river crossing failure may be classified as direct and indirect monetary losses, and other potential losses.

3.2.1 Direct monetary losses

Direct monetary losses include:

- Loss of capital investment and damage to river crossing, and
- Loss and damage to property in the vicinity of the river crossing, including:
  - Residential,
  - Commercial,
  - Public,
  - Personal, and
  - Industrial property

These losses may occur mainly due to flooding in upstream reaches of river crossings, or in downstream reaches if debris accumulation causes a river crossing to act as a dam. When the latter fails, the surge may cause damage to or loss of downstream property.

3.2.2 Indirect monetary losses

Disruption of the transportation system may lead to various indirect losses related to the national and/or regional economy, including the following:

- Lost time
- Disruption of communications
- Loss of production
- Loss of wages

- Loss of revenue, including:
  - Business revenue
  - Utility income
  - Taxes

- Loss of utilities, including:
  - Transport
  - Water
  - Energy

3.2.3 Other losses

Other losses include an estimate of the number of lives which could be exposed to danger by river crossing failure, and identification of possible environmental losses.

Environmental losses are often difficult to quantify, and are also not quantitatively accounted for in the risk characterization presented in this edition of the guidelines. These potential losses should be identified.

As the value of human life is difficult to assess, and often considered immoral to even discuss, it is accounted for by estimating the number of human lives which are likely to be endangered by river crossing failure. This will be closely associated with the average daily traffic (ADT) and the layout of the river crossing. A long river crossing with a high ADT will endanger a larger number of human lives, as opposed to a short river crossing with a low ADT.

3.3 Consequences

In order to assess consequences, it is required to obtain an estimate of the probability of failure of a river crossing, and apply it to the expected losses to estimate risk. The Level I estimate of probability of failure of a river crossing is conducted without a detailed analysis of failure mechanisms and system component relationships. Similarly, no use is made of event trees in the Level I analysis to relate consequences to probability of failure of a river crossing. These advanced methods are part of the Level II risk analysis procedure.

Risk is therefore not directly calculated in the Level I analysis. However, this apparent shortcoming is accounted for by graphically relating the design flood exceedence probability, consequences and hazard level in the Level I risk characterization procedure. The risk characterization allows for subjective determination of risk levels and is based on socio-economic research (see Section 3.4).

3.3.1 Probability of failure

The Level I estimate assumes that the probability of failure of a river crossing is the same as the exceedence probability of the flood which will overtop it. This assumption implies that a river crossing will fail by exceeding the serviceability limit state before the ultimate limit state. The assumption is reasonable if risk characterization, as presented in Section 3.4, accounts (as it indeed does) for the other distress modes, viz the impacts of fluvial hydraulics, river stability, floating debris and structural integrity.

If investigation of a particular river crossing indicates that other distress modes (i.e., local scour or structural deficiency), could be predominant during failure of a river crossing (i.e., that one could reasonably expect the river crossing to fail before being overtopped), it is advisable to proceed directly to the Level II risk analysis.

Example 3.2

Problem :

An investigation shows that three river crossings on a stretch of road will be overtopped by floods with recurrence intervals of 1:50, 1:35 and 1:25 years, respectively.

The elements which are exposed to the hazards, viz the foundations, piers, deck, abutments and approaches are well constructed, and all the river crossings are founded on bedrock. The maintenance reports also indicate that the river crossings are currently in excellent condition. There is good reason to believe that the serviceability limit state would be exceeded before the ultimate limit state.

Estimate the Level I probabilities of failure of the three river crossings.

Solution:

River crossing No.	Recurrence interval of overtopping flood	Level I estimate of probability of failure
1	1:50	0.02
2	1:35	0.03
3	1:25	0.04

Note: The estimates of probability of failure are calculated by using the reciprocal relationship between exceedence probability and recurrence interval.

Example 3.3

It is required to make a Level I estimate of probability of failure of a river crossing positioned on a bend in a large river.

Reports on the geotechnical investigations made during the planning, design and construction of the river crossing indicate that the river bed consists of at least 60 m of deep sand. In order to counter this condition, the design engineers decided to utilize friction piles to support the piers and superstructure of the bridge.

The designers also sized the opening of the river crossing by making the assumption that the river bed would not scour (which is often a prescribed practice in South Africa). The peak discharge of the 1:100

year flood was used to size the opening of the river crossing. Floods exceeding the peak discharge of the design flood are expected to overtop the river crossing.

Discussions with the design engineer confirm notes on the design drawing to the effect that the piles were designed to withstand scour equivalent to conditions which are expected to exist under 1:500 year floods. The engineer conducting the risk analysis investigation has experience in fluvial hydraulics, and preliminary calculations satisfy him that the piles would most probably be able to successfully withstand such conditions. Investigations of the bank material on the outside of the river bend indicate that it consists of intact rock.

The engineer conducting the risk analysis therefore considers it reasonable and conservative to assume that the river crossing would be able to pass a flood of 1:100 years without overtopping or failure due to local scour. He considers it appropriate to proceed with the Level I risk analysis procedure and estimates the Level I probability of failure as 0.01 (i.e., 1/100). This estimate may be revised if the characterization of risk (Section 3.4) indicates that more comprehensive risk analysis is required.

3.3.2 Losses

Direct and indirect losses are expressed in monetary terms, representing an estimate of the **actual** losses which would occur in the event of river crossing failure. (This should not be confused with the **expected** losses which are estimated as part of the Level II analysis.)

Other losses are determined by estimating the number of human lives which will be exposed to danger in the event of river crossing failure, and assessing environmental impacts. However, this edition of the guidelines does not provide a well-defined means of characterizing environmental risk, and such risks should be evaluated by environmental experts.

3.4 Risk characterization

The objective of the Level I risk characterization procedure is to interpret the findings of the investigation by determining the acceptability of risk, and relating it to the Level I composite hazard rating. The outcome of the characterization procedure indicates whether the risk is low, moderate, high or unacceptable, and directs the user as to what action should be taken by making use of the composite hazard rating.

The basic relationship between annual probability of failure, acceptability of risk, socio-economic losses and composite hazard rating which is used in the characterization is presented in Figure 3.4. The upper part of the figure was compiled by Oosthuizen (1985), by making use of risk appraisal research (Vanmarcke & Bohnenblust, 1982; Whitman, 1984), whereas the lower part of the graphical relationship consists of three zones, representing low, moderate and significant composite hazard ratings. This basic figure requires additional preparation, which is dependent on the Level I estimate of probability of failure, before it can be used. A graph which has been prepared for an annual probability of failure of 10^{-2} (i.e, a failure which would occur as the result of a 100 year flood) is presented in Figure 3.5.

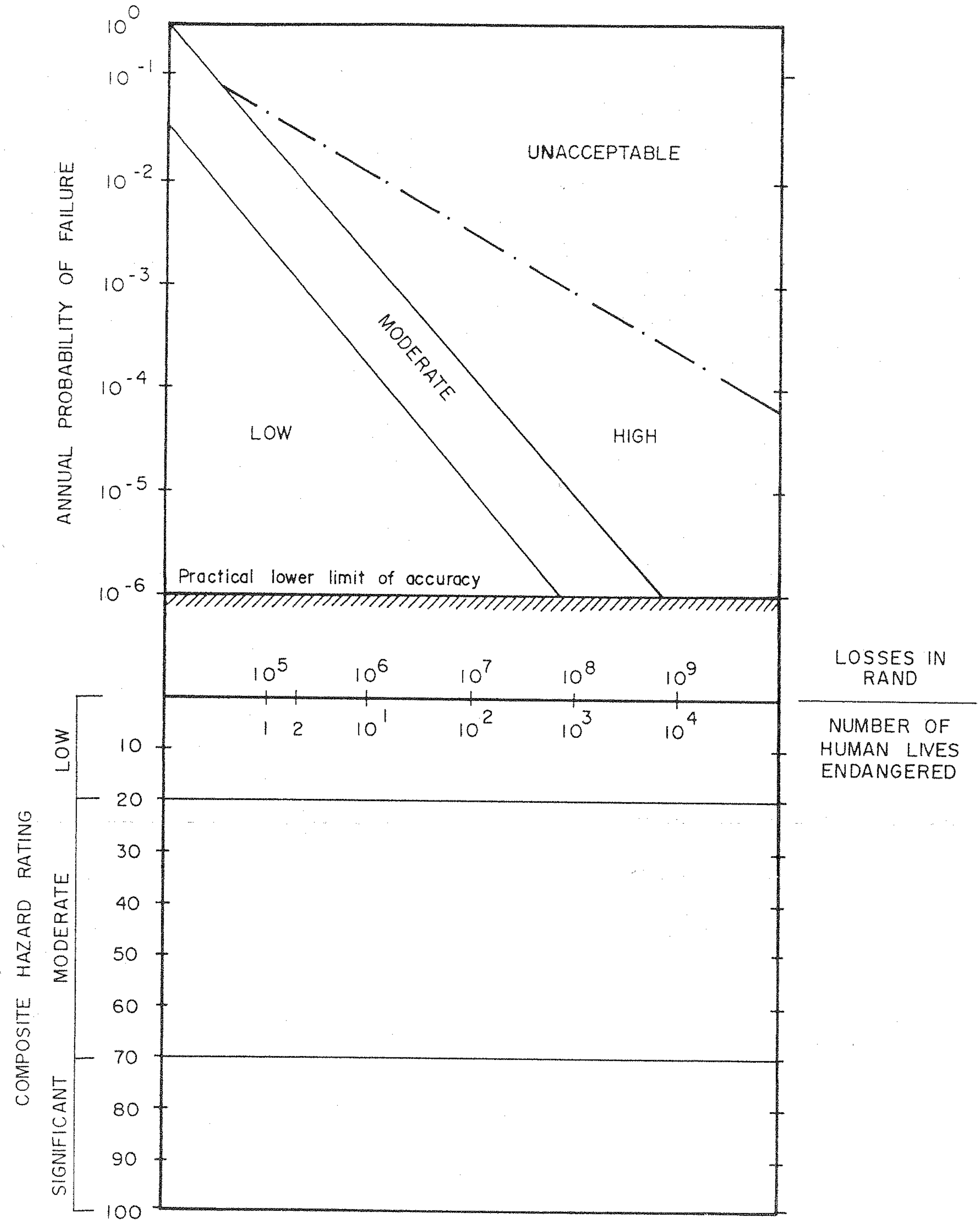

FIGURE 3.4 : RISK CHARACTERIZATION GRAPH

CSRA Guidelines for the hydraulic design and maintenance of river crossings
Volume VI, 1994, Committee of State Road Authorities, South Africa.

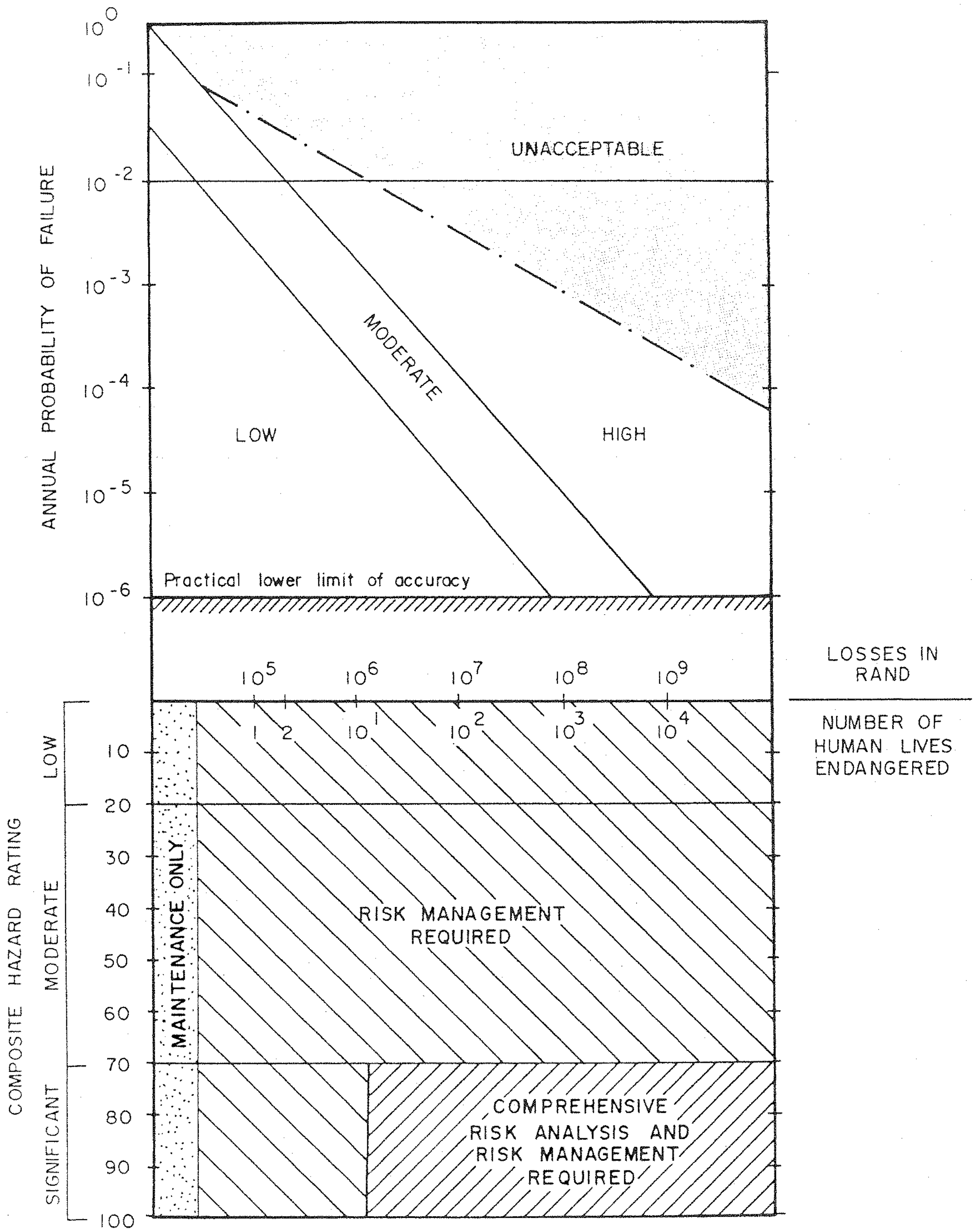

FIGURE 3.5 : LEVEL I RISK CHARACTERIZATION : PREPARED FOR 1:100 ANNUAL EXCEEDENCE PROBABILITY

Figure 3.5 shows that the lower part of the graph is divided into three sectors, viz:

- Sector 1: Comprehensive risk analysis and risk management required,
- Sector 2: Risk management required, and
- Sector 3: Maintenance only.

The identification of these three sectors are explained forthwith, whereas the application of the graph and interpretation is explained in the example at the end of this section.

Delineation of the three sectors commences by drawing a line parallel to the axis representing the socio-economic losses (number of human lives exposed to danger and estimated losses in Rand), and is positioned at the estimated probability of failure (10^{-2} in Figure 3.5). Vertical lines are then drawn from the intersections between this line and the lines delineating low, medium, high and unacceptable risks. The intersection of the vertical lines and the lines delineating the three hazard rating zones defines the three sectors shown in Figure 3.5. The sectors are selected by making use of the following recommendations:

- The joint occurrence of a significant hazard rating and unacceptable risk requires more comprehensive risk analysis (Level II) and a detailed risk management plan,

- The joint occurrence of significant hazard rating and high risk, and the joint occurrence of moderate and low hazard ratings and moderate, high, or unacceptable risk, requires a detailed risk management plan,

- The joint occurrence of low risk and significant, moderate or low hazard ratings require occasional maintenance only.

Example 3.4

Characterize the risk of the river crossing evaluated in Example 3.1, given the following:

- It is estimated that the combined potential economic loss resulting from failure of this river crossing is R 10 million.

- The ADT on the river crossing is high, and it is estimated that failure of this 700 m long, four lane river crossing can endanger the lives of at least 840 people during peak traffic.

- The river crossing was originally designed to pass a 1:100 year flood, whereas the foundations were designed to withstand scour under 1:200 year flood conditions. It is estimated that floods in exceedence of 1:100 years can overtop the river crossing.

- The estimated composite hazard rating of this river crossing, as calculated in Example 3.1 ranges between 32 and 47.

This information is transferred to the Level I risk characterization graph as follows (see Figure 3.6):

- Draw a horizontal line from the exceedence probability of 10^{-2}.

- Compare the economic loss of R 10 million with the 840 human lives exposed to danger, and select the larger of the two to position a vertical line drawn through both the risk and hazard rating graphs.

- Draw horizontal lines representing the estimated limits of the composite hazard rating, to intersect the vertical line drawn in the previous step at points A and B.

By making use of this construction, the interpretation from Figure 3.6 is:

- The risk is unacceptable.

- The combined effect of the potential socio-economic losses, flood exceedence probability and composite hazard rating lead to the conclusion that, in spite of the unacceptability of risk, Level II risk analysis is not required (points A and B). This is mainly due to the perceived good design, construction and maintenance of the river crossing.

However, the risk characterization graph points to the need to devise and implement a risk management plan (see Chapter 5), in which the unacceptability of the risk needs to be addressed in more detail.

Part of the risk management will most probably be a plan to regularly inspect the river crossing, especially the foundations, for signs of potential scour damage, and to devise an information system and contingency plan which will timeously warn motorists of impending dangers under flood conditions.

As part of the risk management plan, an investigation of the road transportation system in the area will also be required in order to ensure that alternative safe routes are available to convey traffic over the river during times of flood. If such an investigation finds inadequacies, it points to the need to extend the road transportation system, which may improve the acceptability of risk.

An improved road system is likely to make risk more acceptable by reducing the number of human lives endangered during flood conditions (the ADT will most probably reduce due to the availability of the alternative route) and by also reducing the potential economic losses (by the availability of an alternative route).

3.5 Reporting requirements

The findings from the Level I risk assessment are reported in standard format by making use of standardized forms presented herewith. The forms guide the user through all the steps required by the Level I risk assessment, and are of assistance in making decisions as to what action is required at completion of the analysis. An example, illustrating the risk analysis of the Jim Fouche bridge over the Caledon River close to Wepener, is presented in Appendix 7.2.

