Australian Rainfall & Runoff

Revision Projects

PROJECT 20

Risk Assessment and Design Life

STAGE 3 REPORT

P20/S3/022

SEPTEMBER 2015

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AUSTRALIAN RAINFALL AND RUNOFF
REVISION PROJECT 20: RISK ASSESSMENT AND DESIGN LIFE

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Project Project 20: Risk Assessment and Design Life	**ARR Report Number** P20/S3/022
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FOREWORD

ARR Revision Process

Since its first publication in 1958, Australian Rainfall and Runoff (ARR) has remained one of the most influential and widely used guidelines published by Engineers Australia (EA). The current edition, published in 1987, retained the same level of national and international acclaim as its predecessors.

With nationwide applicability, balancing the varied climates of Australia, the information and the approaches presented in Australian Rainfall and Runoff are essential for policy decisions and projects involving:

- infrastructure such as roads, rail, airports, bridges, dams, stormwater and sewer systems;
- town planning;
- mining;
- developing flood management plans for urban and rural communities;
- flood warnings and flood emergency management;
- operation of regulated river systems; and
- prediction of extreme flood levels.

However, many of the practices recommended in the 1987 edition of ARR now are becoming outdated, and no longer represent the accepted views of professionals, both in terms of technique and approach to water management. This fact, coupled with greater understanding of climate and climatic influences makes the securing of current and complete rainfall and streamflow data and expansion of focus from flood events to the full spectrum of flows and rainfall events, crucial to maintaining an adequate knowledge of the processes that govern Australian rainfall and streamflow in the broadest sense, allowing better management, policy and planning decisions to be made.

One of the major responsibilities of the National Committee on Water Engineering of Engineers Australia is the periodic revision of ARR. A recent and significant development has been that the revision of ARR has been identified as a priority in the Council of Australian Governments endorsed National Adaptation Framework for Climate Change.

The update will be completed in three stages. Twenty one revision projects have been identified and will be undertaken with the aim of filling knowledge gaps. Of these 21 projects, ten projects commenced in Stage 1 and an additional 9 projects commenced in Stage 2. The remaining two projects will commence in Stage 3. The outcomes of the projects will assist the ARR Editorial Team with the compiling and writing of chapters in the revised ARR.

Steering and Technical Committees have been established to assist the ARR Editorial Team in guiding the projects to achieve desired outcomes. Funding for Stages 1 and 2 of the ARR revision projects has been provided by the Federal Department of Climate Change and Energy Efficiency. Funding for Stages 2 and 3 of Project 1 (Development of Intensity-Frequency-Duration information across Australia) has been provided by the Bureau of Meteorology.

Project 20: Risk Assessment and Design Life

Selection of the appropriate design flood quantile usually considers the probability that the structure will have its capacity exceeded one or more times during its design life. This probability is called the “risk of failure in the UK Flood Studies Report – Volume 1 (Natural Environment Research Council, 1975). However, this definition requires consideration of the design life which may differ from the structural life and the economic life of the structure. There are some situations in which the structure for which the design flood is to be determined has a clearly defined finite life. One example is a cofferdam used during the construction of a permanent dam as in the first worked example on the economic selection of a design flood. However, in other situations such as a permanent dam which is not to be removed at the end of a specific period, the length of time during which it is subject to the risk of having its design capacity exceeded by floods is very long and the probability of this happening becomes very high. Additionally, there is a need to consider the changing AEPs associated with climate change; in other words, a non-stationary flood environment.

Mark Babister
Chair Technical Committee for
ARR Research Projects

Assoc Prof James Ball
ARR Editor

ARR REVISION PROJECTS

The 21 ARR revision projects are listed below:

ARR Project No.	Project Title	Starting Stage
1	Development of intensity-frequency-duration information across Australia	1
2	Spatial patterns of rainfall	2
3	Temporal pattern of rainfall	2
4	Continuous rainfall sequences at a point	1
5	Regional flood methods	1
6	Loss models for catchment simulation	2
7	Baseflow for catchment simulation	1
8	Use of continuous simulation for design flow determination	2
9	Urban drainage system hydraulics	1
10	Appropriate safety criteria for people	1
11	Blockage of hydraulic structures	1
12	Selection of an approach	2
13	Rational Method developments	1
14	Large to extreme floods in urban areas	3
15	Two-dimensional (2D) modelling in urban areas.	1
16	Storm patterns for use in design events	2
17	Channel loss models	2
18	Interaction of coastal processes and severe weather events	1
19	Selection of climate change boundary conditions	3
20	**Risk assessment and design life**	**2**
21	IT Delivery and Communication Strategies	2

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- Associate Professor James Ball
- Mark Babister

EXECUTIVE SUMMARY

Application of appropriate Flood Design Standards should protect potentially affected communities and stakeholders to an acceptable level while minimising over-engineering expense. Where adopted design criteria exceed what may be considered an acceptable level of flood protection, project developers typically bear the economic cost of over-engineering. Conversely, where adopted design criteria fall below what may be considered an acceptable level of flood protection, community members typically bear the cost of under-engineering through increased risk and flood damage. Adoption of design criteria that reflects the accepted satisfactory level of risk is considered to be the most sustainable and equitable solution. However, global standards vary in regards to what is considered to be a satisfactory or acceptable level of risk of failure for infrastructure, being ultimately subjective in nature and challenging to quantify.

This situation is made more complex through the potential for variation in risk over the lifetime of a project and the fact that much infrastructure remains in operation (its Effective Service Life) beyond its original design life. The forecast impacts of climate change upon hydrological regimes as well as anthropomorphic changes to catchment characteristics mean that long-lived projects may experience significant changes to the flooding risks associated with the operation over their Effective Service Life (i.e. the flood criteria to which it was designed against at its inception differ to those realised at the end of its working life). This may have significant impacts for communities facing the costs associated with resultant under-engineering in the future (i.e. damage costs, high replacement costs etc.).

The majority of countries across the globe are moving towards risk based assessment in determination of Flood Design Standards: assessments that consider both the likelihood and consequence of flooding associated with specific projects. This represents a shift away from historical approaches, like those adopted in Australia, which have primarily simply adopted a set Flood Design Standard (e.g. 100 year ARI + freeboard for residential development) or utilise coarse adjustment factors (e.g. +/- 20%) to account for climate change impacts. While such approaches are useful in their simplicity, it can both lead to significant over-engineering in some scenarios (particularly for short-term / temporary projects) and under-engineering in others (e.g. where climate change is anticipated to significantly alter the consequence/likelihood of flood events). Risk assessment in setting of Flood Design Standards allows for project specific context to be incorporated into design requirements, and also provides the mechanism through which changes in the environmental conditions over time (non-stationarity) can be incorporated with design and planning.

In Australia, risk based assessment frameworks are typically underpinned by the Australian Risk Management standard AS/NZS ISO 31000:2009. Under the standard, risk assessments evaluate the likelihood of an event occurring and assess the magnitude of the corresponding impact of the event. The combination of these two factors is taken to represent the resultant risk associated with the event (typically expressed through a qualitative discrete rating system) as shown in the table below.

Table 1: Risk as a function of likelihood and consequence

Likelihood (AEP)	Consequence				
	Minimal	Minor	Moderate	Major	Catastrophic
0.1	Negligible	Negligible	Negligible	Low	Medium
0.5	Negligible	Negligible	Low	Medium	Medium
1	Negligible	Low	Low	Medium	High
10	Low	Low	Medium	High	High
20	Low	Medium	High	High	Extreme
50	Low	Medium	High	Extreme	Extreme
100	Medium	High	Extreme	Extreme	Extreme

Typically, flooding based risk assessments are undertaken assuming stationarity of the environment. This enables the likelihoods of events to be readily expressed and understood in probabilistic terms. Typically, this is done in terms of either:

- **Annual Exceedence Probability (AEP)**: the likelihood of occurrence of a flood of a given size or larger in any one year; usually expressed as a percentage (e.g. a flood protection levee may adopt of Flood Design Standard that offers protection up to the a 1% AEP event);
- **Service Life Exceedence Probability (SLEP)**: The likelihood of exceedence during a project's adopted service life, rather than as an annual likelihood.

A SLEP approach may tend to be favoured for temporary structures in which either an AEP value may not be readily comprehensible (e.g. if a structure is only to be in place for a month) or one in which the consequence of failure are extremely high. It is considered that while design standards are commonly expressed as an annual probability, it may be the case that project developers / authorities actually interpret and apply this more as a SLEP or an Exceedence Frequency over a specified project lifetime.

It is recognised that a large amount of uncertainty is unavoidably present when considering flood infrastructure and associated risks. Uncertainties include the accuracy of the historic flood data; recent changes in the catchment which would not be reflected in the data record; repeated flood events captured in the historic record during exceptionally high prolonged periods of rainfall; seasonal and long term changes to water level; and the accuracy of observations, stage-discharge relationships and hydrological methods. Given these uncertainties, flood modelling and management typically operates from a conservative position so to minimise the impact of uncertainty risk. However, it is noted that the consecutive and continuous adoption of conservative minimums in each phase of risk assessment or project planning may lead to overly cautious development.

The recognition of non-stationarity (i.e. a non-static flood risk profiles) introduces further uncertainty and complexity into project risk assessments and decision making. Despite the complexity, it is noted that, particularly for permanent / long-term projects/programs, there may be a justified need to incorporate non-stationarity into assessments and that a failure to do so may significantly under-estimate project risks. Non-stationarity may develop within a system through either changes to the likelihoods or consequences associated with a project or environment. A large focus on the potential non-stationarity of likelihood tends to be on climate change. However, there are a number of other factors that can affect the likelihood (e.g. seasonality, climatic variability) and consequence (e.g. land-use, demographics) of a given event over time.

Given the complexities of non-stationarity, the number of studies incorporating non-stationarity within flooding infrastructure is relatively low, and the number of policy framework documents incorporating technical non-stationarity assessments is even lower. Examples of application of statistical non-stationary models are available in Rootzen and Katz (2012), Laurent & Parey (2007), Vogel et al. (2011), Condon et al. (2014), Ng et al. (2010), Woodward et al. (2011) and Park et al. (2014) amongst others. Such academic work to date indicates that there is potential for non-stationary models to be incorporated into design considerations and that the scale of catchment change may be of sufficient magnitude in some catchments to warrant consideration in design criteria. However, it may be that the costs of developing such models and assessments is currently prohibitive and unnecessary for the majority of water-affected infrastructure, and that utilisation of traditional static risk profiles remains the more appropriate form of assessment.

As such this report identifies a risk based assessment framework through which both project owners and regulatory approval authorities can determine which proposals can adopt pre-set Flood Design Standards; which proposals may require a stationary Risk Assessment; and which proposals may require a non-stationary based Risk Assessment. The proposed framework is based around the establishment of risk profiles by the relevant approval authority / agency (e.g. what combinations of flooding likelihood and consequence are deemed acceptable, tolerable or intolerable), against which a three step process, involving input from both project owners and relevant approval authorities is undertaken to identify an appropriate standard. This includes:

1. **Initial Project Evaluation –** The project owner determines the Effective Service Life of their project and whether a stationary or non-stationary risk assessment process is justified.
2. **Risk Assessment –** Where the need for a Stationary Risk Assessment is identified, the project owner evaluates the risks associated with their project and compares this against the relevant approval authorities profile to estimate an initial flood-related design requirements. Where the risk assessment needs to consider non-stationarity, this is considered through the selection of appropriate risk assessment horizons.
3. **Application of Design Standard and Adaptation –** The project owner identifies options by which the initial flood-related design requirements can be achieved and the ultimate Flood Design Standards formalised. Economic evaluation of options is recommended as

the tool through which project owners may incorporate options that support design flexibility in response to non-stationary risk scenarios.

Section 7 of this report provides three worked simplified hypothetical case studies demonstrating application of this mechanism.

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1. Introduction

1.1. Background

Australian Rainfall and Runoff (ARR) has long been the standard when determining design flood conditions and characteristics in Australia. The guideline was established in 1987 and subsequently updated in 1999. On-going large scale revision of the document has been underway since 2003, with a view to further informing best practice standards adopted for a range of planning and infrastructure projects.