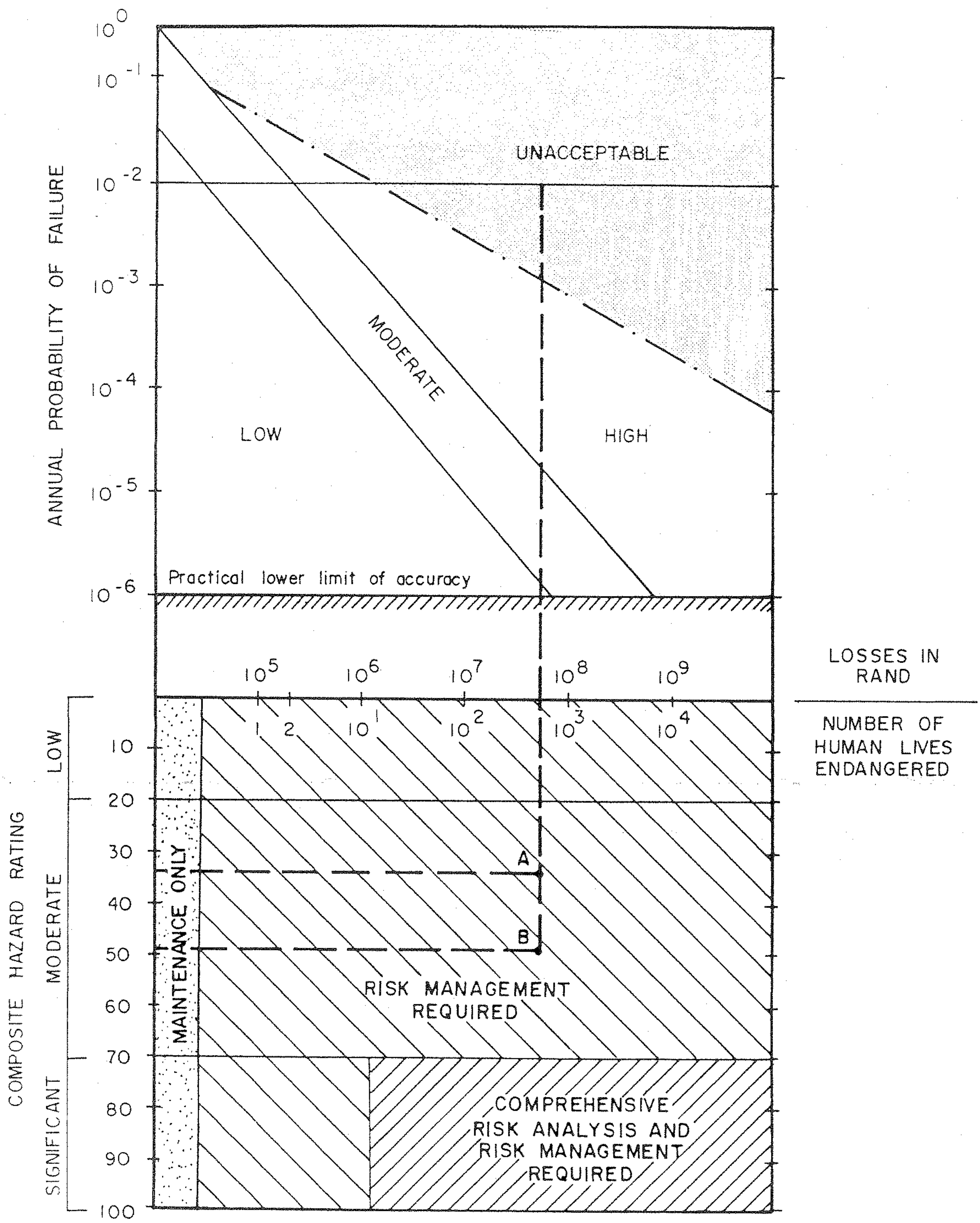

FIGURE 3.6 : RISK CHARACTERIZATION : EXAMPLE 3.4

LEVEL I RISK ANALYSIS FORM

1.0 Identification:

Route: ______________________________

Bridge number: ______________________________

2.0 Description:

Component	Code
Primary structural system	
Deck	
Abutment	
Piers	
Foundations	
Balustrades	
Bearings	

3.0 Hazards

3.1 River/stream stability:

Channel type: ______________________________

3.2 Potential for morphological change:

- Erosion
- Deposition

Low	Moderate	High

3.3 Fluvial hydraulics

Potential for damage:

Aspect	Low	Moderate	High
Location			
Contraction scour			
Local scour			
Debris accumulation			

3.4 Structural Integrity

Integrity:

Component	Intact	Minor problems	Major problems
Foundations			
Piers			
Abutments			
Deck and bearings			

3.5 Hydrology

Recurrence interval of design flood: ______________________

3.6 Composite hazard rating

Table 1(a): f_1 = ______________

Table 1(b): f_2 = ______________

Table 2: f_3 = ______________

Table 3: f_4 = ______________

Composite rating (R) = $f_1*f_2*f_3*f_4$ = ______________

LEVEL I RISK ANALYSIS WORKSHEET

Significance of composite hazard rating:

- Low (R < = 20)
- Moderate (20 < R < 70)
- Significant (R > = 70)

4.0 Consequences

4.1 Probability of failure:

Level I estimate:______________________________

4.2 Losses:

Direct and indirect monetary losses: R ______________

Number of human lives exposed to danger: ___________

5.0 Risk characterization

5.1 Acceptability of risk:

- Low ▪ Moderate ▪ High ▪ Unacceptable

6.0 Response

The following is required:

- Occasional maintenance only
- Detailed risk management plan
- Comprehensive risk analysis and detailed risk management plan

7.0 Comments

____

____

____

4. LEVEL II RISK ASSESSMENT

Level II risk analysis is conducted in exceptional cases only, ie when the hazards are considered significant, with the simultaneous occurrence of unacceptable Level I risks (see Chapter 3).

The Level II assessment requires verification of the hazards identified during the Level I assessment. The identified hazards are used to estimate the risk of river crossing failure, and the investigation concluded by characterizing the risk (see Figure 2.1). The Level II risk estimation and characterization procedures are comprehensive, and requires more effort, expertise and insight than the Level I assessment. This analysis should preferably be conducted by experts in the field, and the information provided in this section is therefore cursory and merely provide an outline of procedures which may be followed in the analysis.

4.1 Hazard assessment

The Level II hazard assessment verifies the hazards identified during the Level I analysis. These hazards include river stability, potential for morphological change due to extraneous factors, fluvial hydraulics, structural integrity and flood hydrology. The Level II hazard assessment consists of a mandatory field visit and collection of outstanding, additional information.

The field visit comprises visits to the upstream catchment, to river reaches both up- and downstream of the river crossing, and to the river crossing site itself. The objective of the visit to the upstream catchment is to compare the actual level of landuse and types of development with information which is available for the Level I assessment. Depending on the circumstances it may be advantageous to conduct the investigation with the aid of a helicopter. The visit to the river reach is used to verify information obtained from maps and aerial photographs during the course of the Level I investigation and should be conducted over considerable distances up- and downstream of the site. Field observations provide information on the stability of the river or stream which cannot be obtained at a similar level of adequacy during desktop studies, eg the state of river bank vegetation reveal information regarding stability which is not available on maps and aerial photographs (see eg Shen, et al, 1981). The same applies to morphological changes subject to extraneous factors. The visit to the river crossing site is also used to verify the Level I conclusions regarding possible effects of fluvial hydraulics and structural integrity, whereas the Level I conclusions on flooding may be verified by discussions with local residents.

Significant differences in the identification of hazards should be noted, taken account of, and reported in the Level II risk assessment report.

4.2 Risk estimation

Risk estimation entails identification of all entities which are exposed to the hazards (either directly or indirectly) and definition of the pathways by which their combined effect will result in failure and consequential loss. The probability of failure can be calculated by using a number of procedures, such as the Method of Moments, Monte Carlo Simulation, and Method of Discrete Probability Distributions (see eg Harr, 1987; Bier, 1987 and Ang & Tang, 1984). Another method which can be used to estimate risk, as summarized in these guidelines, entails the use of Fault and Event Trees (Ang & Tang, 1984). A fault tree represents a quantitative evaluation of the probabilities of various failure events leading to the calculation of the probabilities of the **initiating** events, the latter representing failure of the system. An event tree is a logical approach to identify and model the various immediate subsequent events that follow an initiating event and finally result in the identification of various consequential losses and their probabilities of occurrence.

The fault and event trees are related by means of the initiating event, as illustrated in Figure 4.1. This figure indicates that the **primary events**, comprising all the distress modes which could lead to the failure of the system, are interrelated in a logical way to define how the system could fail (the initiating event). The event tree, comprising the scenario of consequences if the system would fail, is connected to the fault tree through the initiating event. The probability of occurrence of the initiating event is applied to calculate the probability of occurrence of perceived consequences. The risk is finally calculated as the sum of the products of the probabilities of occurrence of the perceived consequences and their loss values.

4.2.1 Exposure

The entities which are exposed to the hazards entails components of the river crossing and all parties which could suffer direct or indirect losses in the event of river crossing failure.

(i) River crossing

The exposure of the river crossing can be investigated by identifying typical distress modes. A state of distress is defined as a state of severe overload, ie a state before failure develops. The different types of distress which could develop are collectively termed distress modes.

Quantification of risk requires identification of all conceivable distress modes. Distress modes leading to river crossing failure were identified by investigating 186 recorded river crossing failures in South Africa and statistics of river crossing failures in the United States of America (Chang, 1973) and New Zealand (Macky, 1990).

Eight distress modes were identified:

- Flooding in the upstream reaches of the river crossing.
- Distress modes leading to structural failure.
- Scour.
- Debris accumulation.
- Overtopping.
- Erosion of especially the approach embankments.
- Changes in river alignment.
- Sinkhole formation behind abutments.

These distress modes are briefly discussed.

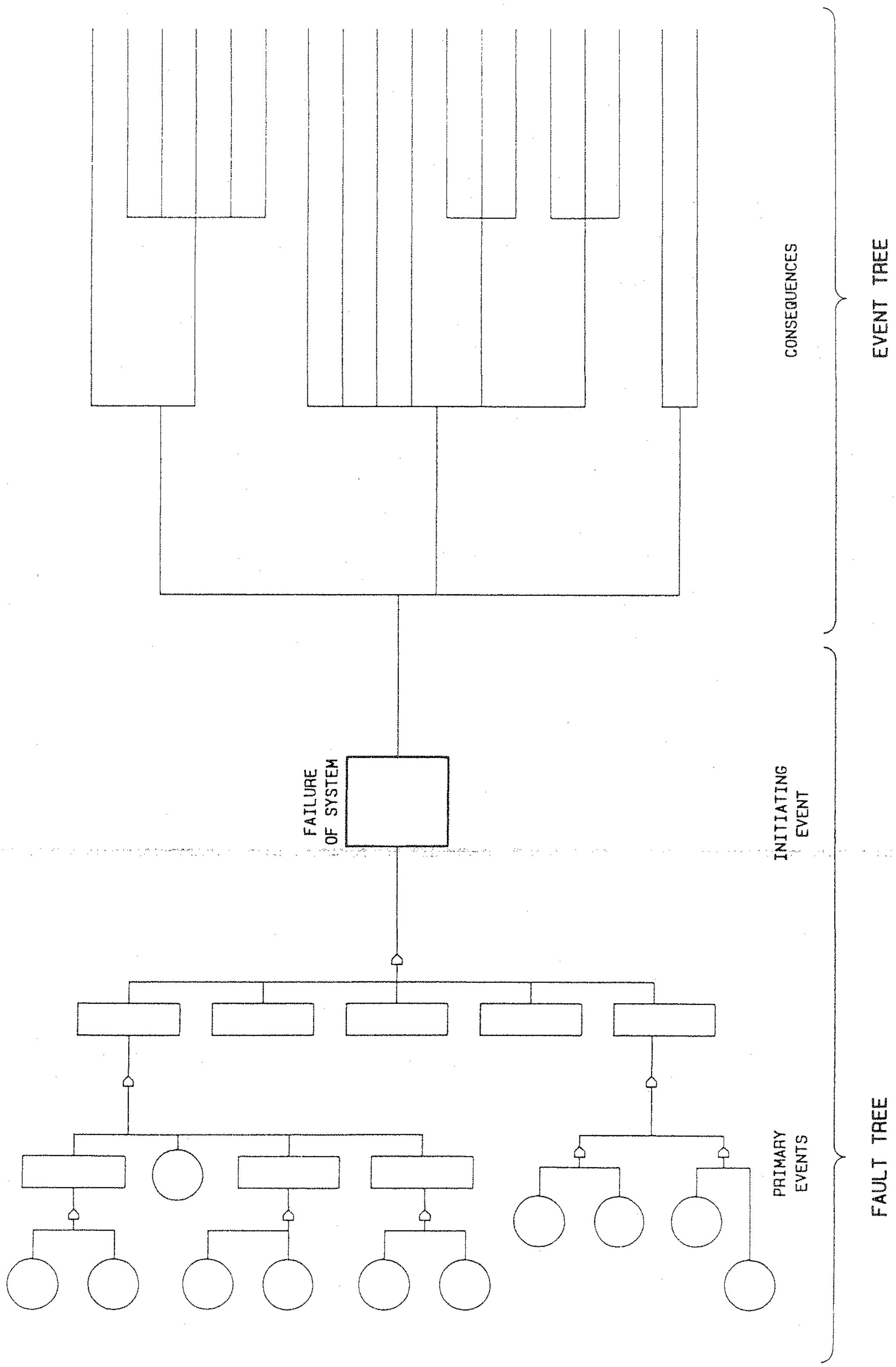

FIGURE 4.1 : INTERRELATIONSHIP BETWEEN FAULT AND EVENT TREES

(a) Flooding in upstream reaches

Flooding in the upstream reaches resulting from inadequate discharge capacity of a river crossing opening or from accumulation of debris, reducing discharge capacity, is considered a distress mode which can lead to damage to property of third parties and possibly loss of life.

Such flooding can also be caused by urbanization and other developments in the catchment area upstream of the river crossing, which might occur after design and construction of the river crossing. The original river crossing opening could therefore have been adequate at the time of design and construction, but its adequacy will decrease as time passes. Regular evaluation of adequacy is therefore required of river crossing discharge capabilities wherever urban or other developments occur in the upstream reaches.

(b) Distress modes leading to structural failure

Distress modes leading to structural failure are caused by excessive hydraulic forces and by scour.

Excessive hydraulic forces against the piers, abutments and deck, often increased by the accumulation of debris, can lead to severe stresses which can exceed ultimate limit state requirements.

Scour around foundations can result in failure or settlement which increases stresses in the piers and deck.

The most common structural failures of the superstructure are:

- Balustrades are damaged by the force of water, aggravated by the accumulation of debris
- The road surfacing is washed off. Damage to balustrades and road surfacing are usually associated with overtopping and presence of debris.
- The deck is damaged by sliding, collapse or hydraulic uplift

An interesting example of deck failure occurred just downstream of Albert Falls dam in Natal, where the uplift forces caused by the formation of a hydraulic jump downstream of the dam, removed the deck of a railway river crossing.

The substructure is often subject to:

- Damage to piles by debris collision and foundation failure after the occurrence of excessive scour.
- Failure of foundations due to the occurrence of excessive scour, leading to failure of the abutment and deck of the bridge.
- Overstressing of the abutments resulting from foundation failure and high hydraulic forces.

- Collapse of piers by overturning. This occurs due to inadequate resistance to overturning moments induced by hydraulic forces.

(c) Scour

The two types of scour which are distinguished are local scour, general and contraction scour. General scour usually occurs due to degradation of the river bed, resulting from increases in sediment carrying capacity which occurs in rivers during flood conditions. Contraction scour occurs between abutments of a river crossing. The latter is caused by the increased flow velocities caused by the artificial restriction. Local scour usually occurs due to the presence of local turbulence caused by the presence of structural elements such as piers and foundations.

Scour can lead to foundation failure, which in turn result in failure of other structural elements such as abutments and decks. Scour at the toe of an abutment can also lead to the formation of sinkholes directly behind the abutment. The formation of these cavities can be extremely dangerous as they happen unexpectedly and have been associated with fatalities.

(d) Debris accumulation

Debris accumulation against a bridge decreases flow area, leading to premature overtopping and also to increased hydraulic forces against the structure. Debris can also be a particular nuisance if deposited on the deck of a river crossing after an overtopping event. Such depositions can delay flow of traffic for considerable periods of time.

(e) Overtopping

Overtopping of a river crossing by flood waters is a distress mode which can incapacitate the facility for either short or long durations.

(f) Erosion

Overtopping of the approaches to river crossings, which normally consists of earth embankments, is more often than not accompanied by severe erosion which leads to complete failure. Failure of the approaches is the most common distress mode leading to failure of river crossings in South Africa.

(g) Changes in river alignment

Changes in the alignment of a river can occur in both the horizontal and vertical directions.

Changes in horizontal alignment are mainly due to changes in location of the river stream by means of meander shifts, avulsion and cutoffs. Such changes are often observed in estuaries on the east coast where avulsion can lead to situations where the river does not flow through a river crossing after a flood has occurred.

Changes in vertical alignment can occur due to aggradation or degradation.

Aggradation of a river is caused by the deposition of sediment and can occur when backwater effects caused by the presence of the river crossing leads to a reduction in sediment carrying capacity in the upstream reaches, and results in sediment deposition. Such depositions of sediment may cause a reduction in throughflow capacity of a river crossing.

Aggradation can also occur due to the construction of a reservoir downstream of a river crossing. An example of such a case, is aggradation which occurred at the site of the Jim Fouche bridge over the Caledon River in the Orange Free State. Welbedacht dam was constructed 42 km downstream of Jim Fouche bridge and sediment deposition in the reservoir is so severe that the discharge capacity of the bridge is decreased to such an extent that it is overtopped on an annual basis. This was not the case previously.

Degradation of a river may occur due to increased sediment carrying capacity during flood events. It may also result due to the presence of constrictions caused by the presence of the river crossing.

(h) Sinkhole formation

Scour at the foundation of an abutment may remove material at the base to such an extent that it could lead to the formation of sinkholes directly behind the abutment.

(i) Observed rate of occurrence of distress modes

Recorded failures of 186 road and rail river crossings in South Africa were investigated by identifying distress modes which were present in each case. Similarly the findings of an investigation by the Federal Highway Administration in the United States of America (Chang, 1973) are summarized in Table 4.1.

The findings of the investigation indicates that erosion of approach embankments is the most common distress mode which has generally been observed in river crossing failure in South Africa. Changes in river alignment and the formation of sinkholes behind abutments are found to occur less often than other distress modes. Scour, overtopping and distress modes leading to structural failure have roughly the same degree of importance, with accumulation of debris appearing to be a significant factor in the Orange Free State. The relative importance of distress modes differ between provinces, as can eg be seen when determining the relative importance of scour in Natal. Scour is the most important distress mode in this province, followed by distress modes leading to structural failure and erosion of approach embankments.