This report has been produced as part of revision of ARR with a specific focus upon the establishment on the setting of Flood Design Standards that consider both existing and future environmental considerations. The need for adoption of suitable Flood Design Standards to protect communities while minimising over-engineering expense is recognised as an important element of sustainable development. However, global standards vary in regards to what is considered to be a satisfactory level of risk of failure for infrastructure and increasingly the difference between infrastructure design life and its actual structural life has been seen increase risks and costs to projects, their surrounding environments and potentially affected communities.

This is particularly of concern in light of the observed changes in historic and future anticipated flood extents and severity. Change in such flooding characteristics is being driven by both anthropogenic catchment disturbance (e.g. urbanisation) and the potential impacts of climate change (e.g. altered Annual Exceedance Probability (AEP) distributions. Consequently, it is recognised that the greater the life-span of any planning policy or infrastructure project, the greater the likelihood that it may operate within a non-stationary flood environment (i.e. the flood criteria to which it was designed against at its inception differ to those realised at the end of its working life).

This report provides advice and examples on how these risks can be incorporated within decision making around Flood Design Standards. The report provides a potential risk based mechanism through which project developers and approval authorities can identify suitable Flood Design Standards. It does not provide details on the design standards themselves, the assessment of impacts on the community or built or natural environment, nor estimates residual risks.

1.2. Proposed Guidelines

This report provides a risk based mechanism through which project developers and approval authorities can identify suitable Flood Design Standards. The mechanism is presented as a structure to guide thinking and shape risk assessment considerations that may be considered in development of Flood Design Standards, from both project owner and approval authority perspectives. It is not inteded to provide guidance on specific Flood Desgin Standards or adoption of appropriate risk profiles. It is the responsibility of project owners and approvel authorities to identify appropriate Flood Design Standards that reflect their specific situation and context. Further advice in the establishment of such standards and other design considerations are detailed within ARR.

The proposed mechanism is based around a four step process, involving input from both project owners and relevant approval authorities. The process is detailed in Section 6 and, in summary, includes:

1. **Identification of relevant determining authority risk profile** – The relevant approval authority (e.g. local / state / federal government) determines its risk profile and identifies what combinations of flooding likelihood and consequence are deemed acceptable, tolerable or intolerable.
2. **Initial Project Evaluation** – The project owner determines, based on a high level assessment of its project, whether a detailed risk assessment process is justified or whether simple adoption of a pre-set Flood Design Standard is appropriate. The evaluation also identifies whether the risk assessment should / should not consider non-stationarity in risk.
3. **Risk Assessment** – Where the need for a detailed Risk Assessment is identified, the project owner evaluates the risks associated with their project and compares this against the relevant approval authorities profile to estimate an initial flood-related design requirements. Where the risk assessment needs to consider non-stationarity, this is considered through the selection of appropriate risk assessment horizons.
4. **Application of Design Standard and Adaptation** – The project owner identifies options by which the initial flood-related design requirements can be achieved and the ultimate Flood Design Standards formalised. Economic evaluation of options is recommended as the tool through which project owners may incorporate options that support design flexibility in response to non-stationary risk scenarios.

1.3. Report Terminology

Clarity of terms is crucial to providing clear and definitive guidance. The terms detailed below are used throughout this report and define key parameters.

1.3.1. Project Timeframes

- **Risk Assessment Horizon** – is the period at which risk is assessed. For instance it could be assessed at present state, or at a point in the future;
- **Economic Service Lif**e: The total period to the time when the asset, whilst physically able to provide a service, ceases to be the lowest cost option to satisfy the service requirement;
- **Design Service Life (DSL)**: The total period an asset has been designed to remain in use;

and

- **Effective Service Life (ESL)**: The total period an asset remains in use, regardless of its Design Service Life.

Effective Service Life can differ from Design Service Life as shown in Figure 1-1 (derived from United States Environment Protection Agency – 2007). Effective life can be enhanced by factors which increase life such as maintenance, or diminished due to factors that reduce life such as significant weather events.

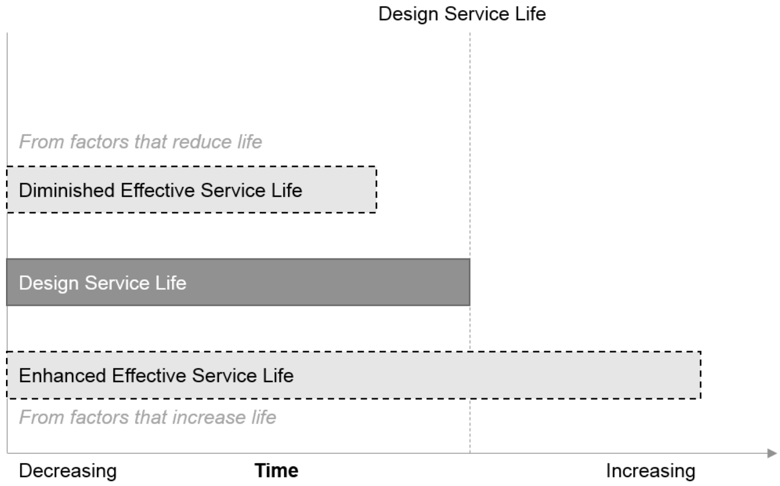


Figure 1-1 Design Service Life versus Effective Service Life

1.3.2. Probabilistic Expression of Flood Occurrence

- **Annual Exceedance Probability (AEP):** the likelihood of at least one occurrence of a flood of a given size or larger in any one year. This is usually expressed as a percentage; however, other forms of expression may be used for rare and very rare events.
- **Average Recurrence Interval (ARI) / Return Period (RP)**: statistical estimates of the average period in years between the occurrence of a flood of a given size or larger. The ARI or RP of a flood event gives no indication of when a flood of that size will occur next;
- **Service Life Exceedance Probability**: The likelihood of exceedance during a project's adopted service life, rather than as an annual likelihood; and
- **Exceedance Frequency**: The number of exceedance events occurring over a defined period (e.g. a year, a project's Design Service Life, etc.).

1.3.3. Flood Design Standard / Level of Service Standards

- **Flood Design Standard**: The level at which a structure is designed to protect against flooding of a given magnitude. This can be expressed as a target design event (e.g. 200 year ARI, 0.5% AEP) or height (e.g. 17.5 mAHD); and
- **Level of Service Standard**: The level of service provided by a project that is to be maintained under flooding events of a particular scale.

While the methods discussed in this report relate specifically to the Flood Design Standard, it may be valid adopt this methodology to inform the choice of an appropriate Level of Service Standard for some projects.

1.4. Report Structure

This report is structured as follows:

- Section 1 provides an overview of the issue and key recommended guideline response;
- Section 2 provides a review of existing flood design standards both internationally and nationally;
- Section 3 provides a summary of the flood risk management processes used in Australia;
- Section 4 discusses identification of appropriate Flood Design Standards under a stationary risk environment;
- Section 5 discusses identification of appropriate Flood Design Standards under a non-stationary risk environment;
- Section 6 provides a recommended mechanism by which stationary and non-stationary risks can be incorporated into project decision making and design; and
- Section 7 provides a case study of application of the mechanism.

2. Review of Existing Flood Design Standards

A review of international and national practices was undertaken to identify current methodologies used to select Flood Design Standards and to inform the development of an appropriate Australian risk assessment approach.

2.1. International Examples of Flood Design Standards

2.1.1. Countries Explored in this Analysis

The countries explored in this analysis include:

- United Kingdom (UK);
- Netherlands;
- Japan;
- United States of America (USA); and
- Australia.

With the exception of Australia, practises in the above countries have previously been explored in 'Flood Risk Management Approaches' published by the Institute for Water Resources (IWR, 2011) with the following governmental contributors collaborating in its preparation:

- Japanese Ministry of Land, Infrastructure, Transport and Tourism (MLIT);
- Dutch Rijkswaterstaat;
- Environment Agency (UK); and
- Army Corps of Engineers (USA).

This paper (IWR, 2011) provided a valuable and trusted source of information for the current analysis. The five countries offered varied frequencies, scales, cultural and governmental characteristics for exploration in this document.

2.1.2. United Kingdom

The Department for Environment, Food and Rural Affairs (DEFRA) is the government department responsible for policy and regulations on environmental, food and rural issues in the United Kingdom (UK). Although DEFRA only works directly in England, it works closely with the devolved administrations in Wales, Scotland and Northern Ireland, and generally leads on negotiations in the EU and internationally.

In England, with delegated powers from DEFRA, the Environment Agency (EA) has the ultimate responsibility for managing the risk of flooding from main rivers, reservoirs, estuaries and the sea. The EA also administers 24,000 miles of river and coastal protection structures, on behalf of the Crown (EA, 2009). Due to the centralised approach of funding for managing flood risk, the processes are well developed and guidance is well detailed. Projects undertaken within the UK have access to a consistent and standardised approach that makes best use of lessons learned over time, with the guidance provided updated regularly (approximately every 5 - 10 years). Supplementary technical notes are also provided as required where an additional process or a change to a standard evaluation process is identified.

While prescriptive indicative Flood Design Standards have traditionally underpinned flood engineering in the UK, there has been a progressive movement over the last few decades to establish Flood Design Standards based on risk-based decision-making (Sayers et al, 2002).

2.1.2.1. Indicative Standards of Protection

A series of six Flood and Coastal Defence Project Appraisal Guidance (FCDPAG) documents were developed by DEFRA in 1999. These covered the various aspects of design and appraisal in the flooding realm, with detailed guidance for undertaking strategic planning, economic, risk and environmental assessments.

As part of an economic assessment process, the guidance set various structure design indicative ‘standards of defence’ (the term was later revised to ‘standard of protection’) to be applied in technical assessments, the results of which subsequently fed back into the costings of potential mitigation options which were part of the economic viability and affordability assessments. Figure 2-1 shows the Indicative Standards of Protection required in assessments, based on the land-use and number of houses per kilometre of river or coast. High value areas with larger populations would have defences designed to an event return period (RP) of 1 in 50 year RP to 1 in 200 year RP, whereas areas of land of low productivity and little to no population numbers would be less than a 1 in 2.5 year RP. Higher standards of protection were seen to be associated with higher construction and maintenance costs. As such, finite central government budgets meant that in the past there have been examples of the financial benefits of schemes needing to outweigh the costs by upwards of 8:1 before public funding was secured to undertake works. This led to many schemes that were economic but not affordable and therefore were not taken forward. In recognition of this problem, the UK government shifted towards a Minimum Insurable Level approach (Section 2.1.2.2).

Land use band	Indicative standards of protection			
	Fluvial		Coastal/saline	
	Return period (years)	Annual probability of failure	Return period (years)	Annual probability of failure
A	50–200	0.005–0.02	100–300	.003–01
B	25–100	0.01–0.04	50–200	.005–02
C	5–50	0.02–0.20	10–100	0.01–0.10
D	1.25–10	0.10–0.80	2.5–20	0.05–0.40
E	<2.5	>0.40	<5	>0.20

Land use band	Indicative range of housing units (or equivalent) per km of coastline or single river bank	Description
A	≥50	Typically intensively developed urban areas at risk from flooding and/or erosion.
B	≥25 to <50	Typically less intensive urban areas with some high-grade agricultural land and/or environmental assets of international importance requiring protection.
C	≥5 to <25	Typically large areas of high-grade agricultural land and/or environmental assets of national significance requiring protection with some properties also at risk, including caravans and temporary structures.
D	≥1.25 to <5	Typically mixed agricultural land with occasional, often agriculturally related, properties at risk. Agricultural land may be prone to flooding, water-logging or coastal erosion. May also apply to environmental assets of local significance.
E	>0 to <1.25	Typically low-grade agricultural land, often grass, at risk from flooding, impeded land drainage or coastal erosion, with isolated agricultural or seasonally occupied properties at risk, or environmental assets at little risk from frequent inundation.

Figure 2-1 Indicative standards of protection and the equivalent land-use band information

2.1.2.2. Minimum Insurable Level

New appraisal guidance was released in 2010 (FCDPAG became the Flood and Coastal Erosion Risk Management Appraisal Guidance (FCERM-AG)). The revised guidelines promoted adoption of a minimum insurable level: a 1 in 75 year RP. As this level was generally lower than previous, it helped make urban schemes more economically viable through lower construction costs. However, this also exposed urban areas and landowners to increased costs through increased potential damages following flood events. As such, the system also incorporated a process of optimisation to maximise design and also consider the implications of private contributions, e.g. if the private sector were to contribute ‘x’ pounds to the construction and upkeep of defences then the governmental would undertake additional works to further reduce potential future damages. Based on the economic appraisal of damages and costs of defences an acceptable equilibrium was considered to be able to be reached.