The findings for South Africa as a whole differ from the observations in the United States of America, where scour has been identified as the most common distress mode, followed by erosion of the approaches. Distress modes leading to structural failure and overtopping are the next two most important modes. Debris accumulation appears to have less importance than in South Africa, with river alignment changes only occurring on rare occasions.

Province	Owner	Distress mode							No of bridges failed
		Structural	Scour	Debris	Overtop	Approach failure	River align	Sinkhole	
CAPE	CPA	5	5	0	15	21	0	0	29
	SATS	6	6	0	5	8	0	0	12
	Subtotal	11	11	0	20	29	0	0	41
NATAL	NRD	31	28	5	4	27	4	3	53
	SATS	16	21	0	16	16	0	0	39
	KWAZULU	0	1	0	1	1	0	0	1
	Subtotal	47	50	5	21	21	4	3	93
OFS	OFS	15	6	26	27	35	1	2	42
	SATS	0	0	0	0	0	0		0
	Subtotal	15	6	26	27	35	1	2	42
NAMIBIA	NAMIBIA	1	0	0	1	2	0		2
	Subtotal	1	0	0	1	2	0	0	2
SWAZILAND	MOWS	6	6	0	4	2	1		7
	SR								
	Subtotal	6	6	0	4	2	1	0	7
TVL	TPA	0	0	0	0	0	0		1
	SATS	0	0	0	1	1			
	Subtotal	0	0	0	1	1	0	0	1
TOTAL RSA		80	73	31	74	113	6	5	186
USA	USA	147	298	39	111	171	19		420
	Subtotal	147	298	39	111	171	19		420
TOTAL		227	371	70	185	284	35	5	606

TABLE 4.1 : RATE OF OCCURRENCE OF DISTRESS MODES IN RIVER CROSSING FAILURES IN THE REPUBLIC OF SOUTH AFRICA AND IN THE UNITED STATES OF AMERICA

(ii) Direct and indirect losses

Those elements in the national and/or local economy which are expected to be affected by the failure of a river crossing or system of river crossings should be considered. These may be classified as direct and indirect monetary losses, and other potential losses.

(a) Direct monetary losses

Direct monetary losses include:

- Loss of capital investment and damage to river crossing, and
- Loss and damage to property in the vicinity of the river crossing, including:
  - Residential,
  - Commercial,
  - Public,
  - Personal, and
  - Industrial property

These losses may occur mainly due to flooding in upstream reaches of river crossings, or in downstream reaches if debris accumulation causes a river crossing to act as a dam. When the latter fails, the surge may cause damage to or loss of downstream property.

(b) Indirect monetary losses

Disruption of the transportation system may lead to various indirect losses related to the national and/or regional economy, including the following:

- Lost time
- Disruption of communications
- Loss of production
- Loss of wages
- Loss of revenue, including:
  - Business revenue
  - Utility income
  - Taxes
- Loss of utilities, including:
  - Transport
  - Water
  - Energy

(c) Other losses

Other losses include an estimate of the number of lives which could be exposed to danger by river crossing failure, and identification of possible environmental losses. Environmental losses are often difficult to quantify, and should therefore be addressed by experts in the field.

The value of human life is, likewise, difficult to assess, and often considered immoral to even discuss. The most practical means of considering this parameter is by estimating the number of human lives which are likely to be exposed to danger when a river crossing fail. This estimate will be closely related to the ADT and the layout of the river crossing. A long river crossing with a high ADT will endanger a larger number of human lives, as opposed to a short river crossing with a low ADT.

4.2.2 Pathways

(i) Fault trees

The pathways which would lead to structural failure can conveniently be defined by making use of a fault tree. A fault tree representing the relationship between events which can lead to river crossing failure is presented in Figure 4.2. The objective of the fault tree diagram is to identify and model the various system conditions, ie faults or failure events that can result in the occurrence of the **top event** or **initiating event** (i.e. the "Failure of the System due to Flood"). The different faults or failure events, also called **primary events**, that could lead to the top event are logically related to the top event by either "OR" or "AND" gates. "AND" gates are represented by periods (.), and "OR" gates by plusses (+) in Figure 4.2. An "AND" gate represents the simultaneous occurrence of events, ie if both occurs a failure would result. The "OR" gates on the other hand represent conditions where failure would result if one event or the other or both would occur. These gates are used to calculate the probability of failure of the system (see Section 4.2.3).

An important aspect of fault tree analysis is to divide the failure process into its most basic elements, and then to determine the failure mechanism of each. The process of identification of failure mechanisms requires the input of experts in the field of river crossing design. Once the failure modes have been hypothesized, the probabilities of failure of the primary events are estimated, which, likewise, requires the input of experts in the field of estimating probability of failure. Calculation of the probability of failure of the river crossing then follows by combining the calculated probabilities as already explained.

(ii) Event trees

An example of an event tree, relating the consequences to the initiating event (failure of the river crossing), is presented in Figure 4.3. This figure indicates the relationship between the various consequences, with their probabilities of occurrence represented by the symbols p_i. Separate branches exist for direct, indirect and other losses.

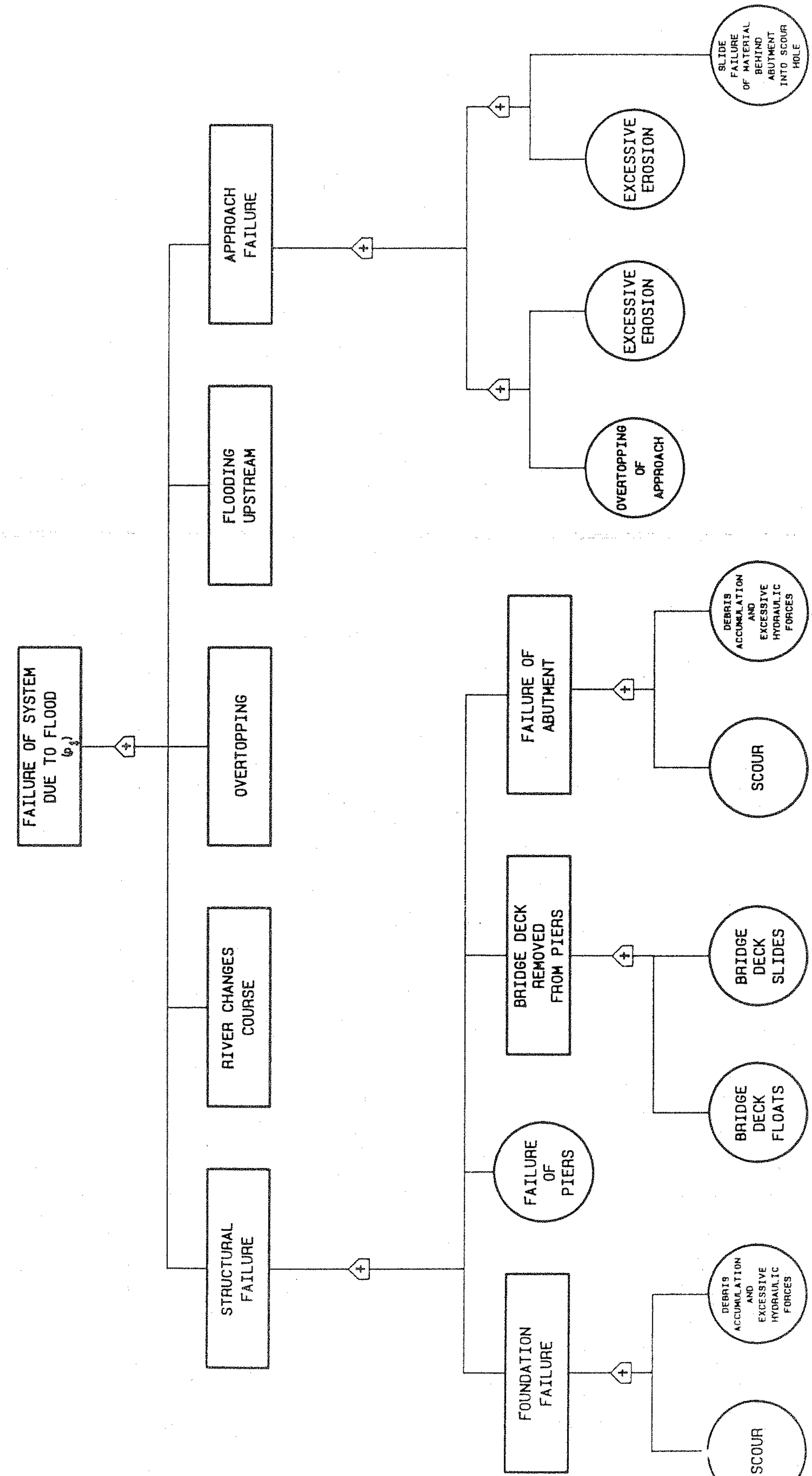

FIGURE 4.2 : RIVER CROSSING FAILURE FAULT TREE

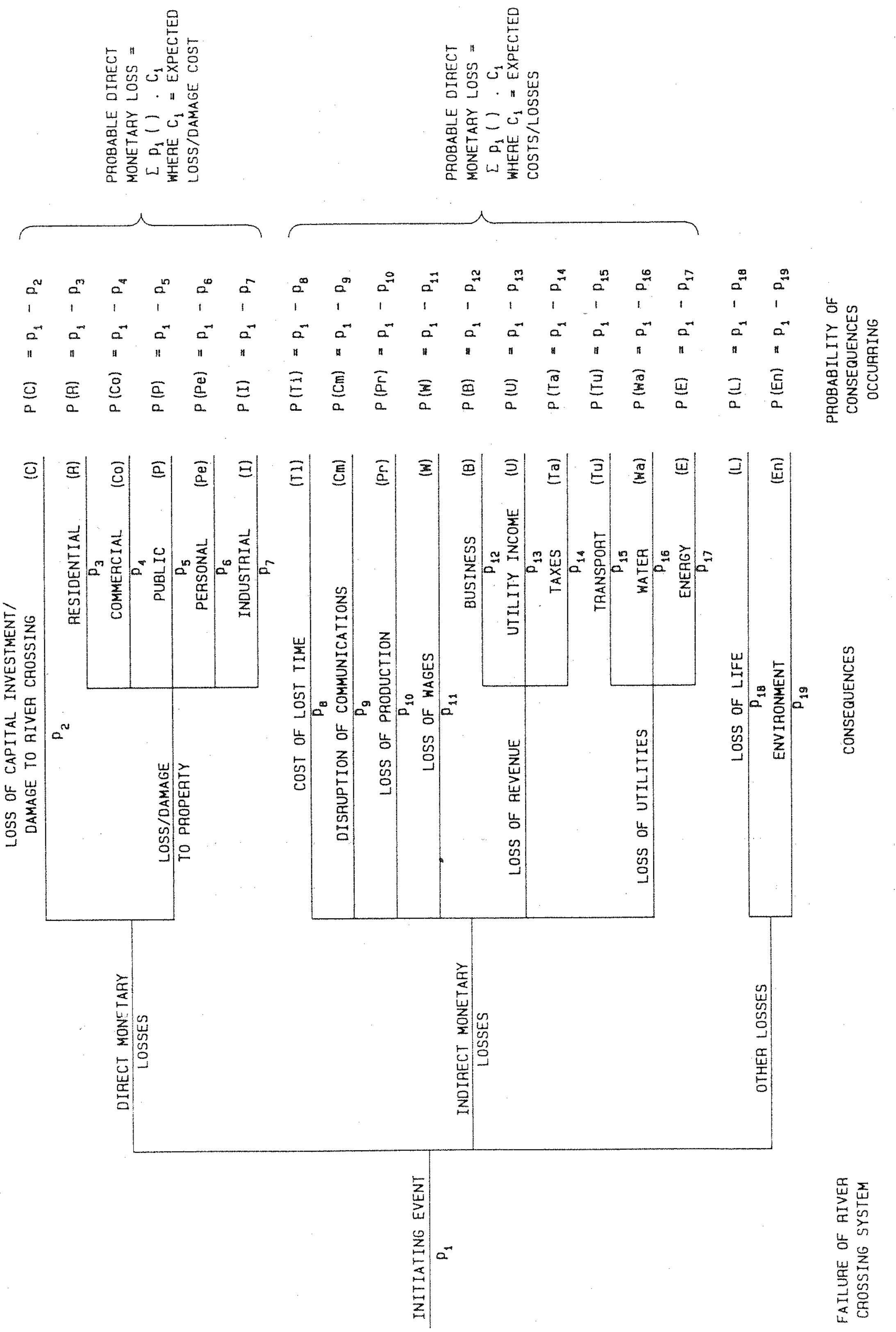

FIGURE 4.3 : TREE OF CONSEQUENCES DUE TO FLOOD RELATED RIVER CROSSING FAILURE

4.2.3 Probability of failure

The probability of failure of a river crossing can be determined by estimating the probability of occurrence of the primary events, which is calculated as follows:

- "AND" gate: If two basic events E1 and E2 can occur simultaneously, then the probability of simultaneous occurrence, given that the events are statistically independent, is represented by:

  p[primary event] = p[E1]*p[E2]

- "OR" gate: If two basic events E1 and E2 are considered, the probability that either E1 or E2 or both can occur, given that the events are not mutually exclusive, is given by

  p[primary event] = p[E1] + p[E2] - p[E1]*p[E2]

  If it is known, though, that the events are mutually exclusive, calculation is simpler and given by:

  p[primary event] = p[E1] + p[E2]

  where

  p[E1] = probability of event E1 occurring.

  The error which is made by assuming mutual exclusivity, even if this is not true, is not significant in the case of "OR" gates when working with the small probabilities normally associated with component failure in river crossings.

When calculating the probability of failure of a river crossing by making use of Figure 4.2, it is important to note that analyses will not always consider all the elements presented in the fault tree diagram. Less important distress modes are often left out in an analysis. A criterium which could be used in this regard is the concept of **de minimus** risk. Spangler (1987) suggests that distress modes (sub-events) with a likelihood of occurrence of 10^{-7} and less are usually considered so insignificant that they are left out of the analysis.

4.2.4 Risk

Risk is calculated by multiplying probability of occurrence and the value of the consequence (loss). In the case of failure of a river crossing, with multiple consequences, the process is facilitated by making use of an event tree which relates the initiating event to the consequences (Figure 4.3).

The probability of failure of a river crossing system is presented by the symbol p_1, the value of which is obtained from the fault tree analysis. Figure 4.3 indicates the relationship between the various consequences, with their probabilities of occurrence represented by p_i, where i = 2, 3, ... The probability of a specific event occurring is calculated by multiplying the respective estimates of probability of occurrence, eg the probability of the cost of lost time occurring, is calculated by multiplying p_1 and p_8.

The risks of direct and indirect monetary losses are then calculated by adding the products of these probabilities and the estimated losses.

4.3 Risk characterization

Risk, in engineering terms, is usually defined as the product of probability of occurrence and consequence. The risk of flooding would eg be calculated as the product of probability of exceedence of a flood of specified magnitude and the expected cost of flooding. This expression of risk is simplistic, but interpretation complicated, because perceptions of risk by individuals, society and government differ, resulting in a number of distortions from the traditional engineering model (Bohnenblust & Schneider, 1987). It is therefore necessary to develop a systematic approach to interpret risk because the simplistic approach which is used in the Level I risk characterization is often not adequate. No simple solution to this problem is presented here, but the approach which is followed is to present a discussion of topics which are relevant to the interpretation of risk of river crossing failure, and also to provide references.

Uncertainties about definitions (eg definition of probability), scientific facts (eg disagreement about failure modes), perceptions of risk and value systems of various parties imply that risk characterization is not definitive and will never be (Covello et al, 1987). Risk characterization should be a collective effort, preferably involving all affected parties. However, this is not always feasible, as society is not organized nor used to making safety decisions in interdisciplinary fashion (Whipple, 1982). Characterization of risk which takes cognisance of values and perceptions of individuals, society and Government can nonetheless be attempted by making use of research in this field of endeavor. In order to do this, definition of the risk characterization environment in terms of affected parties and influences, as proposed in Figure 4.4, is required for systematic characterization of risk. This figure indicates that the acceptability of risk is influenced by perceptions of individuals, society and Government, and that these parties also influence one another against a background of politics, economics, technology and culture. This complicated relationship is addressed by reviewing relevant research in Sections 4.3.1 to 4.3.3, and by providing a summary in Section 4.3.4.

4.3.1 Individual perceptions of risk

(i) Politics

Politics, considered to be the art and science of government, will normally only influence the average individual's perception of acceptable risk when it is exploited by politicians seeking office. In the ideal case, the perceptions of individuals should rather influence Government, which is often not the case in South Africa. It is therefore highly unlikely that politics influence the perceptions of individuals in South Africa.

(ii) Economics

Experience by Bohnenblust & Scheider (1987) indicate that individuals generally do not base their safety decisions on expected damages. They found that risk aversion is often preferred, which in the narrower sense implies that catastrophic events have more impact on perceptions of risk than many small accidents with the same number of fatalities.

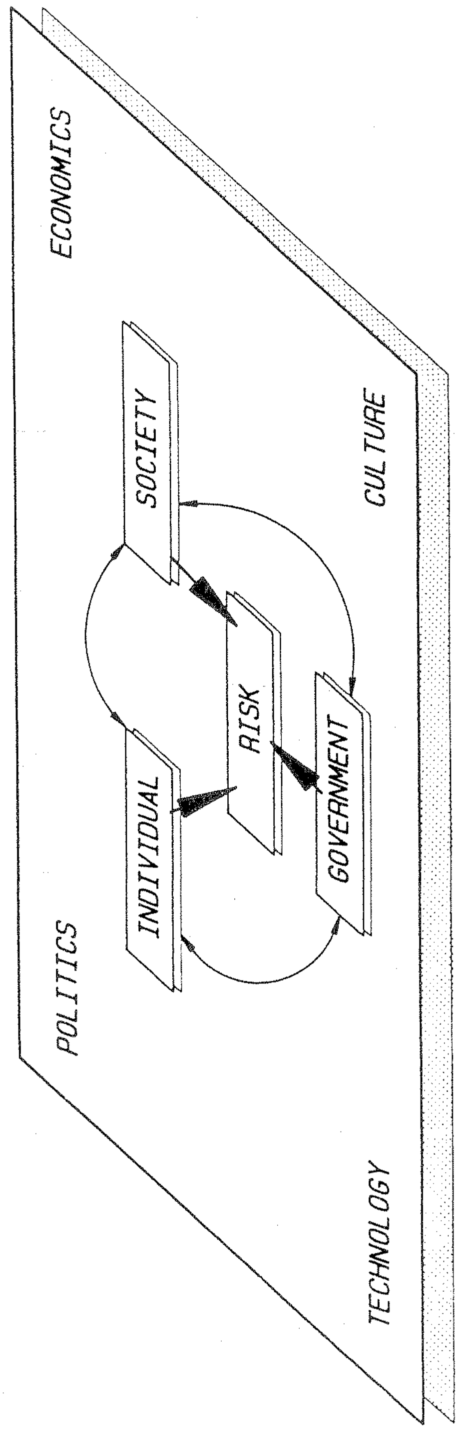

FIGURE 4.4 : RISK CHARACTERIZATION ENVIRONMENT

Schulze (1980) nevertheless attempted to define a relationship between monetary benefit and acceptability of increased level of risk. He found that the individual in the United States of America would accept an 0,1 percent increase in risk for every $300 to $1000 increase in benefits for "moderate" risks. However, whether this finding can be applied to assess the acceptability of risk of failure of river crossings is debatable as failure of river crossings are normally perceived to be "catastrophic".