2.1.2.3. Risk-Based Planning

In addition to FCERM-AG, the United Kingdom issued Planning Policy Statement 25: Development and Flood Risk Practice Guide (PPS25) in 2006 as part of an holistic approach to managing risk as set out in the Government's strategy for flood and coastal management, 'Making Space for Water' (DEFRA, 2005). It underwent a number of revisions through until 2010 and in 2014 was integrated into new online planning practise guidance.

The approach assesses risk so it can be avoided and managed through the methodological flood risk management hierarchy summarised in Figure 2-2.

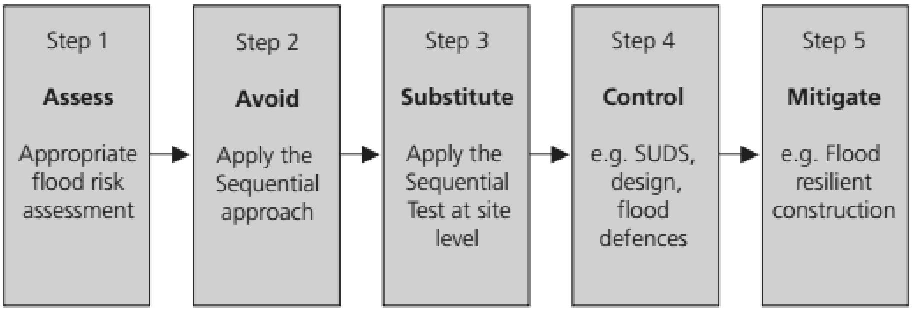


Figure 2-2 Sequential Risk Based Planning Approach

To apply the above steps, geographical areas are broken down into flood zones based on the annual probability of flooding as follows:

- **Flood Zone 1, Low Probability**: This zone comprises land assessed as having a less than 1 in 1000 annual probability of river or sea flooding in any year (<0.1%);
- **Flood Zone 2, Medium Probability**: This zone comprises land assessed as having between a 1 in 100 and 1 in 1000 annual probability of river flooding (1% – 0.1%) or between a 1 in 200 and 1 in 1000 annual probability of sea flooding (0.5% – 0.1%) in any year;
- **Flood Zone 3a, High Probability**: This zone comprises land assessed as having a 1 in 100 or greater annual probability of river flooding (>1%) or a 1 in 200 or greater annual probability of flooding from the sea (>0.5%) in any year; and
- **Flood Zone 3b, Functional Floodplain:** This zone comprises land where water has to flow or be stored in times of flood.

These flood zones refer to the probability of river and sea flooding, ignoring the presence of defences.

PPS25 aims to avoid inappropriate floodplain development by requiring planners to initially allocate future development sites in low risk areas. Alternative sites are only to be considered if it can be demonstrated that no suitable sites exist within these low risk areas. Table 2-1 details the appropriate types of development permitted within the various flood zones and Figure 2-3 details the sequential testing process to be followed by local planning authorities in considering development applications. Under this system, if a proposed development is needed for wider sustainable development reasons in flood risk areas it must then satisfy an Exception Test which ensures the development is safe for occupants, and does not lead to an overall increase flood risk.

Table 2-1 Appropriate Land Uses based on Flood Zone in the United Kingdom

	Essential Infrastructure	Highly Vulnerable	More Vulnerable	Less Vulnerable	Water Compatible
Examples	*Essential transport and utilities.*	*Basement-dwellings, Caravans.*	*Hospitals, residential nightclubs, hotels.*	*shops, agriculture*	*Flood control infrastructure, docks and amenity.*
Zone 1	Y	Y	Y	Y	Y
Zone 2	Y	E	Y	Y	Y
Zone 3a	E	N	E	Y	Y
Zone 3b	E	N	N	N	Y

Y = Development is Appropriate

N = Development should not be permitted

E = Exception test required prior to permitting development

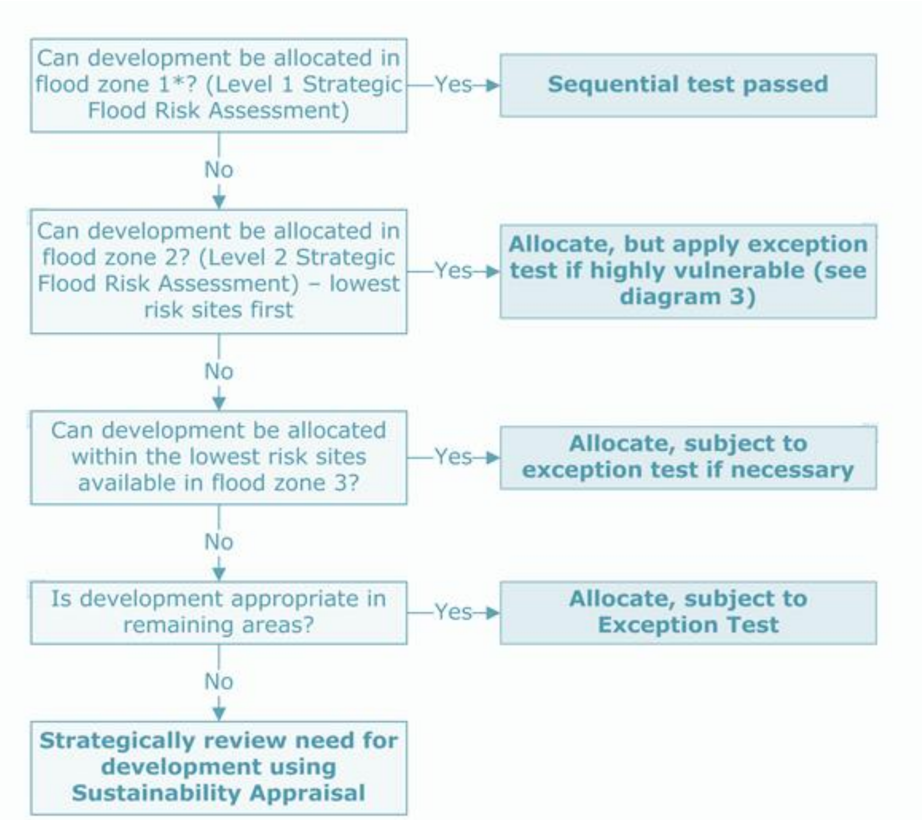


Figure 2-3 The Sequential Test used for land use planning in the United Kingdom

2.1.2.4. Incorporating Non-Stationarity

More recently, the United Kingdom is starting to recognise the role of non-stationarity within its planning procedures. In 2011 the EA published '*Advice for Flood and Coastal Erosion Risk*

Management Authorities' which presents a process to include non-stationarity in design (Figure 2-4):

Steps	Question to address
a. Build on the assessment of current risks	What drives flood or coastal erosion risk today? What is the vulnerability to current climate? Is there information on areas that could be susceptible to change?
b. Assess potential future sensitivities	What is the sensitivity to future changes? Where is adaptation required and for what level of change?
c. Identify feasible options	What adaptation options are available across the range of possible future changes? Are there opportunities to sequence options or build in flexibility?
d. Refine options	Is additional information or modelling necessary? What are the best options? What should be implemented and when?
e. Monitor, evaluate and review	Have the objectives been met? Does additional adaptation need to be undertaken or planned?

Figure 2-4 Overview - Advice for Flood and Coastal Erosion Risk Management Authorities

All determining authorities must apply this guidance to projects or strategies seeking government flood and coastal erosion risk management grant funding. The guideline offers a credible economical appraisal that takes account of the uncertainties associated with climate change. The steps in the process include:

1. Build on the Assessment of Current Risks

   This is used to help identify areas sensitive to change, set priorities and identify thresholds.

2. Assess potential future sensitivities

   Components of this step are as follows:

   - Understand the range of possible future changes:
     - Evaluate the potential range of changes;
     - Develop test scenarios.
   - Broadly evaluate sensitivity to future changes:
     - Undertake broad risk assessment;
     - Identify areas sensitive to change.
   - Refine the assessment of sensitivity to future changes:
     - Undertake more detailed assessment in areas susceptible to change; and
     - Iterate (to consider what adaptation options are available).

3. Identify feasible options

   Components of this step are as follows:

   - Identify options that could deal with a range of change - One approach is to develop options that reduce risk over the range of change or could be designed from the outset to cope with the upper end estimate of climate change.
   - Build in flexibility - Another approach is to build in the ability to adjust an option should it be required; i.e. build in flexibility. Examples include purchasing an area behind a

flood wall to enable the wall to be raised if necessary.

- Delay decisions that would be difficult to change — adaptive management- A complementary approach is to build flexibility into the decision process itself over time through waiting and learning. For example, sequencing options so that no or low regret options are taken earlier and more inflexible measures are delayed in anticipation of better information.

4. Refining options

   The preceding steps will have provided an understanding of the sensitivity of the system to future change and may have enabled options to be developed sufficiently to inform the final decision-making processes. Where this is not the case then some refinement will be necessary which is likely to involve considering change over interim periods of the overall plan or appraisal period.

   The approach recommended is to sequence the investment over time, rather than implement a robust (precautionary) design from the outset. The aim is provide a more responsive design to adjustment for changes in climate change knowledge in the future, and so be more cost-effective.

5. Monitoring, Evaluation and Review

   It is recommended that thresholds are established to trigger the need for future review as required.

2.1.3. Netherlands

In the Netherlands, the design process takes a more cautious approach due to the inherent high flood risk nature of the landscape and the potentially catastrophic consequences of protection structure failure.

Protection against large scale flooding in the Netherlands is provided for by law. In the 1950's the Delta Committee undertook a risk analysis from which protection levels were based upon, following a catastrophic flood event in 1953 (FLORIS, 2005). Similar to the UK, protection levels for flood structures are expressed as the probability of exceeding a certain water level. The Flood Defences Act of 1996 furthered this and defined protection levels for the country's ringbanks ranging from 1 in 500 year RP to 1 in 10,000 year RP for the western 'Ranstad' area which is the country's most populous area and economic hub (FLORIS, 2005). The high stands of protection mean that flooding is rare (IWR, 2011).

In 2008 a new flood risk management approach was adopted to incorporate cost-benefit analysis, loss of life, societal and individual risk calculations. This led to the calculation of the economic optimal flood probability for each levee system and the potential costs of construction and maintenance (levee reinforcing) to the appropriate standards in the year 2050 (IWR, 2011). The potential number of fatalities was assessed and 'social disruption' due to failure of the levee systems. Following on from these assessments, in 2010 a probabilistic risk analysis was undertaken for six of the country's major levee systems to provide further thorough information beyond the studies already carried out. The assessment included identifying failure mechanisms and weak sections of levee based on this, as well as safety priorities and the implications (and changed probabilities) of strengthening levees and hydraulic structures (IWR, 2011).

The risk process shows the changing attitudes forwards flooding and the recognition of the usefulness of a more thorough and integrated approach that considers more than the economic losses associated with flooding.

2.1.4. Japan

The Japanese approach to flood risk has developed since the turn of the last century with the establishment of the River Law (IWR, 2011). Increases in population levels led to increased water demand and a growing awareness of the environment. The law has been revised a number of times since its establishment to include new findings and changing values. Comprehensive flood control measures are favoured in Japan and combine physical (e.g. structures, levees) and non-physical methods (e.g. appropriate land-use, awareness and emergency management). The occurrence of flooding in Japan is relatively frequent and represents a significant developmental and management cost to the country.

Flood structures in Japan are typically designed to have a 50 year Design Service Life, with the Flood Design Standard specified as a discharge capacity. Japan has established future target discharges that are to be met (IWR, 2011). Due to the complexity and time associated with constructing dams, improving river capacity as much as possible is encouraged as part of primary design, with storage structures designed to cater for the remaining excess flow (Figure 2-5).