It is considered that the influence of economics on the individual's perception of risk is ill-defined.

(iii) Technology

Lay people generally have a poor understanding of technology and technological risks and the individual's perception of risk is shaped by his confidence in its effective management (Starr, 1987; Rayner, 1987; Rogers, 1987).

Trust therefore plays an important role in shaping the individual's perception of technological risk. If risk management is executed in a way which promotes trust, individuals will feel "safe". Mistrust will lead to perceptions of high risk, irrespective of whether the applied technology is adequate or not.

(iv) Culture

Attitudes towards risk are further shaped by the culture (value system) of an individual. Willingness to take risks is part of the accepted value system of individuals in Western Civilization. However, the level of acceptable risk depends on circumstances. Bohnenblust & Schneider (1987) identify four factors which influence the level of acceptable risk:

- The acceptable level of **voluntary** risk (eg mountaineering) by the individual is usually considerably higher than acceptable levels for other risks (acceptable level: 10^{-2} to $2 * 10^{-3}$ per year).

- The acceptability of **avoidable** risks, such as road travel, is usually lower than that of voluntary risks (acceptable level: $2 * 10^{-3}$ to $5 * 10^{-4}$ per year).

- If individuals or society perceive that they can **influence** risk, eg by means of public policy, an even lower level of risk is demanded (acceptable level: $5 * 10^{-4}$ to $9 * 10^{-5}$ per year).

- The acceptable level of risk if benefits are perceived to flow from the activity, eg coal fired power stations which pollutes the air but delivers the benefit of electricity, can be even lower (acceptable level: $9 * 10^{-5}$ to 10^{-5} per year).

When applying Bohnenblust and Schneider's findings to risk of river crossing failure, the reasoning can be as follows. The individual making use of road transport may feel unhappy about the rate of road incidents, but accepts the risk when travelling. The individual has the ability to avoid risk, and measures of acceptability of risk of river crossing failure should therefore fall within the "avoidable risk" category.

Annual risks associated with fatal road accidents are given by:

- Bohnenblust & Schneider (1987): between $2*10^{-3}$ and $5*10^{-4}$,
- Wilson (1984): $2*10^{-4}$, and
- Oosthuizen (1985): $9*10^{-4}$ for South African conditions (assuming 450h of travel per annum).

These values are presented in Figure 4.5. A relative measure of the perceived severity of these risks can be found by comparing it with the finding of Spangler (1987) that risks with values of the order of 10^{-6} are usually considered to be insignificant (also see Figure 4.6).

4.3.2 Society

(i) Politics

The role of politics in influencing society's perception of acceptability of risk is similar to its role in influencing the individual's perception (Section 4.3.1(a)).

(ii) Economics

The influence of economics on society's perception of acceptable levels of risk will reflect the influence of economics on individual perceptions. Society, being a collection of individuals, will have an enhanced view which develops through debate of issues. Debates on the perceived relationship between the acceptability of risk and aspects of regional and national economies, the "willingness to pay" (tax) and the "value of life" will influence society's perception of acceptability of risk.

The business community, being part of "society", may place a high value on the reliability of river crossings especially after catastrophic events. The loss in revenue and additional costs resulting from catastrophic failures of river crossings are usually estimated by Chambers of Commerce and Industry after such events. Society therefore has a financial measure of the cost of failure for a particular catastrophic event, and can relate this to taxes (and their willingness to pay it) for the construction of improved river crossings and the perceived benefits which can flow from it.

Debates on the "value of life" are usually considered immoral, and society prefer to avoid debating the issue.

It is concluded that society's perception of the influence of economics on the acceptability of risk will change from time to time. Society will be more "willing to pay" for improved reliability of river crossings directly after catastrophic events, and may even be able to justify monetary values, but as time passes memories will fade, perceptions will change and society will be less willing to pay for upgrading infrastructure such as river crossings.

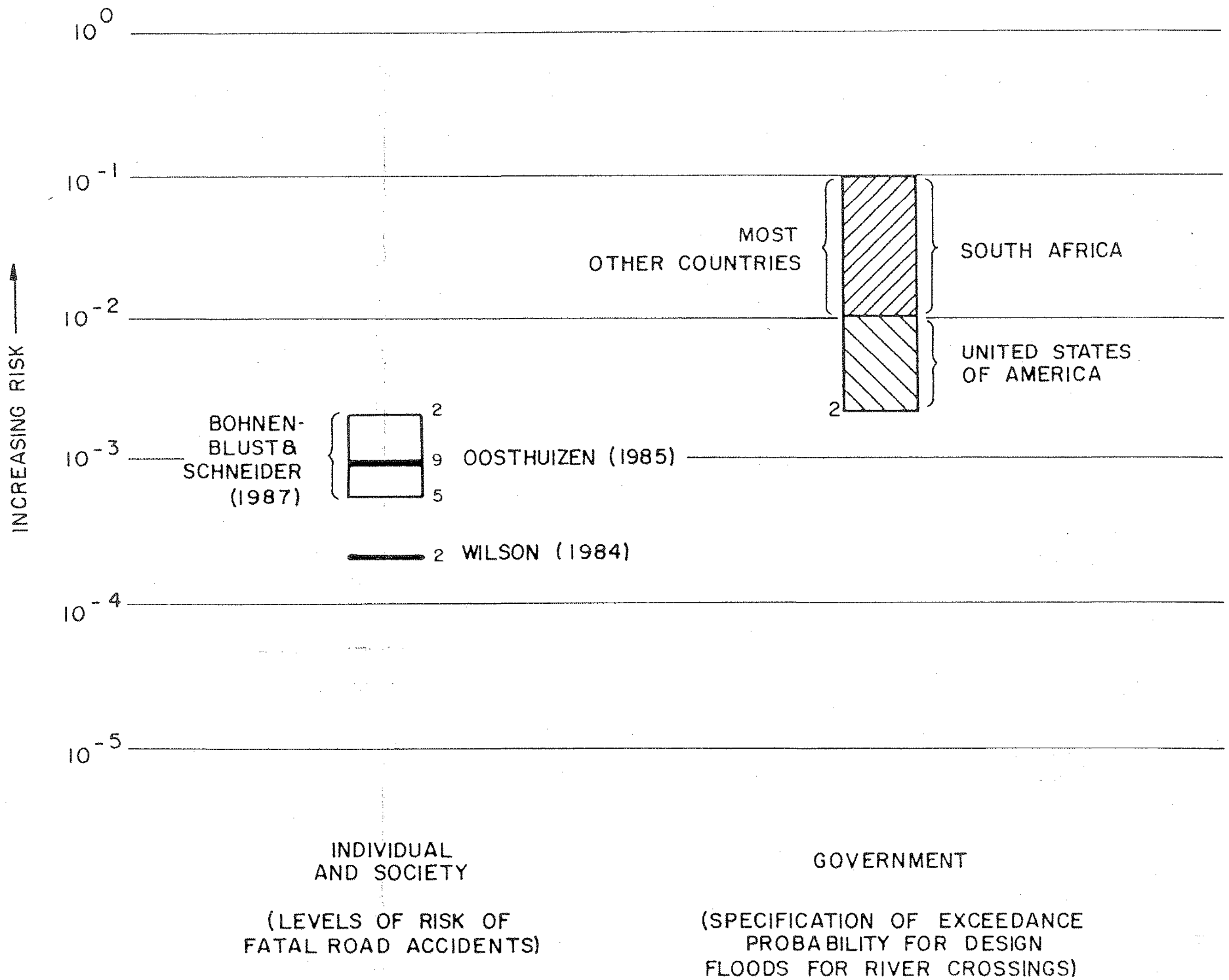

FIGURE 4.5 : CURRENT LEVELS OF ACCEPTABLE AND SPECIFIED RISK FOR ROAD USEAGE AND RIVER CROSSINGS

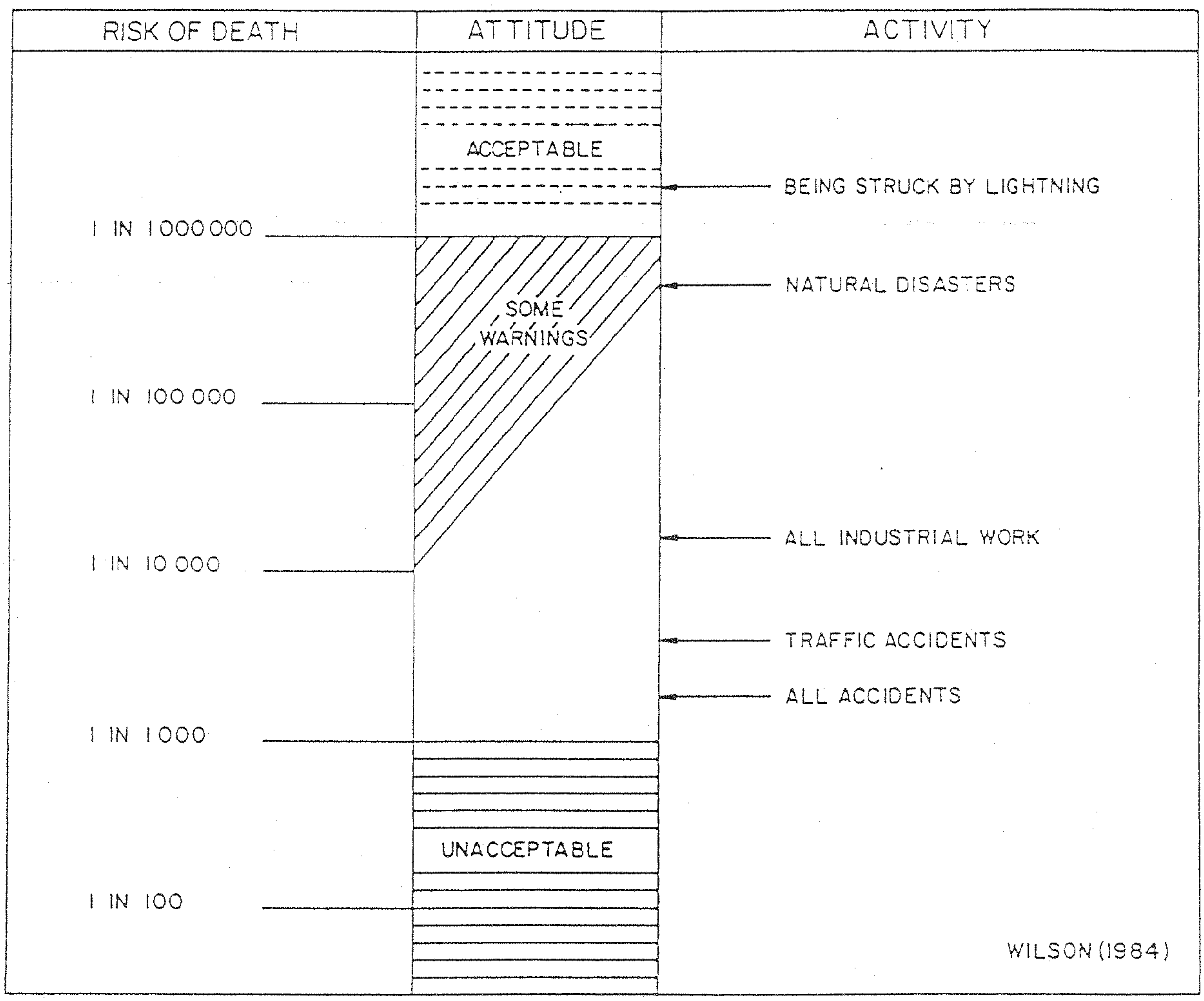

FIGURE 4.6 : PROBABILITY OF DEATH FOR AN INDIVIDUAL PER YEAR OF EXPOSURE (ORDERS OF MAGNITUDE) IN TERMS OF ACCEPTABLE/UNACCEPTABLE RISK (WILSON 1984)

(iii) Technology

Society generally does not have a good understanding of technology and perceptions of acceptability of risk as regards this subject are shaped by the press, catastrophic events and public perceptions of how well risk is managed. Trust plays, similar to the individual, a major role in determining society's perceptions of acceptability of technological risk. This emphasizes the importance of efficient management of risk.

(iv) Culture

The influence of culture on society's perception of acceptability of risk will be similar to that of individuals. Society's regard for life and material belongings will shape these perceptions.

Inferences made from Cole (1987) indicate that developed countries have the means to, compared to world averages, ensure a ten fold decrease in the risk of fatality due to natural disasters. This may imply that the perception of acceptability of risk by society in developed countries will be different to that in developing countries.

4.3.3 Government

(i) Politics

Politics should influence Government's decisions on the acceptability of risk. Bohnenblust & Schneider (1987) reports that Government often adopts an attitude of risk aversion in order to ensure that its image is not adversely affected.

However, whether Government adopts an attitude of risk aversion in managing risk of river crossing failure is debatable. When comparing South African specifications of exceedence probabilities with those of other countries, it is found that specifications are generally comparable. Table 4.2 indicates that most countries specify exceedence probabilities of up to 10^{-2}, and in the case of Austria river crossings must also be checked for the maximum expected flood. Design flood specification in the USA often requires that a river crossing must be able to pass a 100 year flood, and resist scour resulting from a 500 year flood (exceedence probability of 2×10^{-3}). South African specifications range between 10^{-1} and 10^{-2} (10 to 100 year floods). However, when comparing design flood exceedence probability specification for the different countries with levels of risk which are acceptable to individuals and society (Figure 4.5), one can conclude that Government generally does not adopt an attitude of risk aversion in specification of design flood exceedence probabilities for river crossings. Government generally appears to specify higher risks (except for Austria, and possibly France and Switzerland) than what is acceptable to society and individuals.

Country	Return period (years)	Exceedence probability
Austria	30<T<100 and maximum expected	$3{,}3 \times 10^{-2}$ to 10^{-2} and maximum expected
France	cost/benefit analysis	
Switzerland	no prescription	
USSR	50<T<100	2×10^{-2} to 10^{-2}
Most other countries	10<T<100	10^{-1} to 10^{-2}
United States of America	50<T≤500	2×10^{-2} to 2×10^{-3}
South Africa	10<T<100	10^{-1} to 10^{-2}

TABLE 4.2 : SPECIFICATIONS OF DESIGN FLOOD EXCEEDENCE PROBABILITIES FOR RIVER CROSSINGS (KOVACS, 1989)

(ii) Economics

Government, in developing infrastructure, is responsible to society for the optimal allocation of resources. The idealized process in the development of infrastructure consists of the identification of a social need, development of a solution for the need, and a benefit/cost analysis to justify funding to implement the proposed solution. Once funding has been obtained, the infrastructure is engineered and constructed in a way which will ensure optimal expenditure. However, in the case of river crossings the benefits and costs are usually accounted for as part of the benefits and costs of the entire transportation system under investigation. It rarely happens that benefits and costs are determined for individual river crossing structures. Therefore, the main concern in the engineering of river crossing structures is often the optimal expenditure of funds which have already been allocated. The design flood for which a river crossing should be designed should, in the ideal case, be determined by making use of an economic analysis for each individual river crossing structure, as demonstrated in Figure 4.7. This is rarely the case. In South Africa it is more common to utilize a design flood provided in a design specification (usually provided by Government) to size the opening of the river crossing, and once this has been determined optimize the river crossing design without altering the design flood magnitude. This approach is likely to be inadequate, as demonstrated in Figure 4.5. The comparison in the latter figure indicates that current design flood specification falls short of what the public's perception of acceptable risk is.

This shortcoming can be corrected by changing design flood specifications or by conducting detailed economic analyses on unique river crossings. The latter can be conducted by making use of the procedure recommended for river crossing design by Corry et al (1981). The former requires the development of an approach for the blanket specification of recurrence intervals which can be economically justified. New recommendations for the blanket specification of design flood recurrence intervals, justified by marginal economic analysis, is presented in Appendix 7.3.