Case	Existing Capacity (m^3/s)	River Improvement (By Widening) (m^3/s)	Dam Cut (m^3/s)	Long Term Target Discharge (m^3/s)
I	2,000	0	3,000	5,000
II	2,000	1,500	1,500	5,000
III	2,000	2,000	1,000	5,000
IV	2,000	3,000	0	5,000

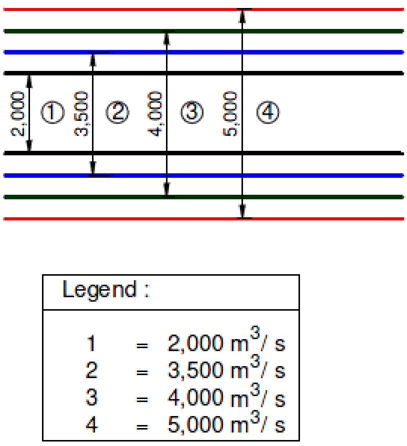


Figure 2-5 Example of discharge targets and improved river capacity due to widening

(DPWH, 2002)

Similar to the UK, the Japanese Flood Design Standard is usually expressed by a return period. The Flood Design Standard is determined based on the catchment area, the degree of importance of the proposed project area and the economic viability of the project. The costs and benefits of proposed options are assessed to determine the economic viability. The procedure to determine the discharge associated with the Flood Design Standard is as follows (DPWH, 2002):

1. Calculate the discharges corresponding to several flood frequency levels;
2. Calculate the existing river flow capacities on several control points;
3. Investigate the flood damages caused by past major floods and develop the relationship between flood discharge and flood damage;
4. Discuss the possibilities of river improvement;
5. Determine the preliminary river improvement plan;
6. Evaluate the cost to be incurred in the preliminary river improvement plan. If the preliminary river improvement planning is not realistic, back again to 3; and
7. Determine the most appropriate plan.

2.1.5. United States of America

Traditionally, flood mitigation planning within the United States has been the responsibility of local and state level governments. This is demonstrated in the Federal Emergency Management Agency's (FEMA) encouragement of community-based approaches to implementing flood mitigation efforts. FEMA created a Flood Mitigation Assistance (FMA) program as part of the National Flood Insurance Reform Act of 1994 (42 U.S.C. 4101) with the goal of reducing or eliminating claims under the National Flood Insurance Fund (NFIP). FMA funding for local communities can be secured from FEMA if schemes are shown to be:

- Cost- Effective - based on benefit-cost ratios;
- Cost beneficial to NFIP and reduce flood damages in a participating NFIP community; and
- Technically feasible.

Across the country, the different states have developed a variety of state based management systems and guidance policies to manage flood events. FEMA provides both flood hazard mapping and multi-hazard mitigation planning guidance ("Blue Book") which promote a high level risk based approach to flood plain management.

2.1.6. Australia

In Australia the 100 year ARI flood has historically been the key Flood Design Standard for planning purposes in Australia, particularly in regards to residential development within urban areas. CSIRO (2000) explains that this standard was first adopted in Australia after the fatal 1971 Woden Valley flood, which was estimated to have an AEP of 1%. The 100 year ARI event standard was subsequently adopted by various states as floodplain management procedures were revised as follows:

- Early 1970s – ACT;
- 1977 – NSW;
- 1978 – VIC;
- 1981 – NT;
- 1983 – SA; and
- 1985 – WA.

Although this has become standard practice, the use of somewhat arbitrary flood recurrence intervals as the main element of planning development and building controls is discouraged by CSIRO (2000). Rather, the use of 'flood risk' is encouraged to avoid confusion in a local community when flood levels "change". Current, risk management approaches require the consequences of events up to and including the PMF to be considered.

Progressively various authorities are now moving towards risk based approaches but traditional prescriptive methods exist and are often used in conjunction with these methods. For instance:

- Melbourne Water has developed a risk based framework to prioritise mitigation actions which '*represents a shift in the thinking that surrounds flood risk assessment. Previous assessment tools have largely focused on the economic cost of floods. This new approach places equal emphasis on the personal 'social' and 'safety' effects of floods*'. However it is also stated that the '*1 in 100 year drainage standard has been adopted as it is considered an appropriate balance between the likelihood of and the consequences of flooding for most developments*' (Melbourne Water Corporation, 2010).
- The Australian National Committee on Large Dams (ANCOLD) has recommended a risk based approach to the sizing dam capacity in the most recent guidelines (2000). It is however suggested that this approach should be used in conjunction with the prescriptive methods detailed in the earlier 1986 guidelines.

2.2. Findings of the Flood Design Standard Review

In summary, the major approaches to determining the Flood Design Standards for mitigation are as follows:

- United Kingdom, United States of America and Australia – all moving towards risk based approaches;
- Netherlands – risk approach based on quantitative analysis of cost-benefits, loss of life, societal and individual risk calculations; and
- Japan – flood mitigation structures tend to have a 50 year Design Service Life and the capacity is sized based on current flow capacity, risks and economic viability (costs and benefits).

The majority of counties utilise formal risk management and assessment guidelines that are considered over the course of a flood or design project. In particular, European countries were seen to typically offer the best examples of integrated guidance to aid land managers in assessing risk levels and how this can be factored into the design process. However, it is noted that the availability of documentation behind legislated or recommended guidance varies between countries.

In general, it was observed that although the incorporation of risk assessment and consideration of potential climate change impacts are frequently discussed in guidelines, the integration of infrastructure/program Effective Service Life considerations into these risk assessments is less obvious. Similarly, few guidelines were observed to consider the non-stationarity implications of climate change over the course of a project's Design Service Life or Effective Service Life. Where a risk assessment is incorporated into guidelines, the assessment is typically carried out in reference to the asset's Design Service Life (DSL). Similarly, it is seen that further assessment and analysis regarding the technical engineering and economic implications of design criteria are also based upon an assets DSL (e.g. when the evaluation of options for asset maintenance or upgrade), and do not incorporate consideration of risks, asset Effective Service Life (ESL), non-stationarity considerations.

Although simple methods can be used to incorporate a changing Service Life and changing climate into a risk assessment, more complex statistical methods exist and are discussed in Section 5. These are mostly derived from research in peer reviewed academic articles rather than as general guidelines widely used in day to day design assessments.

3. Australian Flood Risk Management

The risk based frameworks implemented by state and local authorities are typically underpinned by the principle tasks set out in the Australian Risk Management standard AS/NZS ISO 31000:2009. This Standard was prepared by Joint Standards Australia/Standards New Zealand Committee OB-007, Risk Management to supersede AS/NZS 4360:2004, Risk management. The risk management approach detailed in AS/NZS ISO 31000:2009 offers consistent processes within a comprehensive framework to ensure risk is managed effectively and coherently. The risk management process presented in this Standard is summarised in Figure 3-1 below.

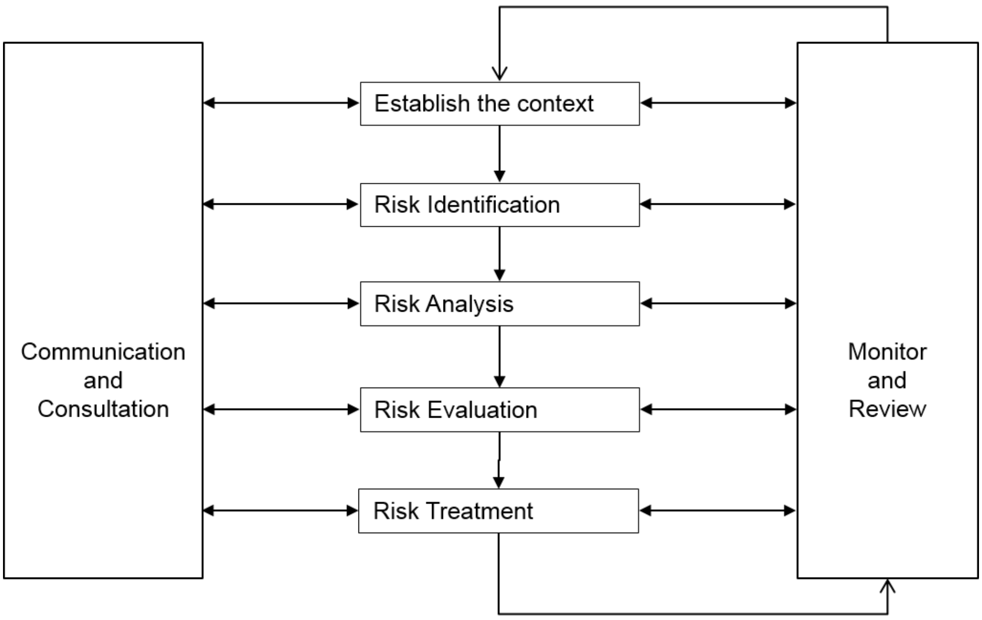


Figure 3-1 Risk Management Process (AS/NZS ISO 31000:2009)

The key components of risk management are discussed in the sections that follow.

3.1. Establishing the Context

Emergency Management Australia (2004) describe 'establishing the context' as developing a shared understanding of the basic parameters within which risks must be managed, and defining the scope of the rest of the risk management process. In regards to flooding, this is typically done in terms of catchment, rainfall and floodplain behaviour characteristics.

3.1.1. Setting the Risk Assessment Horizon

The Risk Assessment Horizon is the timeframe over which risks are assessed. As summarised in Section 2.2, it is often current practise to conduct the risk assessment at solely based on the current risk profile and assume that this will not change over a nominated Economic, Design or Effective Service Life. The impacts of discounting on the value of risk over time (e.g. risks arising 100 years in the future may be of lower concern to the same risk occurring in the present) mean that the benefit in adopting extended Risk Assessment Horizons, in comparison to medium term horizons, may be marginal. Conversely adoption of too short an assessment horizon may significantly underplay project risks and costs.

3.2. Risk Identification

Risk identification is defined in AS/NZS ISO 31000:2009 as "*identify sources of risk, areas of impacts, events (including changes in circumstances) and their causes and their potential consequences*". This is interpreted by Emergency Management Australia (2004) as identifying and describing the nature of risks through risk statements documented in a risk register. In regards to flooding, this typically relates to the potential for physical damage to property, injury, harm or loss of life in relation to storm events. However, it may also refer to localised uncontrolled discharges or spillages associated with water infrastructure (e.g. pipe overflow, dam breakage).

3.3. Risk Analysis

Risk Analysis involves considering the "*causes and sources of risk, their positive and negative consequences, and the likelihood that those consequences can occur*" and includes analysis of existing or proposed controls and their effectiveness (AS/NZS ISO 31000:2009). It can be used to inform decisions on the acceptability of residual risk providing input into risk evaluation and risk treatment decisions. It can be conducted at varying degrees of detail and can be qualitative, quantitative or a combination.

Flood risk is usually analysed based on the process shown in Figure 3-2, or variations of it.

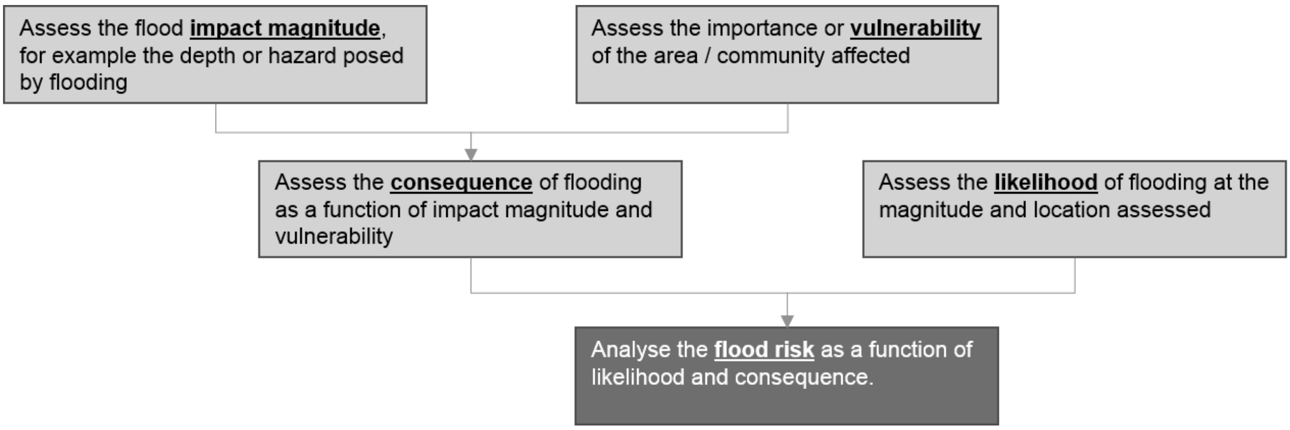


Figure 3-2 Typical Approach to determining Flood Risk

3.3.1. Consequence

As noted in Figure 3-2, consequence typically combines both the physical magnitude of an event (a characteristic of the event) and the vulnerability of the affected area (a characteristic of the environment in which the event is occurring). Emergency Management Australia published the Disaster Loss Assessment Guidelines (2002) which offer a step by step approach to assessing consequence ("loss"). The guidelines highlight the importance of considering direct and indirect, tangible and intangible losses in the consequence assessment. Examples of these losses are provided below.

Table 3-1 Types of Loss (Direct, Indirect, Tangible and Intangible)

Can the lost item be bought and sold for dollars?	Direct loss Loss from contact with flood water	Indirect loss No contact, loss as a consequence of flood water
Yes—tangible	For example, Buildings and contents Cars Livestock Crops Infrastructure	Disruption to transport etc. Loss of value added in commerce and business interruption where not made-up elsewhere Legal costs associated with lawsuits
No—intangible	For example, Lives and injuries Loss of memorabilia Damage to cultural or heritage sites Ecological damage	Stress and anxiety Disruption to living Loss of community Loss of non-use values for cultural and environmental sites and collections

Consequence / loss assessments based on hypothetical events are used to provide comparative data for establishing mitigation action priorities. This data can be either quantitative or qualitative in nature. However, typically quantitative measures are used as they represent the most readily comparable metrics.

3.3.1.1. Damage Quantification

Consequences that can be quantified as damage can be readily incorporated into decision making. As noted in Table 3-1, for flooding, most physical assets represents readily quantifiable goods, the loss or damage to which can be easily determined based on current market values. These can comprise both direct (e.g. damage to a car) and indirect (additional costs of taking public transport due to the damage to a car).

When options are being compared rather than using damages associated with a specific event, ‘average annual damages’ tends to be used (Emergency Management Australia, 2002). Average annual damages calculated across a range of flood events provide a robust understanding of the financial benefits and limitations of a project.

Figure 3-3 shows the financial benefits of a treatment measure, such as a levee, aimed at reducing flood damages and associated risks for events up to a 1% AEP flood (McLuckie 2015).

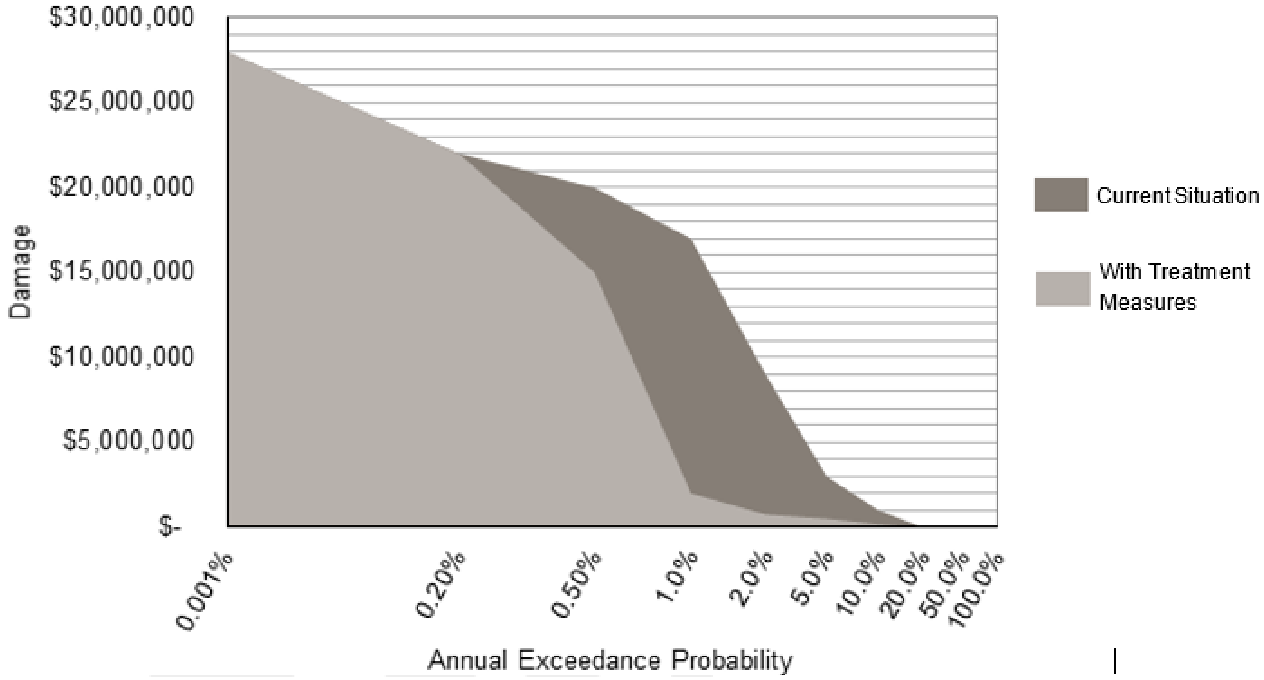


Figure 3-3 Financial Benefits of a Treatment Measure (McLuckie 2015)

In some circumstances, flooding events may impact upon intangible assets (e.g. health, heritage etc.). Where it is considered that the magnitude of this impact is such that it is worth determining in monetary terms, a variety of non-market valuation assessment tools exist to facilitate this process. For instance, it is possible to assign metrics to loss of life:

"Some people consider it unethical to put a price on human life. However, arguably, not taking the economic value of human life into account leads to a lower (economic) damage and thus results in a lower safety of the considered system." (Jonkman et al 2003)

There are a number of ways to quantify risk to human life for the purposes of risk assessment, with most approaches first determining the Population at Risk (people who would be directly exposed to flood waters assuming they took no action to evacuate (ANCOLD, 2012)) or Potential Loss of Life in association with a flooding event and then assigning values to the determined population / lives at risk. These values are commonly determined through stated preference or willingness-to-pay analysis (e.g. Value of Preventing Fatality, Life Insurance estimates). Estimates of the value of life vary significantly across the world but are typically within AUD$1 million and $10 million. Following assignation of value, the proportionate value of risk reduction/increase can be determined (e.g. if the estimated value of preventing a fatality is seen to be $1,000,000, a reduction in risk of 1 in 100,000 (0.001%) would be considered equivalent to $10 for an individual (Passey et al, 2014).

The quantified consequences are typically then used to either:

- Generate estimated monetary values associated with damages / loss of life associated with a particular flood event; or
- Converted back to qualitative consequence categories for utilisation within further risk

assessment.

3.3.1.2. Consequence as a function of Impact Magnitude and Vulnerability

In some situations it is possible to distinguish between contributions to the consequence of a specific flood event from both the characteristics of the flood events (its physical magnitude and extent: Impact Magnitude) and the characteristics of the receiving catchment (the importance of the affected area or its resilience to a given flood event: Impact Vulnerability). For example, two houses inundated to a depth of 0.5m may have the same impact magnitude, but differ in their vulnerability (i.e. one may be heritage listed and therefore any damage may be considered to be of greater value). The concept of vulnerability recognises that not all catchments respond to a given magnitude flood event in the same manner. This approach allows for incorporation of non-readily quantifiable risk elements (e.g. flooding affecting access ways to emergency or community services would generate greater social costs than flooding that does not). Table 3-2 below shows how both impact magnitude and vulnerability can be combined into a single consequence score (in the below case High, Medium, Low or Beneficial).

Table 3-2 Example matrix - Consequence as a function of vulnerability and impact magnitude

Increasing Magnitude Category

Vulnerability	0	1	2	3	4	5
Extreme	**B**	**L**	**M**	**M**	**H**	**H**
High	**B**	**L**	**M**	**M**	**H**	**H**
Moderate	**B**	**L**	**L**	**M**	**M**	**H**
Low	**B**	**L**	**L**	**L**	**M**	**M**
Negligible	**B**	**L**	**L**	**L**	**L**	**M**

Consequence: H = High, M = Medium, L = Low, B = Beneficial

While this is typically considered to be stationary during assessment for a specific event, it is recognised that, in terms of flooding, vulnerability is unlikely to remain stationary over time. For instance, the vulnerability of an area to flooding can alter due to land use change. The treatment of non-stationarity in consequence is discussed further in Section 5.

3.3.2. Likelihood

Likelihood can be considered as an annual likelihood of occurrence or as the chances of an event occurring during the structure's Economic/Design/Effective Service Life. How this has been incorporated into current risk assessment practices is detailed in Section 4. However, it is again noted, that as with vulnerability, the likelihood of a flooding event occurring is not stationary over time. The most obvious example of this is the case of climate change. Treatment of non-stationarity in likelihood is discussed further in Section 5.

A variety of standards exist to classify the likelihood of events occurring. For example, the Australian National Emergency Risk Assessment Guidelines (NERAG) utilise the following probabilistic based breakdown of event likelihood:

- Almost Incredible: ARI > 300,000 years;
- Very Rare: ARI - 30,000 to 300,000 years;
- Rare: ARI - 3,000 to 30,000 years;
- Unlikely: ARI - 300 to 3,000 years;
- Possible: ARI – 30 to 300 years;
- Likely: ARI – 3 to 30 years; and,
- Almost Certain: ARI < 3 years.

3.3.3. Risk

Although risk is often equated to likelihood or possibility, it is best defined as a function of Likelihood and Consequence. Typically, a subjective matrix similar to that below (Table 3-3) is used to define the level of priority associated with each combination of consequence and likelihood. These priorities are considered to be the resultant risk of the scenario in question. As risk is ultimately a subjective issue that reflects and individuals / organisations risk profile (averse – preferring) there is no one standard matrix, and the definitions for what constitutes an “extreme” of “low” risk rating is typically determined on a case by case basis.

Table 3-3 Example matrix – Risk as a function of likelihood and consequence

	Consequence level				
Likelihood level	**Insignificant**	**Minor**	**Moderate**	**Major**	**Catastrophic**
Almost certain	Medium	Medium	High	Extreme	Extreme
Likely	Low	Medium	High	High	Extreme
Possible	Low	Low	Medium	High	High
Unlikely	Low	Low	Medium	Medium	High
Rare	Low	Low	Low	Medium	Medium
Very rare	Low	Low	Low	Low	Medium
Almost incredible	Low	Low	Low	Low	Low

Following the application of Risk Evaluation (Section 3.4) and Risk Treatment (Section 3.5), it is common practice that the risk matrix will be re-applied to the original scenario while also considering the identified risk treatments to determine the Residual Risk (i.e. the remaining risk present following application of the identified flood mitigation measures).

3.4. Risk Evaluation

Risk evaluation involves determining which of the identified risks should be treated and the prioritisation of how such treatment. It also allows for the assessment of the risks associated with a project as a whole, and whether the inherent risks associated with a project/program are considered acceptable (with appropriate treatment measures) for the project/program to proceed. To evaluate risk, pragmatic principles such as ALARP (As Low As Reasonably Practicable) are commonly used to define boundaries between risks that are considered generally intolerable, tolerable or broadly acceptable. DEPI 2012 recommend the use of the ALARP principle if safety standards of are either impractical or not feasible (Figure 3-4).

What level of risk is considered appropriate to a project is a function of the risk profile of the relevant proponent / authority. Typically, risks may be considered to be either unacceptable (i.e. too great to be permitted to arise), tolerable (i.e. higher than is preferable but may be permissible if unavoidable), acceptable (i.e. the level of risk is permissible). These risk ranges are subjective and vary between guidelines and authorities. For example, the NSW Dam Safety Guidelines adopt the following range of tolerance in regards to the potential for loss of life:

- Acceptable – less than 1 in 1,000,000 per annum;
- Tolerable – between 1 in 1,000,000 and 1 in 10,000 per annum; and
- Unacceptable – greater than 1 in 10,000 per annum.