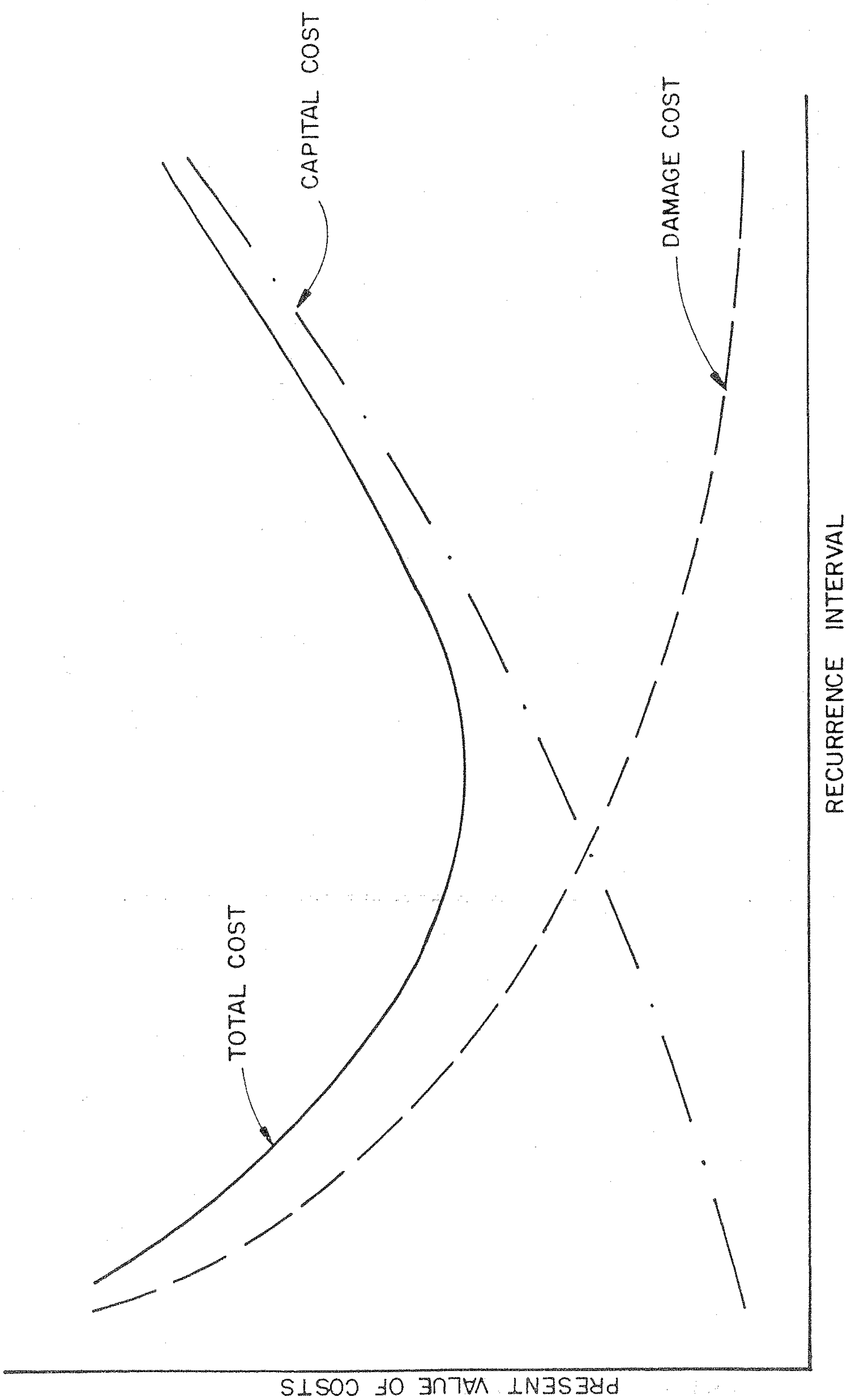

FIGURE 4.7 : TRADITIONAL APPROACH TO ECONOMIC OPTIMIZATION

(iii) Technology

Government's response to risk of technology is portrayed in design codes and regulations. These documents reflect the trust of Government in technology and engineering capabilities.

It is generally accepted that compliance to design codes and regulations would result in a minimization of technological risk.

The acceptability of risk by Government for river crossings is portrayed by the specification of design flood exceedence probabilities in design codes and regulations. It is therefore important to ensure that such specification is rational and consistent. Current specifications are compared to public perceptions of acceptable risk in Figure 4.5. This figure shows a discrepancy which can be reduced by risk management and/or a revision of specified design flood recurrence intervals. A revised approach to design flood recurrence interval specification is presented in Appendix 7.3.

(iv) Culture

The culture (value system) of a nation will be reflected in the Government's approach to the assessment of risk. The Government's accepted norms should therefore be similar to that of society as far as cultural values are concerned.

4.3.4 Summary

Thresholds of acceptable risk of failure of river crossings can be determined by considering the influence of Politics, Economy, Technology and Culture on perceptions of acceptable levels of risk of Individuals, Society and Government. These were discussed in the foregoing sections and are summarized in Table 4.3.

The foregoing sections and the summary in Table 4.3 implies that current Government opinion is that river crossing design is not important from a political point of view. This is borne out by the fact that current design flood exceedence probabilities specifications expose the individual and society to higher risks than what are considered acceptable.

This discrepancy can be reduced with adequate risk management plans. Such plans should be sufficient to ensure the trust of society and individuals. Risk management strategies can partly be portrayed in Governments response to Technological risk and accommodated in design codes and regulations. However, it is also important to prepare contingency plans and other risk management strategies if the discrepancy between specified and acceptable risks is not addressed by means of specification. A reduction in the discrepancy between the public's and Government's perceptions of acceptable risk can be justified economically by making use of marginal analysis (see Appendix 7.3).

Factor	Individual and society	Government
Politics	Individual's and society's perceptions should influence government	Government does not appear to adopt attitude of "risk aversion". A discrepancy exists between acceptability of risk to society and individuals, and design flood exceedence probability specification by Government (Figure 4.5)
Economics	▪ Influence on risk perceptions by individuals ill-defined, would rather opt for risk aversion ▪ Society's perceptions influenced on a time-dependent basis. Will be more "willing to pay" (taxes) to improve crossings directly after catastrophic events than otherwise.	▪ Optimal allocation of resources influences Government's perceptions. New standards are proposed, based on marginal analysis (Appendix 7.3).
Technology	Perceptions shaped by trust of community in technology and how well risk is managed	Responds by means of design codes and regulations. Discrepencies shown in Figure 4.5 may be reduced by following the recommendations in Appendix 7.3
Culture	Accepts risk of river crossing failure as "avoidable" - acceptable levels: $2*10^{-4}$ to $2*10^{-3}$ (recurrence intervals of 500 to 5000 years)	Should be same as that of society and individuals. Discrepancies appears to exist (Figure 4.5)

TABLE 4.3 : INFLUENCE OF POLITICS, ECONOMY, TECHNOLOGY AND CULTURE ON PERCEPTIONS OF ACCEPTABLE LEVELS OF RISK OF RIVER CROSSING FAILURE

4.4 Reporting requirements

The reporting requirements for the Level II assessment would be dictated by the specific project, and are not as readily definable in set format as for the Level I assessment. The report should at least include sections dealing with:

- Site description
- Hazard identification
- Risk estimation
- Risk characterization
- Recommendations

5. RISK MANAGEMENT

The Risk Analysis process is completed by risk management (Figure 2.1). Once the risks have been assessed, risk management strategies needs to be devised and implemented to ensure that the risk of river crossing failure is within acceptable limits. Part of risk management is regular re-evaluation of risk of river crossing failure. Such re-evaluation indicates whether re-assessment of risk is required. If not, the risk management procedures which are implemented at the time are continued, otherwise the risk would be re-assessed and new risk management procedures devised.

This guideline does not prescribe management of risk in detail, as it requires holistic evaluation of the assessment of risk of river crossing failure in systems context for development of appropriate and cost effective procedures to maintain the risk within acceptable limits.

The objective of risk management is to devise strategies and take the necessary actions to ensure that risk exposure to the public is within acceptable levels. Such actions may include conservative design standards, which could result in high expenditures on infrastructure, or, on the other hand, less conservative design standards combined with institutional arrangements which would reduce risk exposure to acceptable levels. Institutional arrangements may include flood warning systems and well-organized emergency response units to assist victims of river crossing failure. The characterization of risk of failure of river crossings (Section 4.3) indicates that the risk associated with current design standards may be socially unacceptable and that such institutional arrangements are currently required to ensure social acceptability of risk.

Management of the risk of existing river crossing systems will almost invariably consist of the development of institutional systems which would reduce risk. However, in certain cases, risk management may require abandonment of existing river crossings and construction of replacements.

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7. APPENDICES

7.1 Description of river crossing types

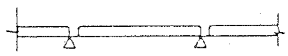
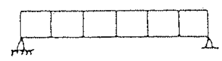
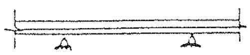
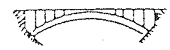
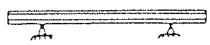
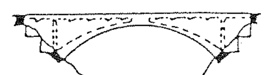
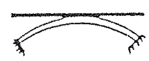
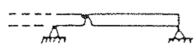
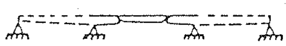
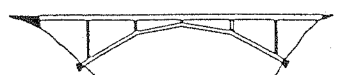
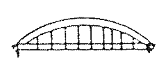
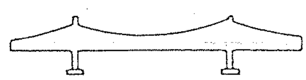
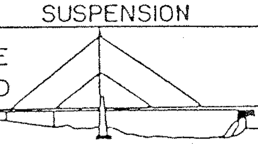
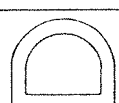
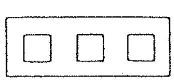
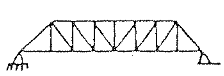
CODE	BRIDGE TYPE	CODE	BRIDGE TYPE
01	 SIMPLY SUPPORTED	13	 GIRDER
02	 CONTINUOUS	14	 OPEN RIBBED SPANDREL ARCH
03	 DOUBLE CANTILEVER	15	 SOLID SPANDREL ARCH
04	 BALANCED CANTILEVER	16	 OPEN SPANDREL ARCH
05	 CANTILEVER WITH BALANCING SPAN	17	 TIED ARCH
06	 CANTILEVER WITH DROP IN SPAN	18	 FUNICULAR ARCH
07	 PORTAL FRAME	19	 BOWSTRING SUSPENSION
08	 FRAME STRUCTURE	20	 SUSPENSION
09	 STRUT FRAME	21	CABLE STAYED 
10	 SINGLE CELL STRUCT.	22	
11	 MULTIPLE CELL STRUCTURE	23	
12	 LATTICE TRUSS	24	OTHER

TABLE 7.1.1 : BRIDGE TYPES PRIMARY STRUCTURAL SYSTEM

CSRA Guidelines for the hydraulic design and maintenance of river crossings
Volume VI, 1994, Committee of State Road Authorities, South Africa.

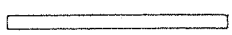
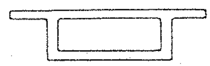
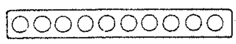
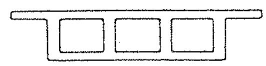
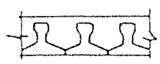
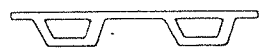
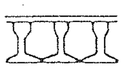
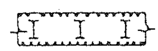
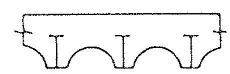
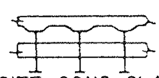
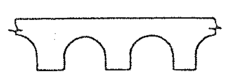
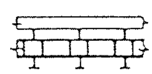
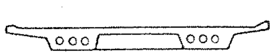
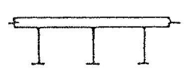
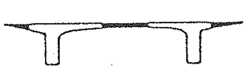
CODE	TYPE DECK	CODE	TYPE DECK
01	 SOLID FLAT SLAB.	12	 SINGLE BOX GIRDER.
02	 VOIDED SLAB.	13	 MULTIPLE BOX GIRDER.
03	 BEAM PLUS SOLID INFILL.	14	 DOUBLE BOX BEAMS WITH CANTILEVER.
04	 INVERTED T-BEAMS WITH SOLID INFILL.	15	 MULTIPLE BOX BEAMS WITH CANTILEVER.
05	 RECTANGULAR BOX BEAMS.	16	 STEEL I-BEAMS ENCASED IN CONCRETE.
06	 BEAM & SLAB.	17	 CONC. SLAB INTEGRAL WITH T-BEAM RIB.
07	 BEAM & SLAB WITH SEPARATE DIAPH.	18	 COMPOSITE CONC. SLAB SUPPORTED ON A STEEL GRILLAGE.
08	 RIBBED DECK.	19	 INDEPENDANT CONC. SLAB SUPPORTED ON A STEEL GRILLAGE.
09	 BOX SLAB BEAM.	20	 STEEL GRILLAGE WITH ANY OTHER FORM OF DECK.
10	 SOLID BEAM		
11	 T - BEAM	24	OTHER

TABLE 7.1.2 : DECK TYPES

CSRA Guidelines for the hydraulic design and maintenance of river crossings
Volume VI, 1994, Committee of State Road Authorities, South Africa.

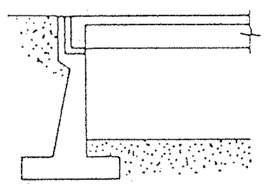
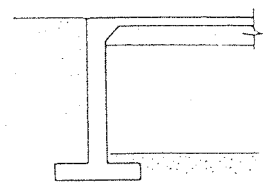
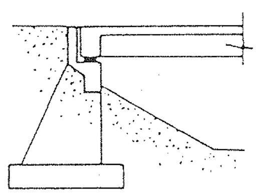
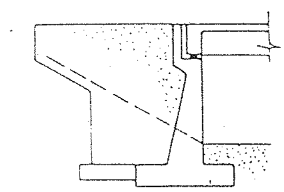
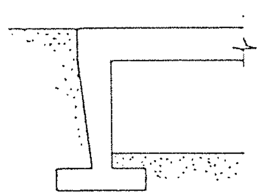
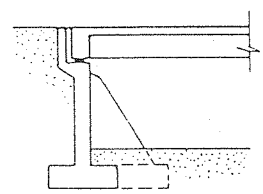
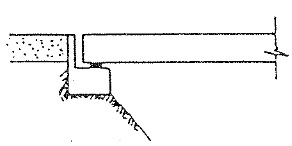
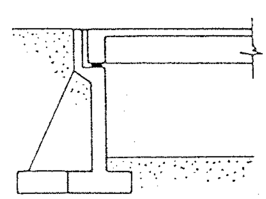
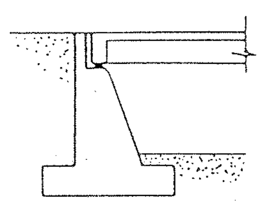
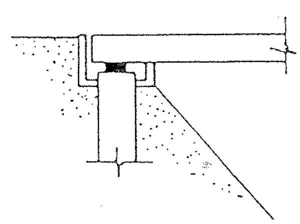
CODE	TYPE	CODE	TYPE
01	 CANTILEVER	06	 DIAPHRAGM
02	 SPILL THROUGH	07	 SOLID WALL WITH INTEGRAL WING WALL
03	 FRAME	08	 BUTTRESSED
04	 SMALL BREAST BEAM	09	 COUNTERFORTED
05	 MASS GRAVITY	10	 INTEGRAL PILE CAP

TABLE 7.1.3 : ABUTMENT TYPES

CSRA Guidelines for the hydraulic design and maintenance of river crossings
Volume VI, 1994, Committee of State Road Authorities, South Africa.

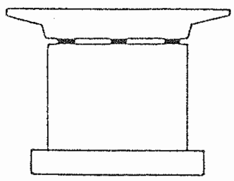
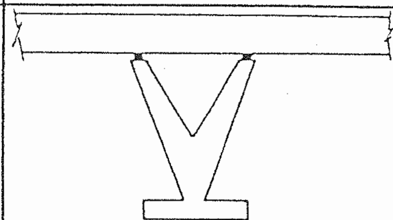
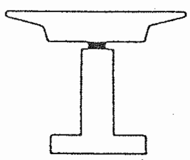
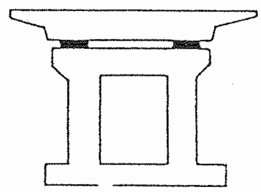
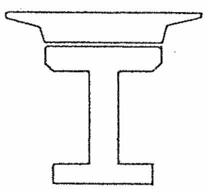
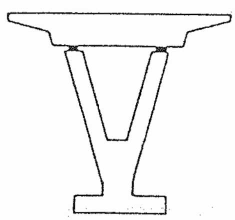
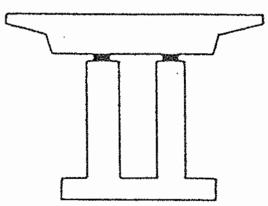
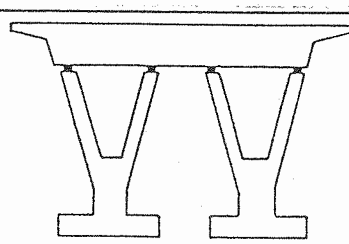
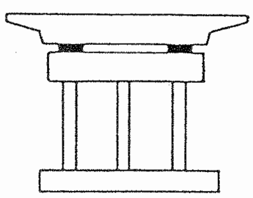
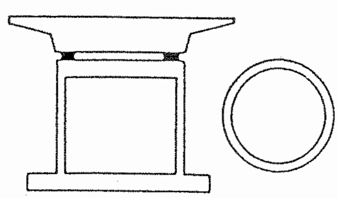
CODE	TYPE	CODE	TYPE
01	 R.C. WALL	06	 SINGLE OR MULTIPLE R.C.SPLAYED
02	 SINGLE R.C. COLUMN	07	 FRAME
03	 SINGLE RC COLUMN WITH HAMMERHEAD	08	 SINGLE R.C.V-SHAPED
04	 MULTIPLE R.C. COLUMN	09	 MULTIPLE R.C. V-SHAPED
05	 MULTIPLE R.C. COLUMN WITH CAPPING BEAM	10	 HOLLOW CAISSON

TABLE 7.1.4 : PIER TYPES

CSRA Guidelines for the hydraulic design and maintenance of river crossings
Volume VI, 1994, Committee of State Road Authorities, South Africa.

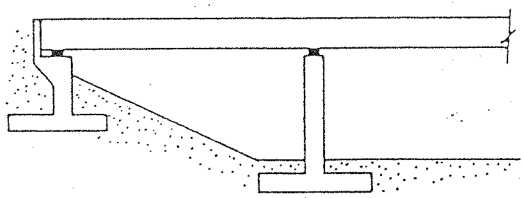
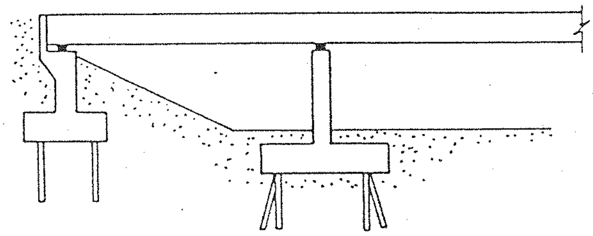
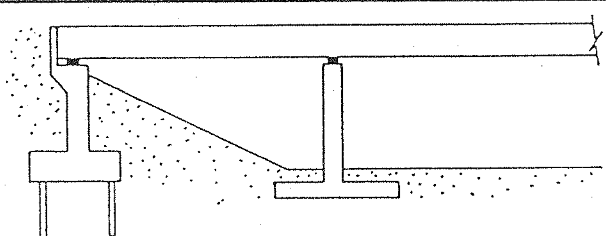
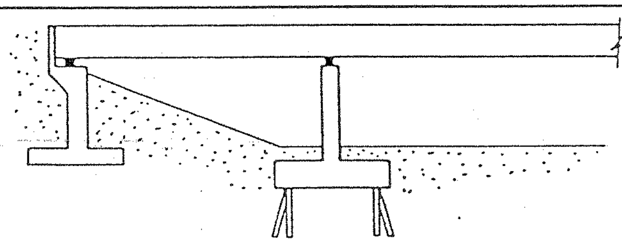
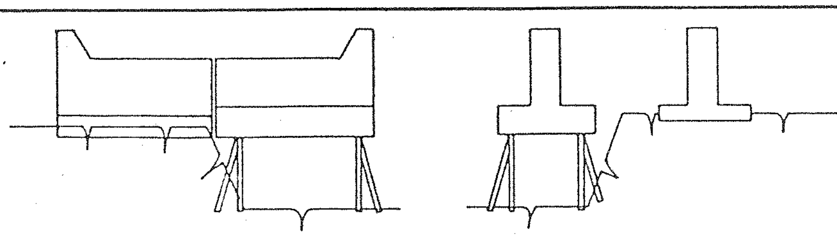
CODE	TYPE
01	 ALL SPREAD FOOTINGS
02	 ALL PILED
03	 ABUTMENTS PILED & PIERS SPREAD
04	 PIERS PILED & ABUTMENTS SPREAD
05	 PART ABUTMENT OR PART PIER PILED
06	COMBINATION OF 01 TO 05

TABLE 7.1.5 : FOUNDATION TYPES

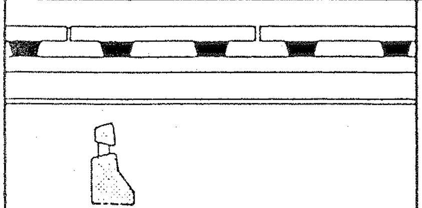
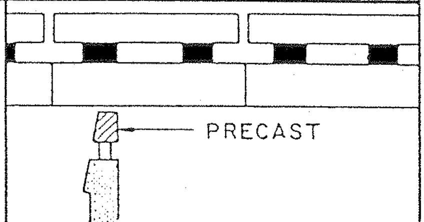
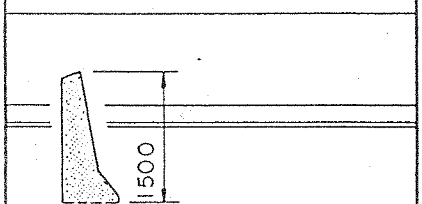
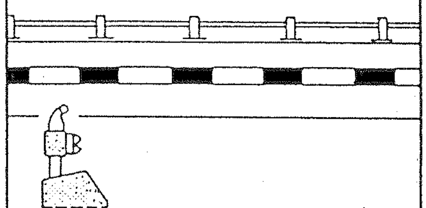
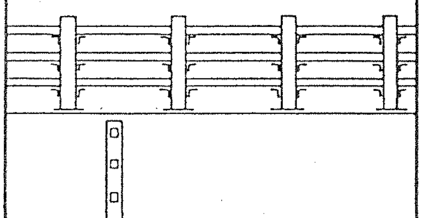
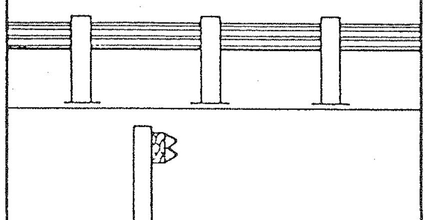
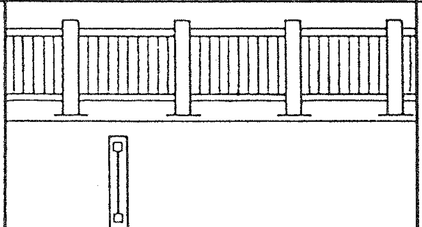
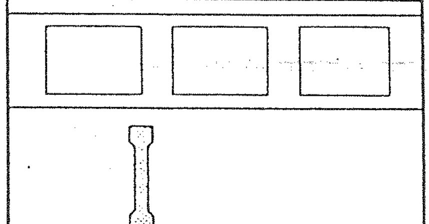
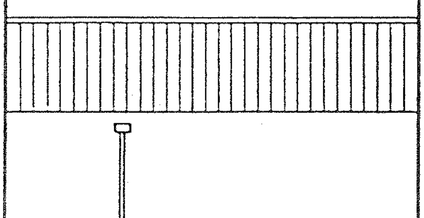
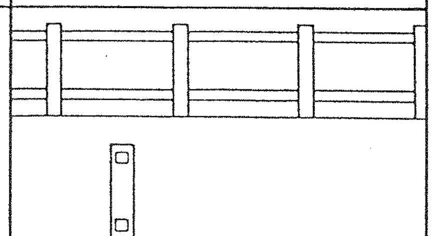
CODE	TYPE	CODE	TYPE
01	 NEW JERSEY (NTC)	06	 PRECAST HORIZONTAL AND IN-SITU STANCHIONS
02	 S.A.T.S. STANDARD SOLID RAIL	07	 STEEL RAIL AND GUARDRAIL
03	 STEEL RAILING (HORISONTAL)	08	 GUARDRAIL ON STEEL POSTS
04	 STEEL RAILING (VERTICAL)	09	 SOLID CONCRETE WALL
05	 LIGHT METAL RAILING	10	 PRECAST CONCRETE BEAM

TABLE 7.1.6 : BALUSTRADE TYPES

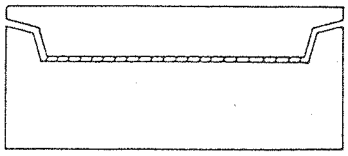
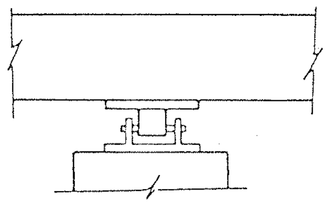
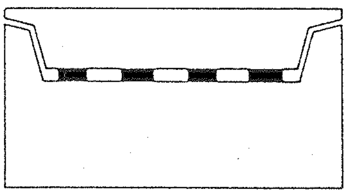
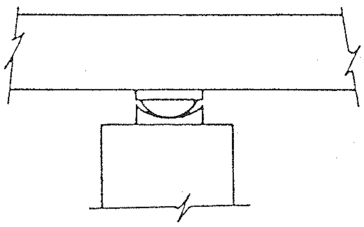
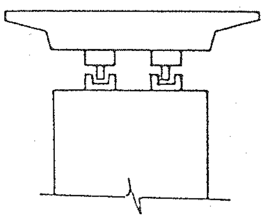
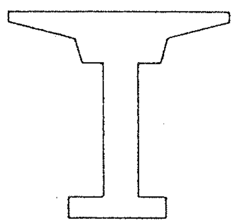
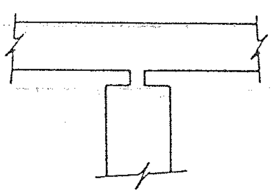
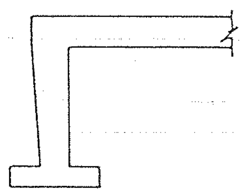
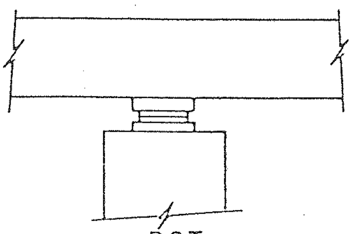
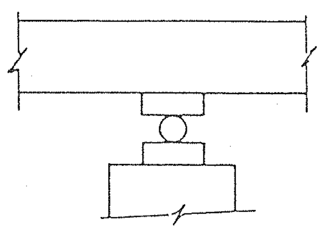
CODE	TYPE	CODE	TYPE
01	 ROOFING FELT OR SLIP MEMBRANE	06	 KNUCKLE JOINT (UPLIFT)
02	 RUBBER PADS (ELASTOMERIC)	07	 SPHERICAL S.S. – P.T.F.E.
03	 SLIDING	08	 PIER MONOLITHIC WITH DECK
04	 CONCRETE OR STEEL HINGED	09	 DECK MONOLITHIC WITH SUBSTRUCTURE
05	 POT	10	 ROCKER OR ROLLER

TABLE 7.1.7 : BEARING TYPES

7.2 Typical Level I risk analysis report

Example 7.2.1

The Jim Fouche bridge (Figure 7.2.1), 119 m long, was built over the Caledon River in 1956. The river crossing consists of five simply supported, equilength spans which are supported on piers. Four of the piers are founded directly on bedrock, whereas one pier is supported by a caisson. The latter is founded on bedrock. The abutments are made of concrete, the one founded directly on bedrock, whereas the other is founded on a caisson which rests on bedrock.

The river crossing is situated on a relatively straight reach of the river, slightly curving to the left in the downstream direction. The possibility of debris accumulation on the structure is relatively high, originating from the uprooting of river bank vegetation. Debris can include trees, as witnessed during a site visit.

An site inspection of the river crossing revealed that it is in a relatively good condition, with only some displacement of the decks. This is most probably caused during flood conditions, by hydraulic forces which are increased due to debris accumulation. Apart from this, the foundations, piers, abutments and bearings are considered to be intact.

The river crossing was originally designed to pass the 1:20 year flood. This ability is severely reduced by the construction of the Welbedacht Dam 42 km downstream of the river crossing. The dam, which was constructed in 1973, caused severe aggradation in the river bed. Figure 7.2.2 illustrates the long section of the river, showing the original 1973 bed profile, the surveyed 1988 profile, and the estimated future average stable profile of the river bed. Figures 7.2.1 and 7.2.2 also illustrates the relation between the river crossing and the aggradation. It is now estimated that floods with a recurrence interval of 1:5 years will overtop the river crossing. The significant aggradation currently limits the possibility of contraction scour. However, the turbulence which is created by the current layout and positioning of the river crossing is expected to fluidize large volumes of sediment during flood conditions, exposing the piers and foundations.

The river crossing has strategic importance because it links the city of Bloemfontein with the country of Lesotho. The river crossing became even more important when the construction of the Lesotho Highlands Water Project commenced. The closest alternative river crossing, is the old, narrow, steel bridge at Jammersdrift. This river crossing is situated upstream of the Jim Fouche bridge, and, due to a sudden drop in the river bed downstream of it, is not influenced by the aggradation in the river. The expectation also is that aggradation would not influence it in future. However, the narrowness of the bridge and limitations on the weight of vehicles which can travel over it, limits its value as an alternative route. Potential economic losses during sustained flooding is expected to be moderate. (The real value has not been determined, but for purposes of this example potential losses of, say, R 1 million during sustained flooding are assumed).

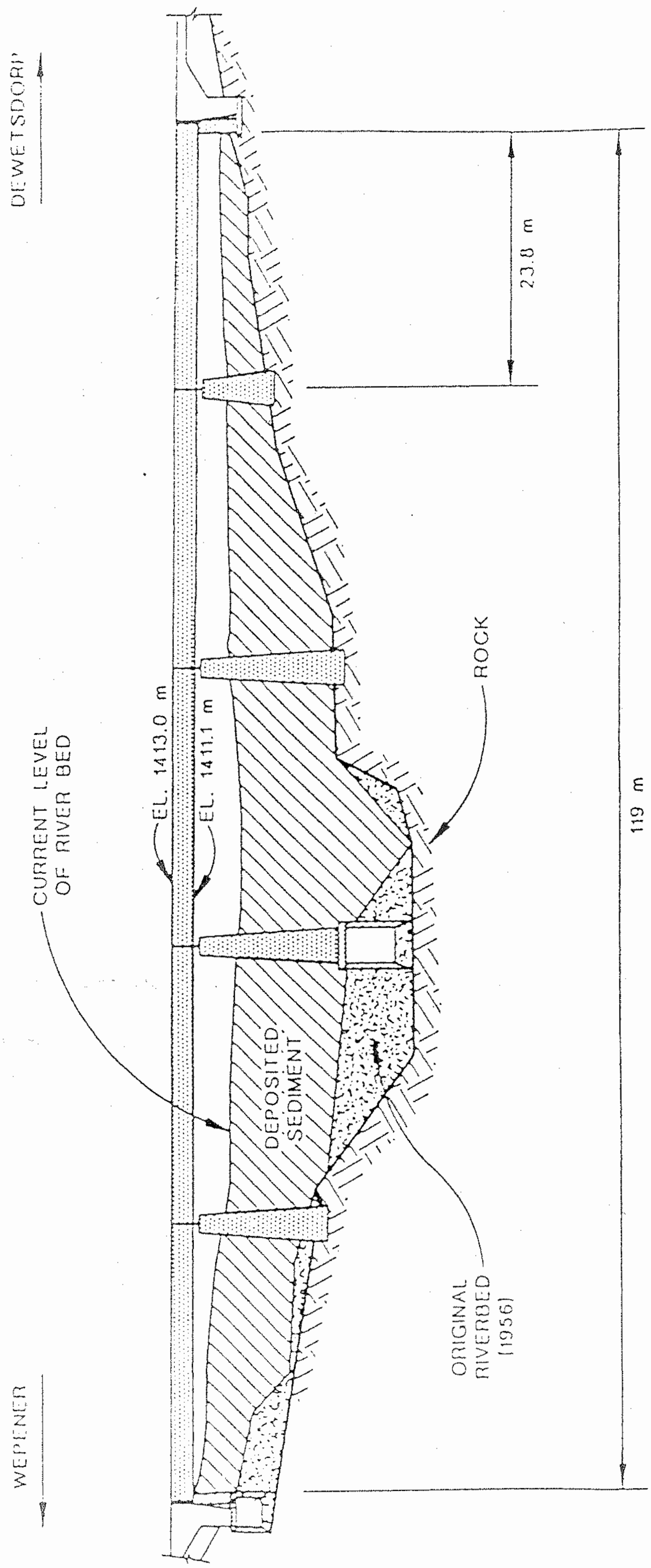


FIGURE 7.2.1 : JIM FOUCHE BRIDGE OVER CALEDON RIVER

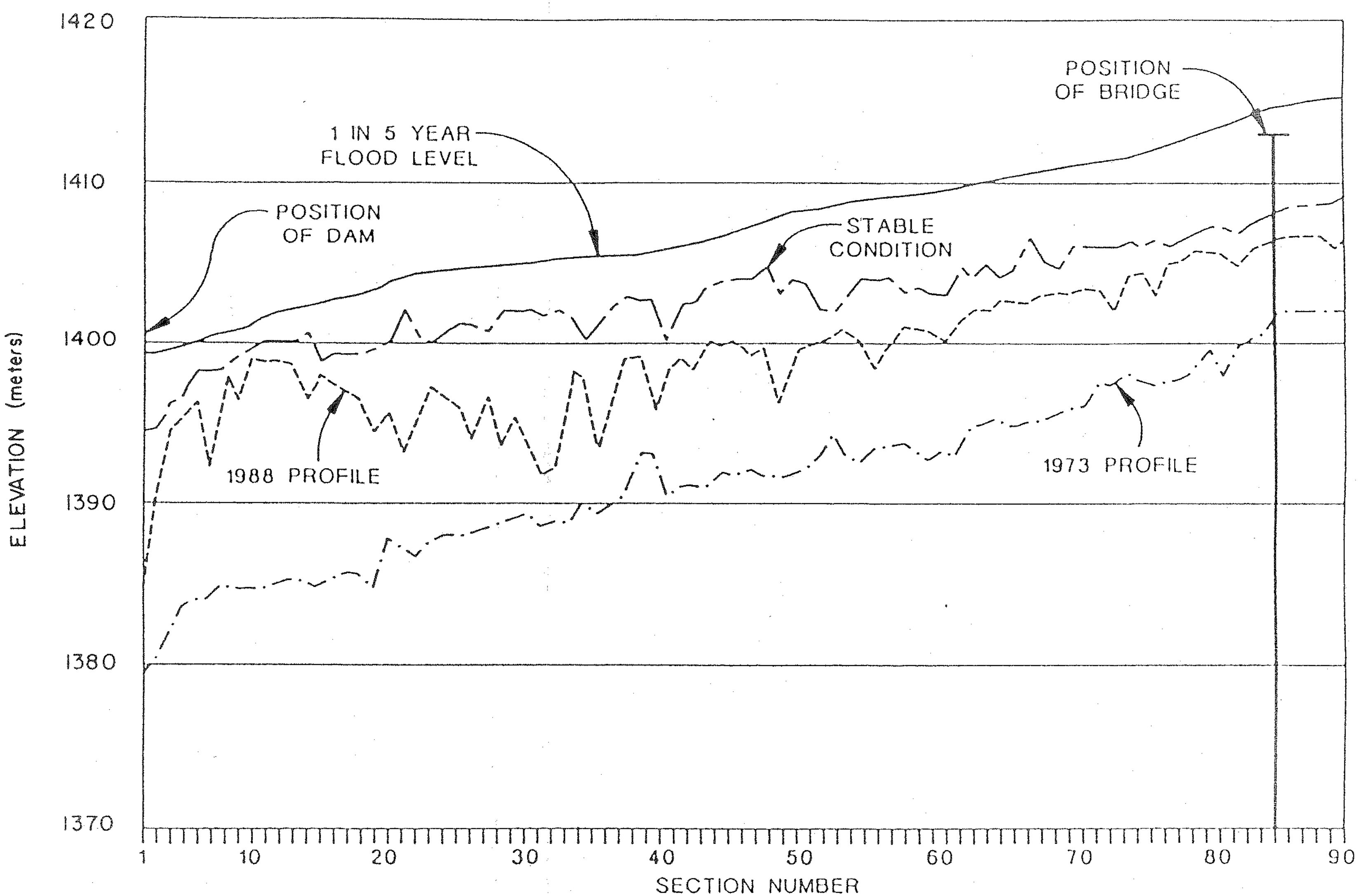


FIGURE 7.2.2 : PROFILE OF CALEDON RIVER SHOWING AGGREDATION UPSTREAM OF WELBEDACHT DAM

The approach road from Wepener forms a bend, leading downhill directly onto the river crossing. This situation is considered dangerous during flood conditions, especially at night when the headlights of vehicles would reflect off the water. Such conditions would make it very difficult for drivers of motor vehicles to observe water flowing over the river crossing. It is expected that vehicles could very easily drive into the water under such conditions, endangering the lives of the people in the vehicle. For purposes of this example it is estimated that the lives of at least five people could be endangered during flood conditions.

The hazard rating of the river crossing is determined as follows:

- Stream stability:

  The stream type is considered to be somewhere between Channel Type 3a and 3b. Assume the factor representing Channel Type 3a for calculation of the composite hazard rating, i.e.:

  f_1 = 2,205 (Table 3.1(a))

- Potential for morphological change due to extraneous factors is considered to be high due to sediment deposition behind Welberacht Dam:

  f_2 = 3,162 (Table 3.1(b))

- The effects of fluvial hydraulics are represented as follows (Table 3.2):

Hydraulic aspect	Potential for damage	Factor
Potential for lateral scour	Low	2,549
Contraction scour	Moderate	1,378
Local scour	High	1,419
Debris accumulation	High	0,564

The aggregate factor is therefore: 2,793

- The structural integrity is rated as (Table 3.3):

Component	Integrity	Factor
Foundations	Intact	1,433
Piers	Intact	1,433
Abutments	Intact	1,433
Deck and bearings	Minor problems	0.774

The aggregate factor is therefore: 2,278

The composite hazard rating, R, is therefore:

R = 2,205*3,162*2,793*2,278

= 44,4

≃ 44

The probability of failure of the river crossing (represented by the serviceability limit state failure of overtopping) is calculated by using the recurrence interval of the flood which would overtop the bridge (5 years).