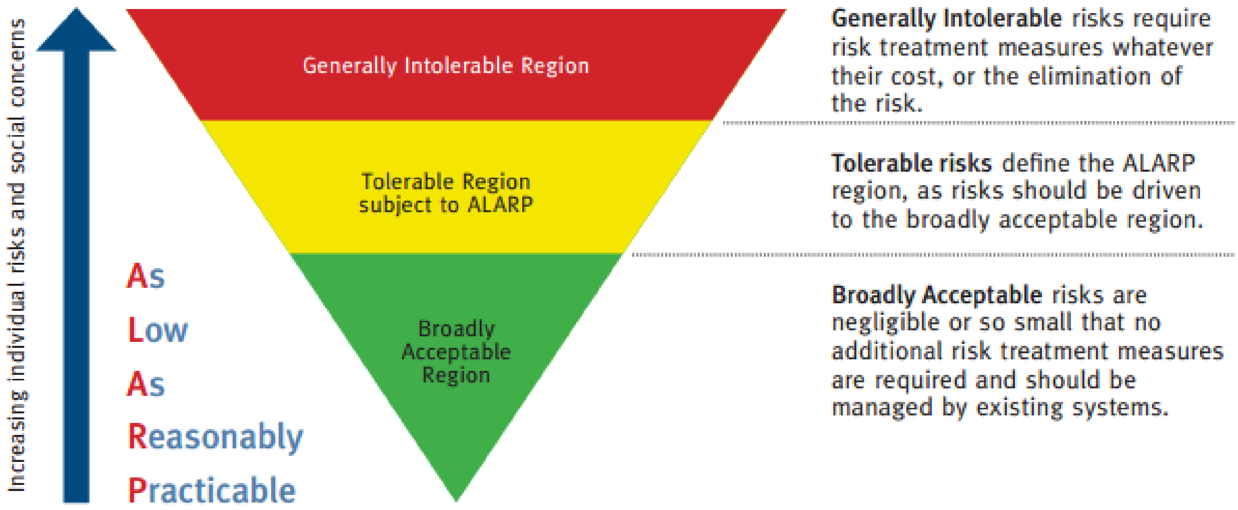


Figure 3-4 ALARP principle

3.5. Risk Treatment

Risk Treatment includes the identification of risk treatment options, their assessment, and the preparation and implementation of treatment plans. In line with the ALARP system, treatment is focussed on reducing the identified risks to as low as reasonably practicable, such that the residual risk is considered to be tolerable as a minimum.

Flood mitigation and the adoption of appropriate Flood Design Standards is a primary component of risk treatment. Risk treatment is a cyclical process of:

- assessing a risk treatment;
- deciding whether residual risk levels are tolerable;
- if not tolerable, generating a new risk treatment; and
- assessing the effectiveness of that treatment.

Flood mitigation measures should be assessed to ensure they are appropriate to the risk posed and that the costs and efforts of implementation can be rationalised against the benefits derived. The Standard (AS/NZS ISO 31000:2009 Risk management) acknowledges that risk treatment itself can introduce risks and that the failure or ineffectiveness of a risk treatment can pose a significant risk. This is most certainly the case for levee failure. The Standard states that monitoring needs to be an integral part of the risk treatment plan to give assurance that the measures remain effective.

Risk treatment measures can be categorised as follows:

- avoid the risk: decide not to proceed with the activity likely to generate risk;
- reduce the likelihood of harmful consequences occurring: by modifying the source of risk;
- reduce the consequences occurring: by modifying susceptibility and/or increasing resilience;

- transfer the risk: cause another party to share or bear the risk; and
- retain the risk: accept the risk and plan to manage its consequence.

A critical factor in the identification of appropriate treatment options is the need to consider the timeframe over which the treatment may apply. Treatment options may be short-term actions which can regularly be updated or expanded or long term fixed actions built into infrastructure in construction. Increasingly, the incorporation of adaptability in design in planning / construction in order to facilitate (and lower the costs) risk management at later stages of a project life is being recognised as potential method to account for non-stationarity in risk.

3.6. Economic Analysis

As it is often possible to quantify, in dollar terms (Section 3.3.1), the perceived level of risk associated with a project, economic analysis is commonly used as a decision making tool for project developers. The expected cost value associated with a flood event (expected value = likelihood of occurrence x value of cost (i.e. consequence, loss)) can be added to other costs associated with project development and compared against the expected benefits through a cost benefit analysis. A project in which the ratio of net benefits to costs, over an adopted economic life, exceeds unity would be considered to be an economically viable project (Figure 3-5).

Calculating Benefit Cost Ratio

$BCR = NPV_{benefits}/NPV_{costs}$

Where: BCR = benefit cost ratio

$NPV_{benefits}$ = Net Present Value of Benefits

NPV_{costs}= Net Present Value of Costs

Note: A range of discount rates (dr) may be used to give a range of NPVs which can in turn be used to determine a range of benefit cost ratios (see below) to test how financial benefits may vary with different financial situations.

Example: Calculating BCR

Step 1. Calculate Net Present Value of benefits **= *$NPV_{benefits}$***

Step 2. Calculate Net Present Value of Life Cycle Costs = ***NPV_{costs}***

Step 3. Calculate BCR. BCR = 1.14 for dr 7%, BCR = 1.51 for dr 4%, BCR = 0.9 for dr 10%

Discount Rate (%)	***$NPV_{benefits}$ $***	***NPV_{costs} $***	***BCR***
4	9,055,194	5,979,277	1.51
7	6,099,257	5,333,171	1.14
10	4,473,916	4,977,905	0.90

Figure 3-5 Calculation of Benefit Cost Ratio (adapted from McLuckie (2015))

Similarly, in regards to flood mitigation / risk treatment measures it is possible to evaluate whether the level of avoided costs (i.e. a benefit) as a result of a specific mitigation measure outweighs the cost of implementation.

The use of economic analysis in such decision making is a powerful tool as it readily allows consideration of a projects costs / benefits over its Design Service Life, Effective Service Life or any other period of interest, through use of forecasting. In particular, the use of economic cost benefit analysis allows for comparison of multiple risk treatment options, enabling authorities / developers to adopt the most efficient form of mitigation to maintain agreed risk exposure levels. For example, a cost benefit analysis undertaken at the present point in time may demonstrate that the costs of implementation of a particular flood mitigation measure outweigh the avoided cost benefits. However, if the benefits were to increase over time (e.g. climate change generating increased flood risk), implementation of the mitigation measure may be seen to be viable if implemented at a later date. In this manner, economic analysis can be utilised to assist in addressing non-stationarity of risk.

However, as noted in Section 3.3.3, risk is ultimately subjective in nature (e.g. some individuals can be risk preferring, others risk averse). As such, individuals will choose flood risk management options to the extent they are willing to pay for likely benefit it will generate. For example, Figure 3-6 provides a standard insurance scenario in which the choice of insurance policy will reflect the individual’s preference for avoiding flood risk. Such stated preference techniques are commonly utilised in determining the value of mitigation measures. As such, it is recognised that economic analysis are also based upon what is considered to be a “tolerable” or “broadly acceptable” level of risk.

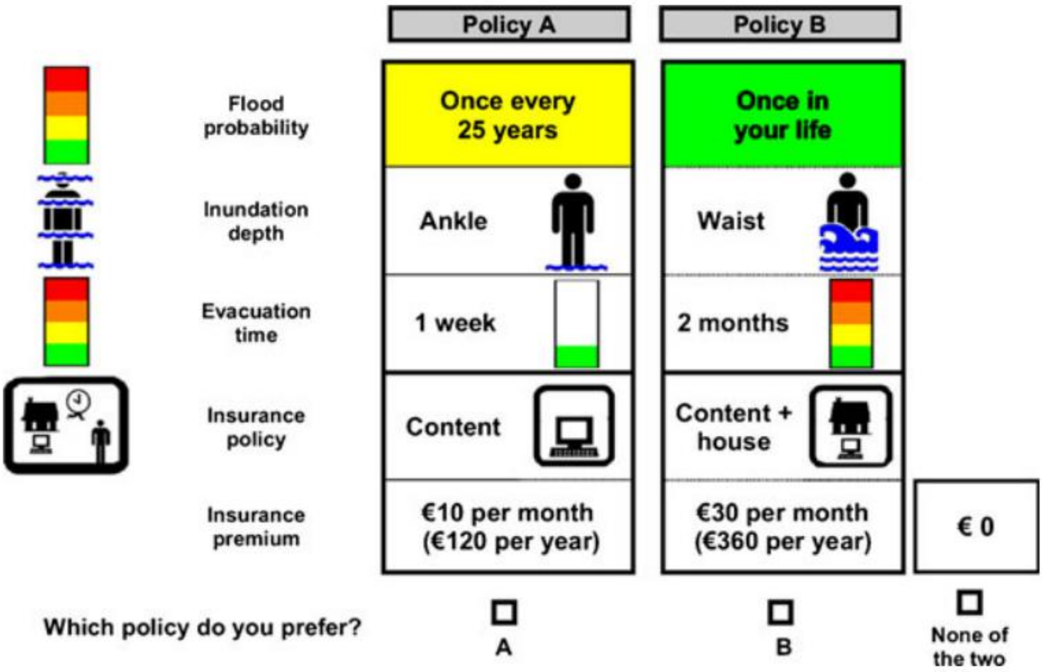


Figure 3-6 Willingness to pay to minimise risk exposure

4. Stationary Risk Profile Decision Making

The risk assessment process outlined in Section 3 is typically applied assuming a stationary risk profile. When risk is assumed to be stationary in time, it enables Flood Design Standards to be expressed readily in probabilistic terms. Typically, this is done as either:

- **Annual Exceedance Probability (AEP):** the likelihood of occurrence of a flood of a given size or larger in any one year; usually expressed as a percentage (e.g. a flood protection levee may adopt of Flood Design Standard that offers protection up to the a 1% AEP event);
- **Service Life Exceedance Probability (SLEP)**: The likelihood of exceedance during a project's adopted service life, rather than as an annual likelihood.

A SLEP approach may tend to be favoured for temporary structures in which either an AEP value may not be readily comprehensible (e.g. if a structure is only to be in place for a month) or one in which the consequence of failure are extremely high.

To illustrate this, consider a flood defence levee being designed under the assumption of stationary flood risk with a Design Service Life of 100 years. If the adopted Flood Design Standard is such that it offers protection from the 0.1% AEP flood event (i.e. a 1000 year Average Recurrence Interval), it would be expected that the likelihood of the levee overtopping once in its lifetime would be 10%. However, if the structure's Design Service Life was 200 years, to retain the same 10% likelihood of overtopping once in its lifetime it would be necessary to approximately increase the levee height to provide capacity for the 2000 year ARI event. It is at this point that the difference between a project's Design Service Life and its Effective Service Life become significant.

It may be difficult to determine whether the project's approval authority considers a once in 100 year overtopping to be a "broadly acceptable" / "tolerable" level of risk, or whether it is that a 10% chance of overtopping over its life is really the basis of the determined level of acceptable risk. It is considered that while design standards are commonly expressed as an annual occurrence probability, it may be the case that project developers / authorities actually interpret and apply this more as a SLEP or an Exceedance Frequency over the adopted service life.

AUSTROADS, the national association of road transport and traffic authorities in Australia use both the SLEP approach and the AEP method depending on the context.

The AEP method is used to define the levels of service of roads:

- Freeways and arterial roads – should generally be designed to pass the 50 or 100 year ARI flood without interruption to traffic. However for arterial roads in remote areas, a reduced standard is commonly adopted where traffic densities are low, AUSTROADS (1994).

The SLEP method is used in the design of bridges:

- All bridges are to be designed so that they do not fail catastrophically during a flood that has a 5% chance of being exceeded during the Design Service Life of the structure. Assuming a 100 year Design Service Life, this equates to a flood with an ARI of 2000 years' AUSTROADS (1994).

The SLEP approach can be more useful or readily understandable for short term measures, in particular as a way of avoiding adoption of unfeasibly large structures that may be recommended under an AEP approach. For instance a temporary cofferdam used during the construction of a permanent dam may not tend be required to offer the same Flood Design Standard as the permanent structure.