Probability of failure = 1/5 = 2×10^{-1}

Risk characterization is conducted by making use of the plots on Figure 7.2.3. This figure indicates that the risk is unacceptable and that risk management is required. Comprehensive risk analysis is uncalled for.

The risk management strategy which was followed, was to relocate the road and construct a new river crossing over the Caledon River.

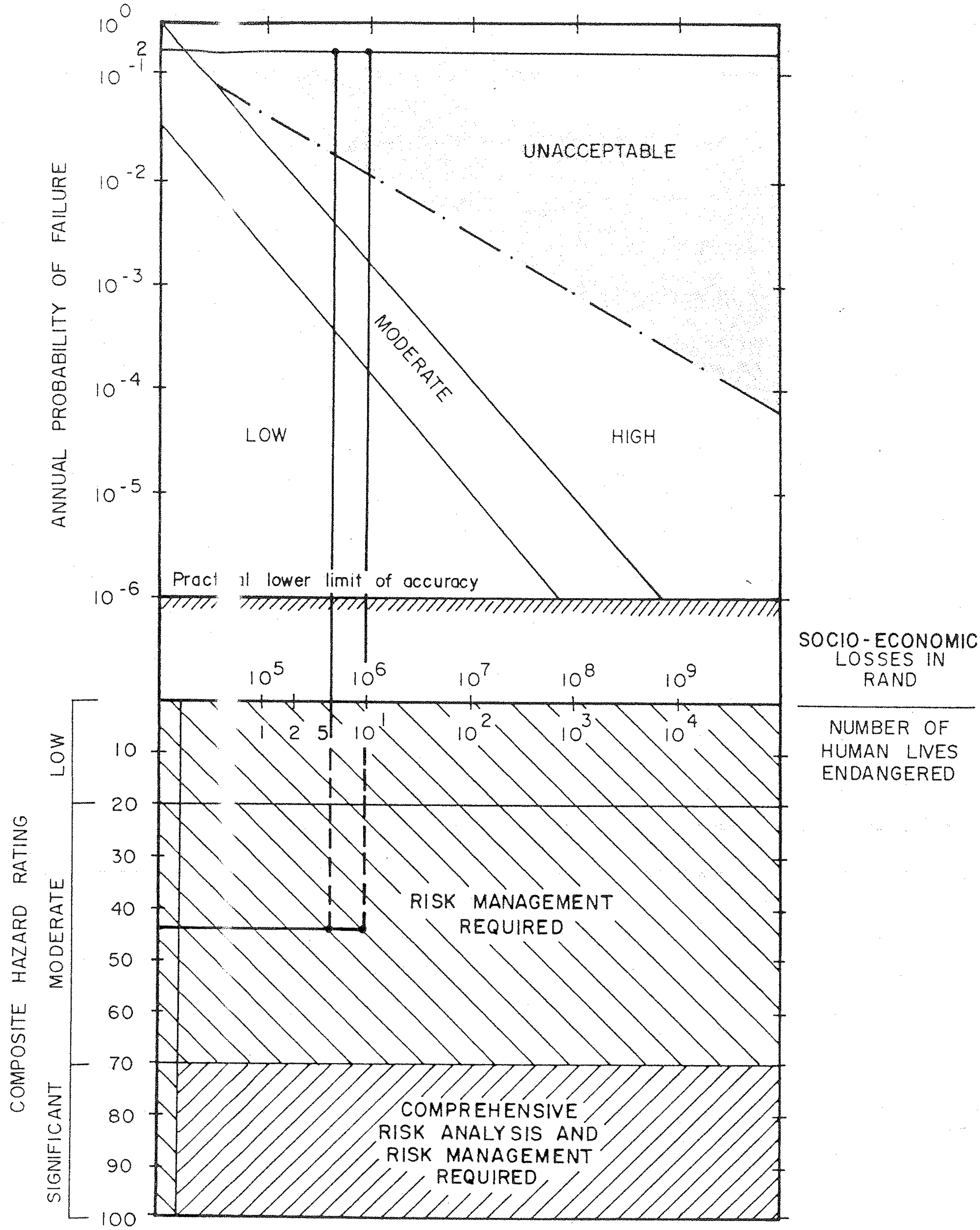


FIGURE 7.2.3 : RISK CHARACTERIZATION FOR JIM FOUCHE BRIDGE

LEVEL I RISK ANALYSIS FORM

1.0 Identification:

Route: *Wepener Dewetsdorp Road*

Bridge number: ____________

2.0 Description:

Component	Code
Primary structural system	*01*
Deck	*06*
Abutment	*07*
Piers	*01*
Foundations	*01*
Balustrades	*04*
Bearings	*02*

3.0 Hazards

3.1 River/stream stability:

Channel type: *3 a*

3.2 Potential for morphological change:

- Erosion

* - Deposition

Low	Moderate	High
		X

LEVEL I RISK ANALYSIS WORKSHEET

3.3 Fluvial hydraulics

Potential for damage:

Aspect	Low	Moderate	High
Location	*X*		
Contraction scour		*X*	
Local scour			*X*
Debris accumulation			*X*

3.4 Structural integrity

Integrity:

Component	Intact	Minor problems	Major problems
Foundations	*X*		
Piers	*X*		
Abutments	*X*		
Deck and bearings		*X*	

3.5 Hydrology

Recurrence interval of design flood: *2×10^{-1} (flood which will overtop river crossing)*

3.6 Composite hazard rating

Table 1(a): f_1 = *2,205*

Table 1(b): f_2 = *3,162*

Table 2: f_3 = *2,793*

Table 3: f_4 = *2,278*

Composite rating (R) = $f_1 * f_2 * f_3 * f_4$ = *44*

Significance of composite hazard rating:

- ▪ Low (R < = 20)
- * ▪ Moderate (20 < R < 70)
- ▪ Significant (R > = 70)

4.0 Consequences

4.1 Probability of failure:

Level I estimate: *2×10^{-1}*

4.2 Losses:

Direct and indirect monetary losses: R *1 000 000*

Number of human lives exposed to danger: *5*

5.0 Risk characterization

5.1 Acceptability of risk:

▪ Low ▪ Moderate ▪ High * ▪ Unacceptable

6.0 Response

The following is required:

- ▪ Occasional maintenance only
- * ▪ Detailed risk management plan
- ▪ Comprehensive risk analysis and detailed risk management plan

7.0 Comments

A risk management plan should be developed possibly considering the following :

- a flood warning system as an interim measure

- relocation of the river crossing as a long term strategy

....

Signed Date

7.3 Blanket specification of design flood recurrence intervals

7.3.1 Introduction

Risk based optimization of river crossing design are currently achieved by implementing one of two possible procedures. One option is to minimize total cost as a function of recurrence interval, whereas the other option consists of utilizing blanket specifications of design flood recurrence intervals. The implementation of blanket specifications of design flood recurrence intervals is a procedure which is more often used than the minimization of total cost. However, the section dealing with characterization of Level II risk (Section 4.3) shows that current specifications in design codes often fall short of the public's perception of acceptable risk. It is therefore considered feasible to reconsider current specifications and develop new methodologies.

Minimization of total cost is more time-consuming and entails determining the minimum value of the sum of capital expenditure and expected damage costs (Figure 7.3.1). A detailed procedure, specifically developed for use of risk-based minimization of total cost in the design of river crossings, is presented by the FHWA (Corry et al, 1981). The FHWA publication not only contains theory, but includes practical case studies dealing with risk-based minimization of total cost. The risk based method of minimizing total cost is therefore not dealt with in any detail in this appendix, but criteria for deciding on its use is proposed.

The objective of this appendix is:

- To provide criteria for deciding between the use of risk-based minimization of total cost and the implementation of blanket design flood recurrence interval specifications for the design of river crossings,

  and

- To recommend values for optimal blanket design flood recurrence interval specifications which are logically related.

The criteria for deciding between the use of risk-based minimization of total cost and the implementation of blanket design flood recurrence intervals are based on equivalence of socio-economic exposure levels, whereas the recommended blanket specification of design flood recurrence intervals are determined by minimizing marginal costs.

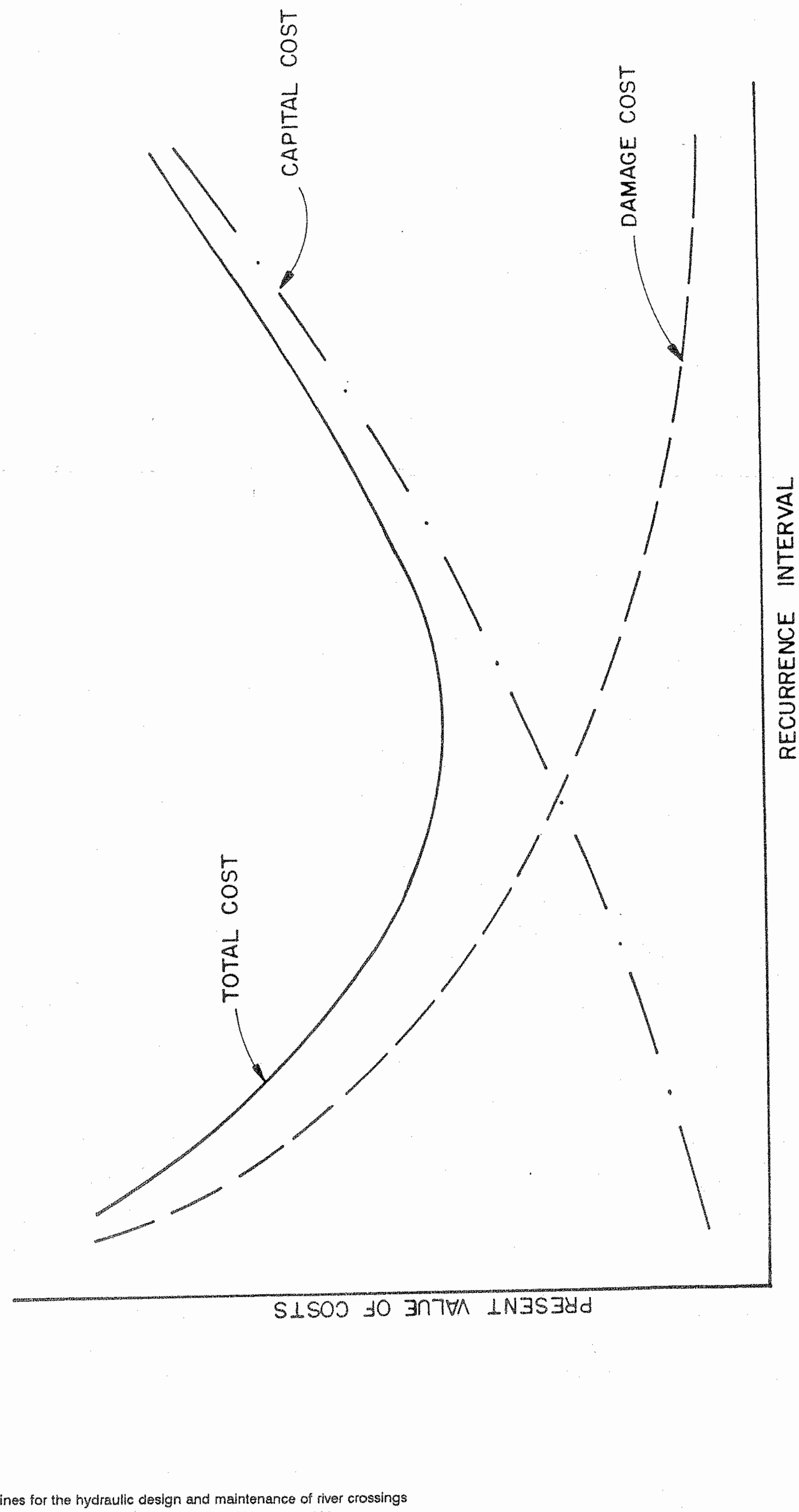


FIGURE 7.3.1 : TRADITIONAL APPROACH TO ECONOMIC OPTIMIZATION

7.3.2 Socio-economic exposure criteria

The criteria which are recommended for deciding between the use of risk-based minimization of total cost and blanket design flood specifications are based on socio-economic risk exposure equivalences. The socio-economic equivalences which are used for this purpose were proposed by Oosthuizen (1984) and are presented in Table 7.3.1. This table implies that exposure of 1 human life to danger is equivalent to an exposure which would result in economic damage equal to one hundred thousand Rand. This does not imply that a human life is worth one hundred thousand Rand, but merely states that endangerment of one human life has an exposure equivalence of one hundred thousand Rand damage.

Economic value (Rand)	Number of human lives exposed to danger
$<10^5$	0
10^5	1
10^6	10
10^7	100
10^8	1000
10^9	10000

TABLE 7.3.1 : EQUIVALENT SOCIO-ECONOMIC EXPOSURE VALUES

It is considered reasonable that the threshold for deciding between the use of blanket design flood specifications and risk-based minimization of total cost be located in the region ranging from one hundred thousand to one million Rand of potential damages and/or potential endangerment of 1 to 10 human lives. The potential losses and danger to human life below this threshold is considered to be so low that blanket specification of design flood recurrence intervals would suffice. Conversely, the potential losses and danger to human life above the threshold is significant enough to warrant more detailed investigation. This proposal is further developed in Section 7.3.4.

7.3.3 Minimization of marginal cost

Bohnenblust and Scheider's (1987) proposal that equivalence of marginal costs should be used as criterion for loss minimization in risk analysis is implemented to determine optimal values for blanket design flood recurrence interval specifications. Equivalence of marginal costs in this case implies that the incremental costs associated with every one year increase in recurrence interval at the optimal specification level would have the same value in all cases, irrespective of the magnitude of the project. This is in line with principles of optimal resource allocation, as implemented with the use of marginal analysis. Marginal analysis addresses the question of whether a particular action adds sufficiently to the benefits enjoyed by the performer to make it worth the cost (Baumol, 1972). By considering marginal costs only, optimality is considered to have been achieved when

- Marginal costs approaches a minimum,

and

- Equivalence of marginal costs has been achieved.

An equation for marginal cost is derived from the total cost (C_t) of the river crossing, which is expressed as follows:

$$C_t = C_c + C_d$$

where

C_c = Capital cost of river crossing

C_d = Present value of maintenance costs and the expected cost of disbenefits, should the river crossing fail

Maintenance cost can reasonably be assumed to be negligible when compared to the expected cost of disbenefits. In this regard it is important to define what is meant by the expected cost of disbenefits. Expected cost of disbenefits is made up of direct and indirect monetary losses, and other losses identified in Section 3.2 of the main body of the report. It specifically excludes the cost of a new river crossing structure, given that the previous structure was destroyed during a flood event. The decision whether to construct a new river crossing structure is a separate decision, and should be dealt with separately.

By defining the design flood recurrence interval as the independent variable, the marginal cost is represented by the slope of the relationship between total cost and recurrence interval. The influence of project design life and discount rate on marginal cost is negligible, as is demonstrated towards the end of this section. The values of these two variables are therefore considered to be pre-specified. An expression of marginal cost can be derived by differentiating total cost with respect to recurrence interval (T), i.e.

$$dC_t/dT = d/dT(C_c + C_d)$$

The inherent assumption which is made when making blanket recurrence interval specifications, is that the relevant facility will be constructed at a certain unknown constant capital cost which will ensure compliance. Blanket specifications are attempts to optimally allocate resources without knowing in advance what the capital investment requirements are. In the case of river crossings the blanket specification subjectively assumes that the design flood will be used to size the river crossing opening, and that the river crossing will then be constructed at some optimal constant capital cost which will ensure that it complies with the design flood requirements.

By assuming an unknown constant capital cost, the marginal cost becomes,

$$dC_t/dT = dC_d/dT$$

Capital cost is therefore not a factor in marginal analysis for determining optimal blanket recurrence interval specifications. This is in line with concepts of marginal analysis, viz that marginal total cost is equal to variable costs as soon as benefits flow from a facility. The expression for marginal cost can be further developed by writing the cost of disbenefits as

C_d = C*K

where

C = cost of disbenefits which could result from a particular flood event

= f(T)

K = factor which is used to calculate the present value of probable cost

= $1/T*((1+i)^L-1)/(i*(1+i)^L)$

= f(T,i,L)

i = discount rate

L = project design life in years

T = design flood recurrence interval in years

The expression for marginal cost then becomes

dC_t/dT = dC_d/dT

= d(C*K)/dT

= dC/dT*K + dK/dT*C

By making the assumption that the blanket specification of design flood recurrence intervals would be such that the marginal cost of disbenefits would be negligible, the above equation can be written as:

dC_t/dT = dK/dT*C

= $-1/T^2*((1+i)^L-1)/(i(1+i)^L)*C$

In order to demonstrate the insensitivity of marginal cost to design life and discount rate, the marginal cost factor (dK/dT) is plotted as a function of recurrence interval in Figures 7.3.2 and 7.3.3 for project design lives of 100, 50 and 30 years, and discount rates of 3% and 6% respectively. The difference in values is so small that the lines virtually coincide. The figures also illustrate that the marginal cost factor is virtually zero for recurrence intervals in excess of 250 to 400 years.

Compliance with the requirements of optimality, formulated at the beginning of this section, can be achieved by equating the marginal cost of disbenefits to a small value, and solving the equation to calculate recurrence intervals for a range of disbenefit cost levels which might occur if no safeguards are provided. Such a solution will ensure equivalence of marginal costs. The minimum value of marginal cost which is selected is equal to R100/year. This value is not only almost negligible when compared to likely disbenefit costs (therefore representing a minimum), but is selected to provide recurrence interval values in the lower disbenefit cost ranges which are intuitively acceptable.

Therefore,

$$dK/dT*C = 1/T^2*((1+i)^L-1)/(i*(1+i)^L)*C = 100$$

From which follows that,

$$T = 1/10*(C*((1+i)^L-1)/(i(1+i)^L))^{0.5}$$

The theoretical relationship between recurrence interval and disbenefit costs for project design lives of 100 and 30 years, and discount rates of 3% and 6% are presented in Table 7.3.2, with the average relationship presented in Figure 7.3.4.

Cost of disbenefits (Rand)	**Project design life (years)**			
	100		**30**	
	Discount rate (%)			
	3	**6**	**3**	**6**
10^2	6	4	4	4
10^3	18	13	14	12
10^4	56	41	44	37
10^5	178	129	140	117
10^6	562	408	443	371
10^7	1778	1289	1400	1173
10^8	5621	4076	4427	3710
10^9	17776	12891	14000	11732

TABLE 7.3.2 : RELATIONSHIP BETWEEN RECURRENCE INTERVAL AND EXPECTED DISBENEFIT COST FOR MINIMUM MARGINAL COSTS

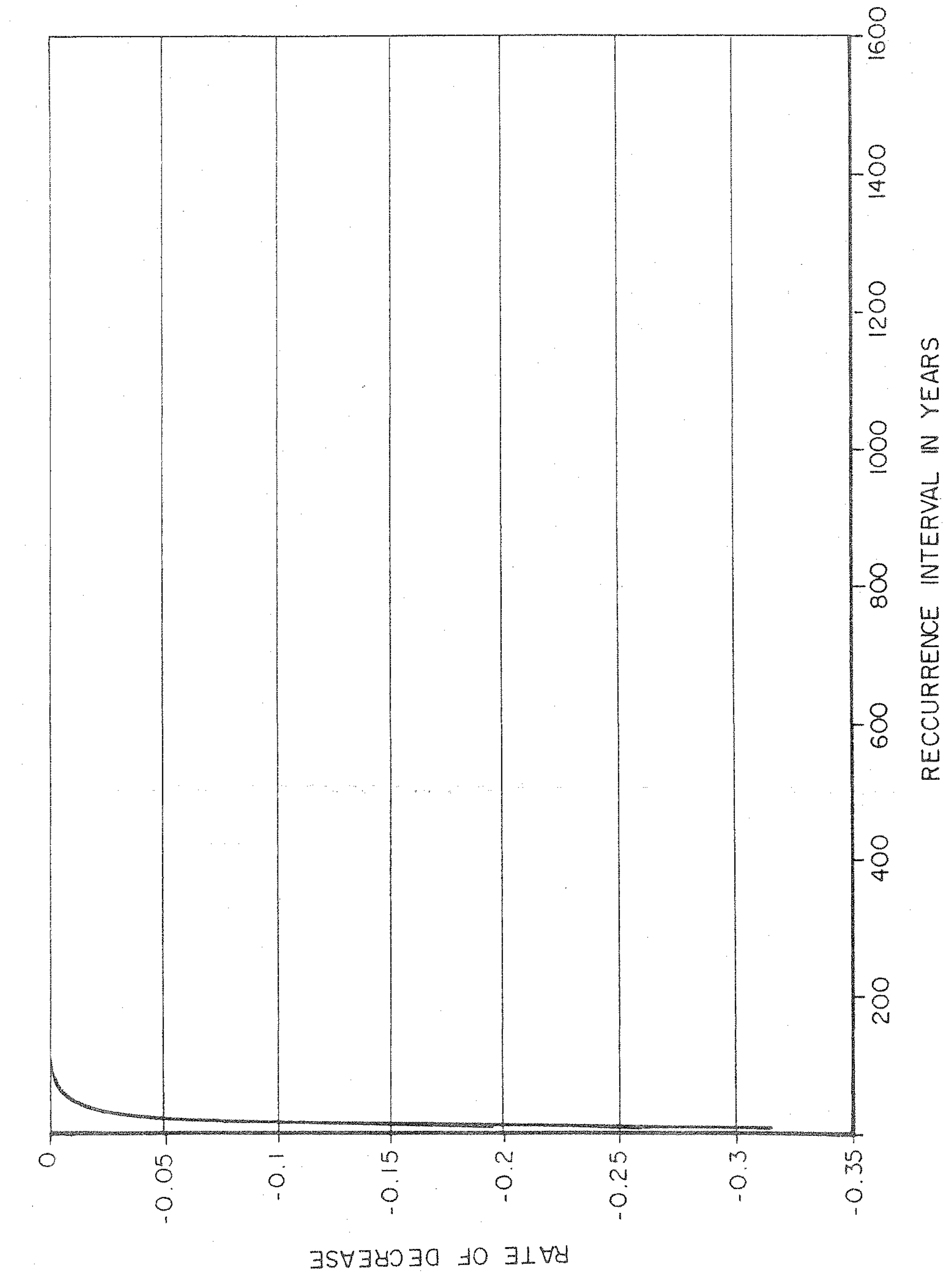


FIGURE 7.3.2 : DIMENSIONLESS MARGINAL DISBENEFIT COST FACTOR : RATE OF DECREASE - DISCOUNT RATE = 3%

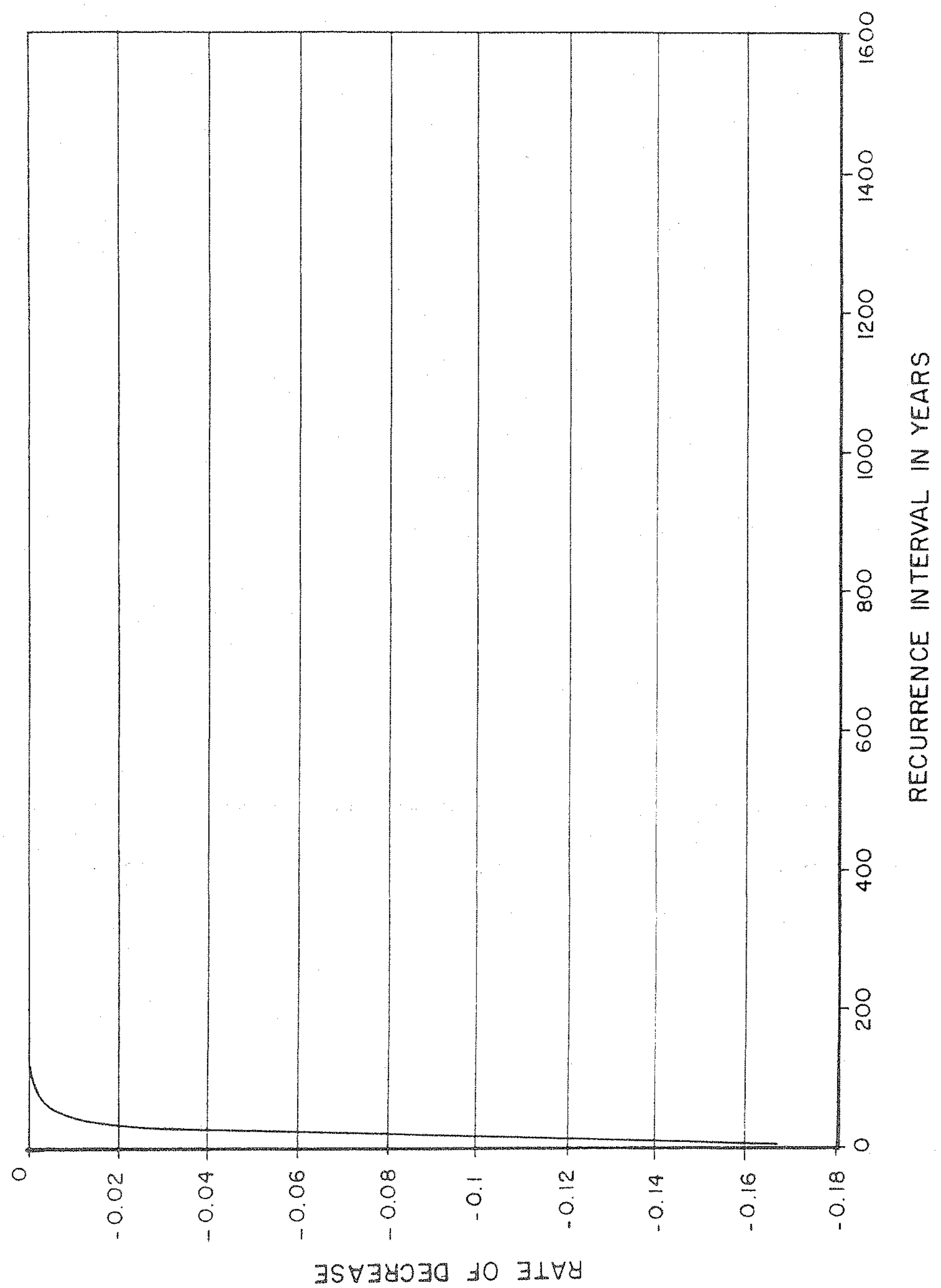


FIGURE 7.3.3 : DIMENSIONLESS MARGINAL DISBENEFIT COST FACTOR : RATE OF DECREASE - DISCOUNT RATE = 6%

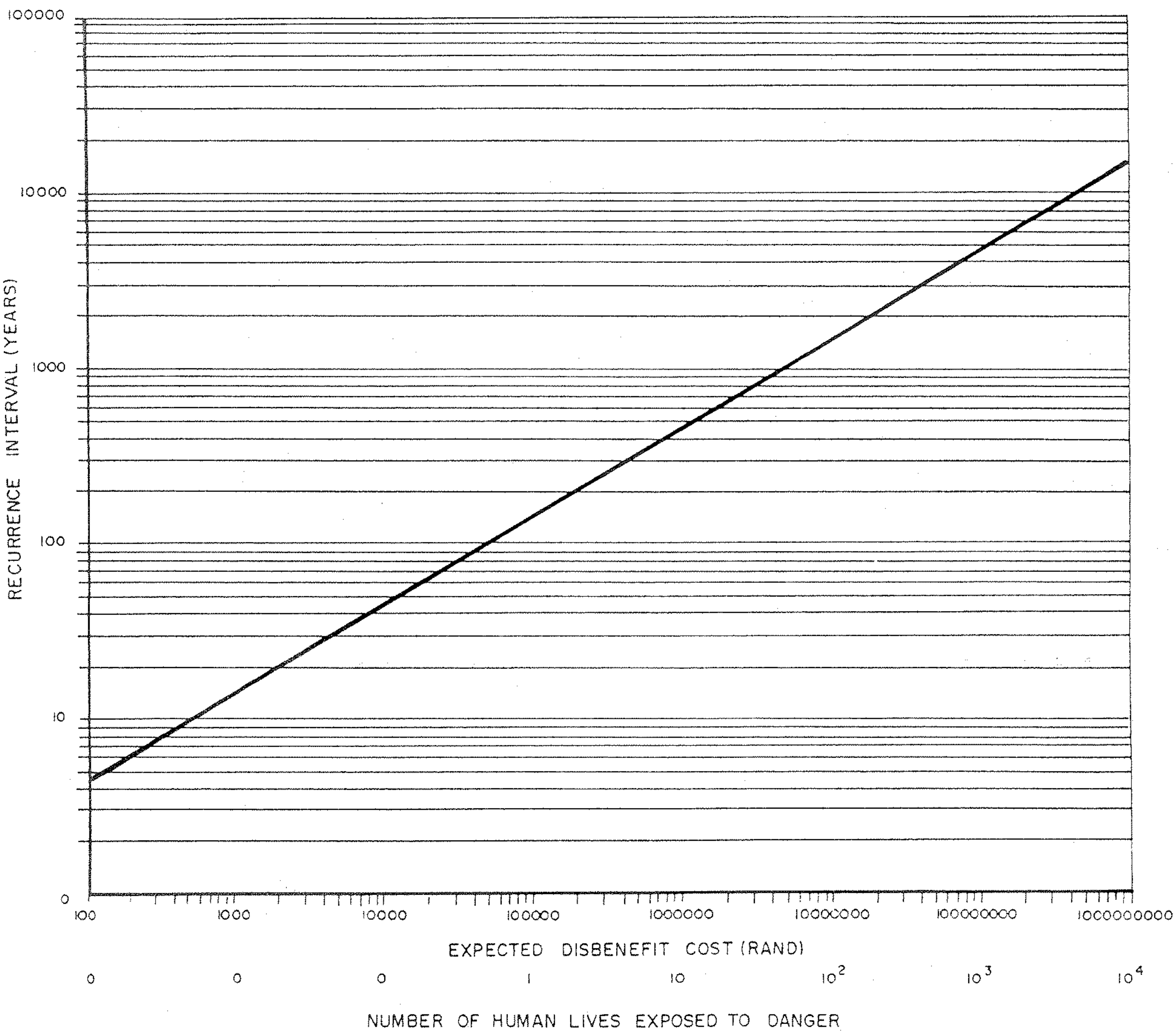


FIGURE 7.3.4 : PROPOSED RELATIONSHIP BETWEEN EXPECTED DISBENEFIT COST AND RECURRENCE INTERVAL SPECIFICATION

7.3.4 Recommended specification

The findings of the analysis in Section 7.3.3 are used to formulate a recommendation as to the recurrence intervals and procedures which should be used for the design of river crossings (Table 7.3.3).

<table>
<tr><th>Economic value of disbenefits (Rand)</th><th>Number of human lives exposed to danger</th><th colspan="2">Recurrence interval (years)</th></tr>
<tr><td>small</td><td>0</td><td colspan="2">5</td></tr>
<tr><td>10^2 to 10^3</td><td>0</td><td colspan="2">5 to 15</td></tr>
<tr><td>10^3 to 10^4</td><td>0</td><td colspan="2">15 to 50</td></tr>
<tr><td>10^4 to 10^5</td><td>0 to 1</td><td>50 to 150</td><td rowspan="2">Risk-based cost optimization should be considered as an option</td></tr>
<tr><td>10^5 to 10^6</td><td>1 to 10</td><td>150 to 500</td></tr>
<tr><td>$>10^6$</td><td>>10</td><td colspan="2">Risk-based cost optimization mandatory</td></tr>
</table>

TABLE 7.3.3 : RECOMMENDED SPECIFICATIONS TO DETERMINE DESIGN FLOODS FOR RIVER CROSSING DESIGN

The recommended values in Table 7.3.3 are spread over a larger range than what is currently the case, with the lower limit of blanket recurrence interval specification being comparable to the lower limit of 500 years, which is used in the United States of America. It is further recommended that risk-based cost optimization (Corry et al, 1981) be used when the composite hazard rating is significant (see Section 3.1 of the main text) while concomitantly exposing the lives of between one and ten people to danger. In cases where the expected cost of disbenefits are in excess of one million Rand and/or more than ten human lives are exposed to danger, it is recommended that risk-based cost optimization be implemented for design of river crossings.

The recommended blanket specifications for design flood recurrence intervals are compared with public and social perceptions of acceptable risk in Figure 7.3.5. This figure indicates that the proposed procedure for determining design floods for river crossing design recognizes the public's perception of acceptable risk in high exposure cases. It also allows the use of less stringent measures in cases where exposure is considered moderate to negligible. Risk management will make risk acceptable to the public in the latter cases.

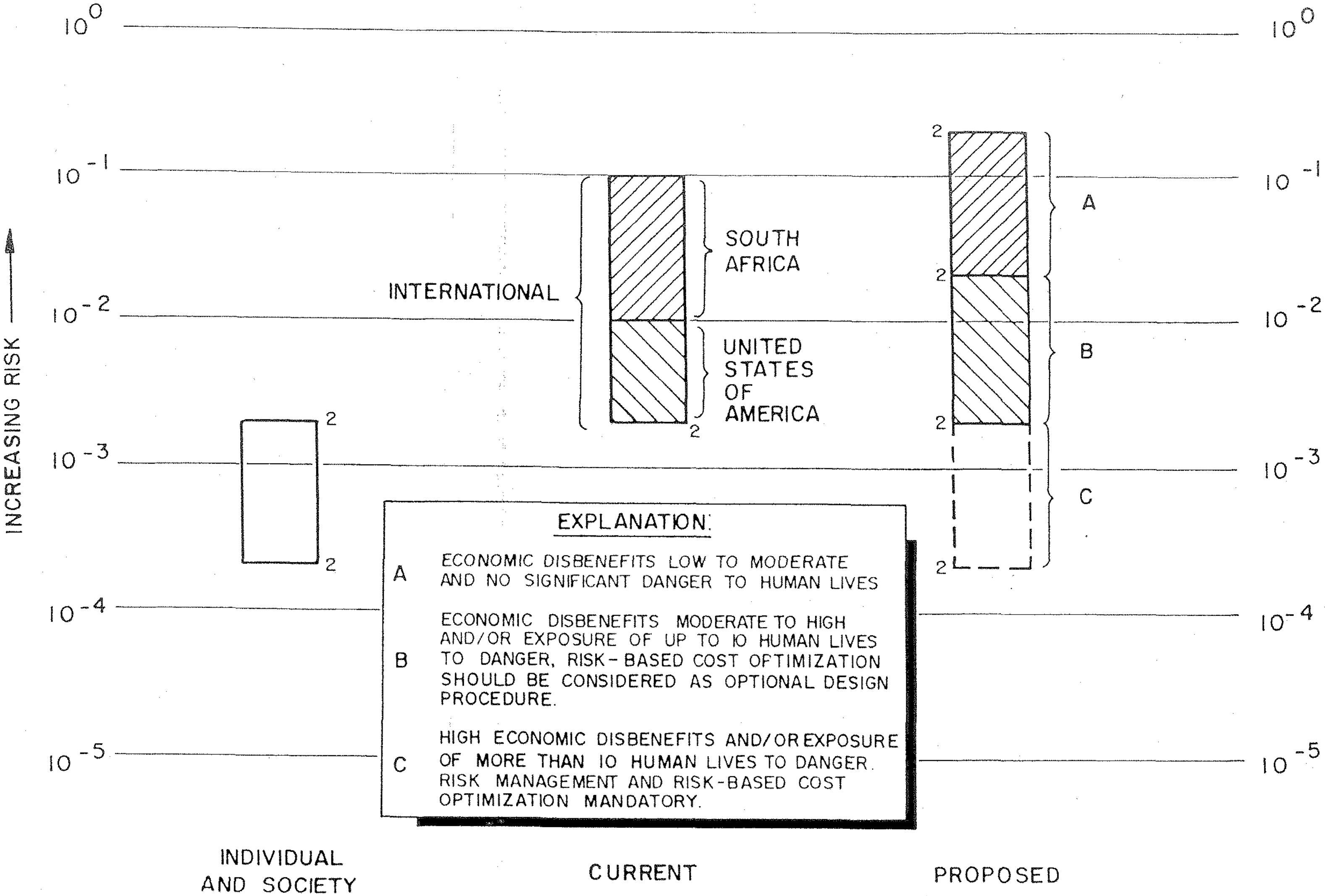


FIGURE 7.3.5 : CURRENT AND PROPOSED LEVELS OF DESIGN FLOOD RECURRENCE INTERVAL SPECIFICATIONS COMPARED TO INDIVIDUAL AND SOCIETY'S PERCEPTIONS OF ACCEPTABILITY OF RISK