Conversely, there may be instances where the consequences of exceedance are sufficient to warrant adoption of the same Flood Design Standard as a permanent structure. A holistic consideration of risk is necessary to determine an appropriate Flood Design Standard. If the consequence of the temporary cofferdam overtopping was flooding of non-vulnerable land, it may be appropriate to have a reduced structure capacity. If the cofferdam is needed during the replacement of a permanent structure protecting a vulnerable community, it would be expected to offer the same level of protection as the permanent dam. The risk analysis and evaluation procedure outlined in Section 3 provides a mechanism by which these elements can be considered for any scenario. However, the subsequent provision of corresponding set design criteria or guidelines to be readily applied is problematic given the diversity of factors which need to be considered. Recommendations regarding design criteria under stationary risk scenarios are discussed further in Section 6.

Although many authorities provide guidance as to the standard of protection (expressed as a return period) (Figure 4-1) a structure should maintain over its Design Service Life, there is less explicit guidance as to how to incorporate the design life into an assessment and account for reduction in remaining service life over time and the change in risk related to this. Typically, less resilient flood structures are designed with design lives ranging from between 20 and 100 years, with 50 years the general standard (e.g. stormwater infrastructure, river walls, levees). More resilient structures are more likely to have design lives in excess of 100 years, e.g. dams and reservoirs commonly 100 to 200 years.

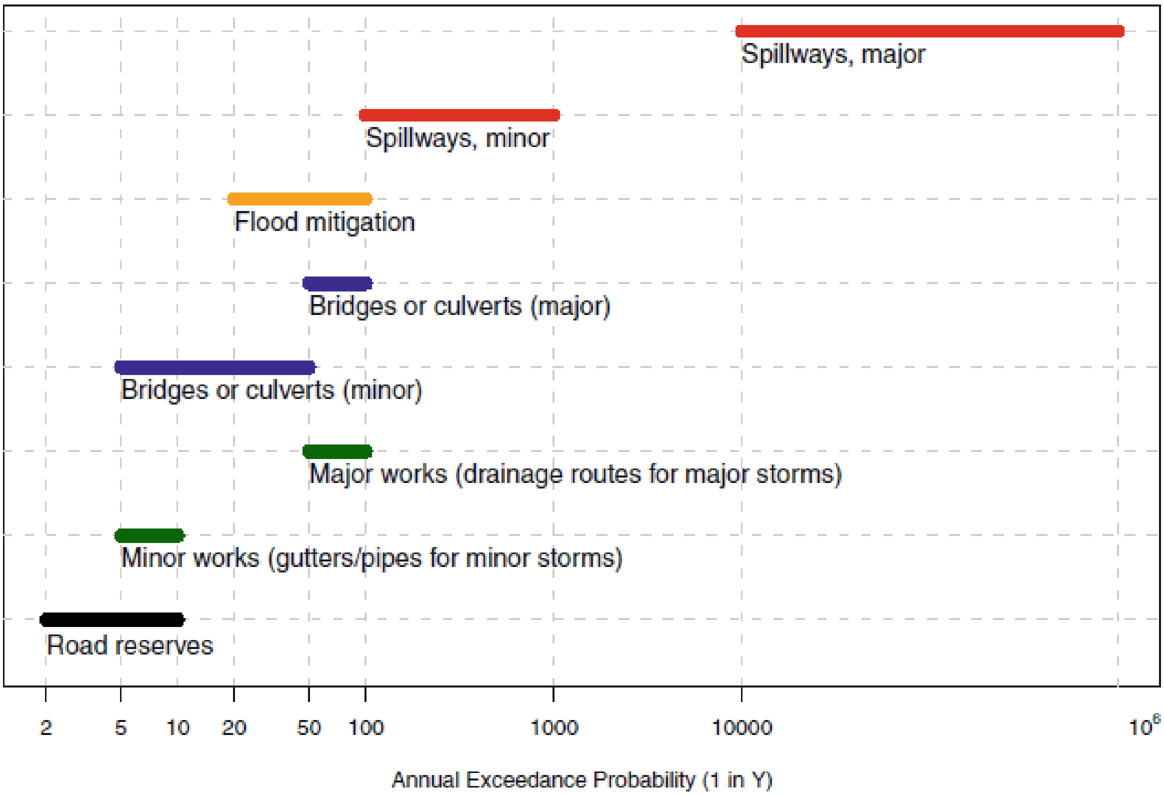


Figure 4-1 Typical Annual Exceedance Probability design criteria (IPCC, 2011)

The 2002 Construction Industry Research and Information Association (CIRIA) Manual on Scour at Bridges and Other Hydraulic Structures (May et. al., 2002) presents an equation that incorporates the both return period and Design Service Life for a stationary climate: where Pr is the probability of the exceedance occurring (0.0 = zero risk, 1.0 = certainty of exceedance), Ly is the Design Service Life (in years), and AEP is the annual exceedance probability.

$$Pr = 1 - (1 - AEP)Ly$$

(Derived from equation 3.20 of May et al, 2002)

This could also be applied to Economic or Effective Service Life estimates.

5. Allowing for Non-Stationary Risk

5.1. Uncertainty and Non-Stationarity in Flood Risk

A large amount of uncertainty exists when designing flood defence systems. Fleming (2002) describes some of the sources of uncertainty as follows:

- Accuracy of the historic flood data;
- Recent changes in the catchment which would not be reflected in the data record;
- Repeated flood events captured in the historic record during exceptionally high prolonged periods of rainfall;
- Seasonal and long term changes to water level – for instance siltation and weed growth; and
- Accuracy of observations, stage-discharge relationships and hydrological methods.

Consequently, flood modelling and management typically operates from a conservative position so to minimise the impact of uncertainty risk. The recognition of non-stationarity (i.e. a non-static flood risk profile) introduces further uncertainty and complexity into project risk assessments and decision making. Despite the complexity, it is noted that, particularly for permanent / long-term projects/programs, there may be a need to incorporate non-stationarity into assessments and that a failure to do so may significantly under-estimate project risks. For example:

'*In many cases, flood studies reflect current conditions at best, and more likely past conditions since the studies often rely on old data …. …..flood risk criteria used to site and design a project should rely on conditions the location is likely to experience during the project's lifetime, not past or current conditions.*' (Floodplain Regulations Committee, 2010).

Risk as a combination likelihood and consequence (Section 3) is often non-stationary.

'.. *neither likelihoods nor consequences are known with certainty. In the context of climate change risk assessment, uncertainty arises because, although we can be confident the climate is changing, we do not know precisely the magnitude of the changes or their associated impacts and in some regions it is not clear whether rainfall will increase or decrease. As well, uncertainty may arise because decision makers do not know the exact point (or threshold) at which a climate change impact has a particular level of consequence*' (Australian Greenhouse Office, 2006).

The potential for changes in both likelihood and consequence are discussed in the following sections.

5.1.1. Sources of Non-Stationarity in Likelihood

The likelihood of given magnitude events occurring may change over time due to a large number of variables including:

- **Seasonality**: the seasonality can alter the statistical likelihood of flood events occurring as some events. For instance some catchments tend to have are prone to flooding associated with summer climates;
- **Climatic Variability**: Various weather patterns such as El Niño influence the likelihood of flooding. El Niño events have a life-cycle during which the impacts vary, both in terms of spatial extent and timing. Typically when the Pacific approaches or exceeds El Niño thresholds, the Australian region experiences less tropical cyclone activity (BOM, 2014);
- **Catchment or flood mechanism changes**: the likelihood of flooding is affected by changes (both natural and anthropogenic) in the catchment. For instance the construction of a storage basin to retard flows would influence the likelihood of flooding downstream;
- **Evolving hydrological / hydraulic estimates**: The likelihood of a given magnitude flood event can vary significantly due to evolving hydrological / hydraulic estimates. For instance expected peak flows derived from flood frequency analysis can be altered by revisions made to the rating table or by extending the record length to include / exclude extreme events; and
- **Climate Change**: Fundamental changes in the climate will alter the likelihood of flooding.

5.1.2. Sources of Non-Stationarity in Consequences

Similar to potential changes in likelihood, the consequences of flooding can change due to a wide range of variables including:

- **Land-use change** – change to a more vulnerable land use. An example is the shift from rural to industrial cited as a key reason for the global increase in flood risk by Au Brecht *et al* (2012);
- **Economic changes** such as inflation;
- **Changes to the community exposed** to risk:
    - Community demographic – for instance has the population evolved to consist of predominantly elderly / retired persons;
    - Level of flood awareness / education in the community– the importance of education is being recognised and initiatives such as SES Floodsafe are being used to reduce the community’s vulnerability to flooding; and
    - Seasonal changes in the population affect the flood risk. For instance holiday destinations often experience a seasonal change in the population.

5.1.3. Sources of Non-Stationarity in Risk Tolerance

It is recognised that just as the components of risk (likelihood and consequence) may vary over time, so to an individual’s evaluation of the ultimate importance of that risk may alter. This may occur through:

- **Altered risk profiles** – Individuals tend to alter the level of what may be considered “acceptable” or “tolerable” (Section 3.4) over time following past experiences or changes in priorities; or
- **Risk discounting** – The value of a risk realised at a future time is typically considered of less significance than a risk realised at a current time. The rate at which this is applied may vary over time; typically the discount rate used reflects the economic discount rate in financial systems.

Typically, risk assessments (in both stationary and non-stationary assessments) assume that risk profiles do not alter and discount rates are held constant as introducing such variability fundamentally undermines the value in undertaken a risk assessment at any one point in time. However, it is worth noting that all risk assessment inherently involves a range of fundamental assumptions and that the appropriateness of these assumptions may be questioned. For example, the long term nature of climate change impacts has raised the issue of inter-generational costs and the value of human life (e.g. is it appropriate to discount the value of human life?) and raises moral and ethical questions for decision makers.

5.2. Review of Approaches – Incorporating Non-Stationarity in Design

A number of examples of exist of where non-stationarity guidelines for application in risk assessments and the design process have been developed. In Victoria, Melbourne Water adopts a 32% increase in rainfall intensities to indicate what may occur by the year 2100. The Department of Environment and Climate Change in New South Wales recommends conducting sensitivity analysis on the following scenarios until further works are completed in relation to Climate Change:

- 10% increase in peak rainfall and storm volume;
- 20% increase in peak rainfall and storm volume; and
- 30% increase in peak rainfall and storm volume.

COST (2013) (Figure 5-1) presents some European examples of where guidelines for changes to design flood levels exist: Norway, the UK (refer Section 2.1.2.4), Belgium and Germany. However, typically these design level changes are in effect incorporated as coarse adjustment factors and act in a similar manner to “sensitivity analyses” under the existing stationary assessment paradigm. For example, regional increases in design flood estimates of 0%, 20% and 40% are included in Norwegian risk assessment studies. However, these studies still assume stationary conditions based on region and season. Smaller catchments use a default of 20% due to the recognition of increases in short-term extreme rainfall and that the smaller catchments are generally more vulnerable.

Country	Region	Variable	Guideline	Reference
Belgium	Flanders	Design floods	30% increase	Boukhris and Willems (2008)
Belgium	National	Design rainfall	30% increase	Willems (2011)
Denmark	National	Design rainfall	20%, 30% and 40% increase for return periods 2, 10 and 100 years	Arnbjerg-Nielsen (2008)
Germany	Bavaria	Design flood with 100-year return period	15% increase	Hennegriff *et al.* (2006)
Germany	Baden-Würrtemberg	Design floods	Increase between 0% to 75% depending on location and return period	Hennegriff *et al.* (2006)
Norway	National	Design floods	0%, 20% and 40% increase based on region, prevailing flood season and catchment size	Lawrence and Hisdal (2011)
Sweden	National	Design rainfall	Increase between 5% and 30% depending on location	SWWA (2011)
United Kingdom	National	Design floods	20% increase for 2085	Defra (2006)
United Kingdom	National	Design rainfall	10%, 20% and 30% increase for 2055, 2085 and 2115	Defra (2006)

Figure 5-1 Summary of existing European guidelines on climate change adjustment factors on design flood and rainfall (COST, 2013)

As seen in Figure 5-1, in Germany, two states have included climate change increases in the guidance for flood assessment. Bavaria adds 15% to the 100 year time frame and Baten-Württemburg have varying factors depending on region and return period that range between 0 and 75% (Hennegriff et. al., 2006; cited in COST, 2013). COST (2013) goes on to note that although increases for climate change are considered in many assessments, there still exists a gap between this recognition and the actual application in prescribed guidelines. In particular, application of true non-stationary risk profiles is currently the subject of significant academic research but has not gained significant practical implementation at the time of writing.

5.2.1. Applying Non-Stationarity

A method for incorporating design standards and design life into risk assessments is presented in Rootzen and Katz (2013). The paper discusses reasons as to why stationarity is becoming less accepted and that assessments need to incorporate the potential climate changes in a robust manner. The paper proposes two methods to quantify risk for engineering design in a changing climate:

- The *Design Life Level* aims to achieve a desired probability of exceedance (or risk of failure) during the Design Service Life. This method is a SELP approach as detailed in Section 4; or

- The *Minimax Design Life Level* is closely related, and complementary, but instead focuses on the maximal yearly probability of exceedance during the Design Service Life. This method is an AEP based approach as detailed in Section 4.

The Design Life Level uses a Generalised Extreme Value (GEV) cumulative distribution function (cdf) to present the extremes in year t and with increasing location and scale parameters (the shape parameter is constant) related to t, the probability changes. The example likens the increase in location parameter to a possible increase in water level, and scale parameter to an increase in climate variability. Another parameter is also introduced, the Expected Waiting Time (EWT) - the amount of time until a particular level u is exceeded. According to the authors, the Design Life Level "captures risk in a way that is tailored for risk assessment". Risk plots are also presented to show the concept and how the probability of failure changes over the design life period.

If what is considered an acceptable level of risk is constant (Section 3.4), it may be desirable to design mitigation measures such that the likelihood of consequence is constant in time. Figure 5-2 (b) shows that if risk is increasing through time, then to keep the standard of risk protection constant, it would be necessary to continuously raise a defence (derived from Rootzen et al 2012). Clearly for many projects it is not possible to continually increase the capacity of flood protection measures, therefore if the mitigation measure is of fixed capacity the standard of risk protection varies with time as shown in Figure 5-2 (a) (derived from Rootzen et al 2012).

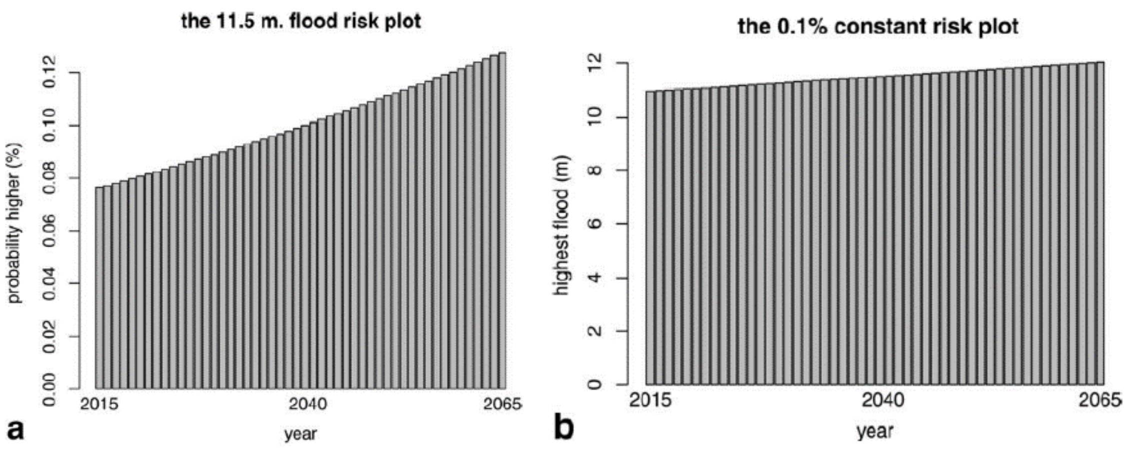


Figure 5-2 Flood Risk Plot versus Constant Risk Plot

Laurent & Parey (2007) used daily maximum temperature data from Météo-France (French national meteorological service) to estimate 1 in 100 year return period temperatures in a non-stationary climate. The metrological data was used to determine extreme values and test the significance of a temporal polymonial trend. When statistically significant trends were found the Peak over Threshold (PoT) method was extended to a non-stationary case to define a new return level. Two IPCC climate change scenario simulations are then compared with the extrapolated temperatures; these are then compared with atmospheric models. Although this was not a design project, it shows that statistical methods can be employed to effectively incorporate change over time; however, according to Rootzen and Katz (2013) the method may not be flexible enough for realistic engineering design.

Astrom, et. al., 2013 uses an influence diagram (ID), which is an extension of a Baysian network, to develop a risk assessment and support framework for pluvial urban flood risk with changes in extreme rainfall over time, i.e. a non-stationary climate. For critical urban infrastructure, the ID is used as a flood risk assessment and decision support tool in which various sources of uncertainties accounted for and modelled. The method is used to contribute to a cost-benefit analysis where damages are based on different adaptation options are calculated and used to compare the costs and benefits of each for two time 'slices' 2063 and 2113. Changes in climate were incorporated into the assessment as climate factors, 1.15 and 1.4 respectively for the time 'slices'. These factors consider the expected increase in the magnitude of extreme rainfall events during the lifetime of the project (a drainage system) and are the "ratio between the best estimate of the design intensity in the future and the design intensity at present" (Gregersen et al. 2011; Arnbjerg-Nielsen 2012; cited in Astrom, et. al., 2013).

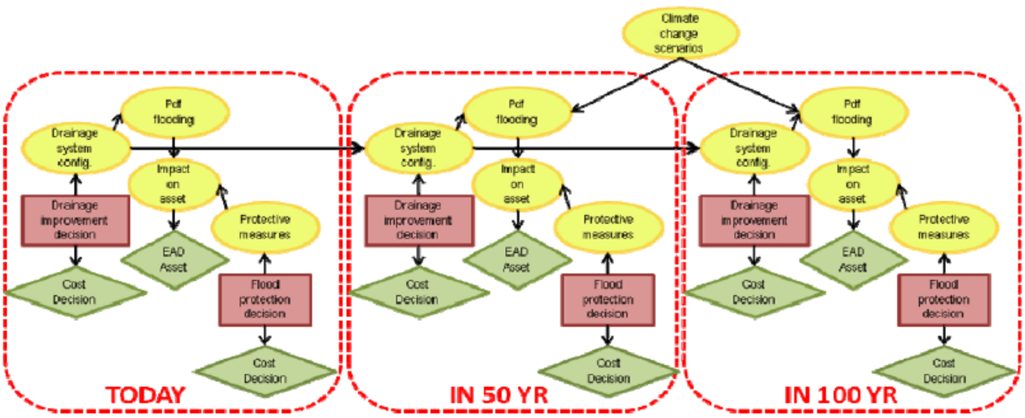


Figure 5-3 ID for flood risk assessment - shows how risk changes over time (Astrom, *et. al.,* 2013)

This method of factoring non-stationarity into an assessment is a simple way of considering changes in a significant parameter by applying the climate factor; however it still assumes some stationarity in the actual climate factor parameter applied.

Salas & Obeysekera (2014) reviewed the return period concept and risk for non-stationary hydrological extreme events. The paper considers the sources of non-stationarity and states that:

- Previous records exhibit some inherent non-stationarity related to low frequency climate variability (e.g. Pacific Decadal Oscillation); or
- Climate change due to increases in greenhouse gases could be the leading cause of significant changes to river basins and their hydrologic cycles.

The paper reviews some recent methods for incorporating non-stationarity into risk assessments in a simple and more understandable way than perhaps what has been presented in the literature to date, the authors also suggest that the complexity of some of the methods may also be why they are not more commonly present in water resource literature.

Salas & Obeysekera present a framework for addressing non-stationarity in risk assessment, stating that advances in extreme event modelling are sufficient to support such an approach. The non-stationarity is considered in terms of increasing events, decreasing events and random shifting events, with the standard return period and risk parameters.

In the case of increasing extreme events, the exceedance probability of floods affecting structures also varies through time i.e. *p1, p2, p3, …..,pt*. The sequence of *p* will also be increasing (refer Figure 5-4):

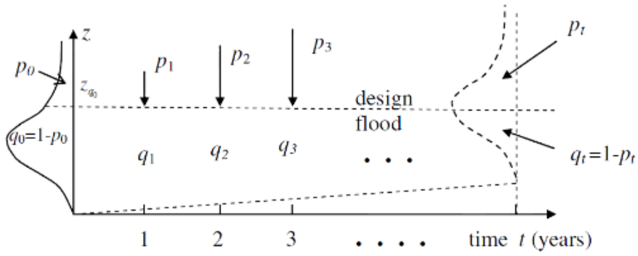


Figure 5-4 Schematic of a design flood with exceeding (P_t) and non-exceeding (q_t = 1-P_t) probabilities varying with time (Salas & Obeysekera, 2014)

If the probability of the first flood exceeding the Flood Design Standard at time x = 1 is *p1*, then the probability at time x = 2 is *(1-p1) p2*. In general, the probability that the first flood exceeding the Flood Design Standard will occur at time x is given by:

$$f(x) = P(X = x) = (1-p_1)(1-p_2)(1-p_3)\ldots(1-p_{x-1})\,p_x$$

The example shows the change in probability with time for increasing events in a relatively straight forward manner. This geometric distribution is developed further for application in a non-stationary framework to allow the waiting time for the first exceedance of the Flood Design Standard to be calculated. *T* in the stationary case now becomes *pt.T* and is a function of the time varying exceedance probabilities. The authors go on to present the same concept for decreasing events, as well as shifting extreme events.

A number of studies have applied elements of non-stationarity to practical real-world scenarios. Vogel et al. (2011) investigated non-stationarity in the United States by considering trends in floods in catchments that are not only influenced by climate change, but anthropogenic factors as well. A simple statistical model was developed which was able to represent observed trends and flood frequency in a non-stationary setting. Recurrence reduction factors were calculated to determine that a present day 100 year RP event would become more frequent in future (Vogel et. al., 2011).

Ng et al. (2010) investigated the effects of both climate change and human activity on stream flow for two Massachusetts rivers simultaneously using stochastic streamflow models. Using a multivariate linear regression, a non-stationary monthly stochastic model of streamflow was developed. These included variables for rainfall, water use and land use which until then had not been included in stochastic streamflow models. This enabled the model to be used in planning and management applications where changes in each of the variables can impact streamflow. The study found that land use had low significance for one river and that generally, the inclusion of the additional variables resulted in an improvement in the 'goodness-of-fit' of the resulting models over traditional stochastic streamflow models which may only consider one variable.

Similarly, Condon et al. (2014) considers climate change and non-stationary flood risk for the Upper Tuckee River basin near Lake Tahoe in California. A variable infiltration capacity model and a non-stationary GEV model were used to simulate historic floods for two gauged locations in the river. Past cool season (Nov-April) monthly maximum flows were fit to the GEV model and the future cool season flood distributions were calculated using downscaled estimates of temperature and rainfall taken from previous model results. To inform the risk assessment, the exceedance probabilities were put into a single risk metric to present a risk profile considering changes over time. The results showed 10 - 20 % increases with climate change when comparing the historical period with the future projections (Condon et al 2014).

5.3. Design Service Life and Non-Stationarity

The academic work to date does indicate that there is potential for non-stationary models to be incorporated into design considerations and that the scale of catchment change may be of sufficient magnitude in some catchments to warrant consideration in Flood Design Standards. However, it may be that the costs of developing such models and assessments is currently prohibitive and unnecessary for the majority of water-affected infrastructure, and that utilisation of traditional static risk profiles remains the more appropriate form of assessment.

In particular, projects for which design / effective is relatively short (e.g. less than five years), it may be reasonable to assume risk profiles to be static for the duration of the project as the extent of change is likely to be negligible in comparison to the current risk level. In contrast, longer life-span projects will be exposed to a higher level of non-stationary risk. Depending on the nature of the project/program to be implemented the way in which the risk assessment incorporates this risk may vary (Section 6). In particular, it is recognised there is a need for consideration of a project's Effective Service Life in addition to its design life.

As risk treatments may be applied at various stages of a projects Design / Effective service life (as and when economically feasible) it is important to note that any one project life-span can be broken into a number (potentially infinite) of stationary periods (e.g. every five years) and that repeated static risk assessments over time may allow approximation of non-stationarity modelling. Similarly, it is also noted that while a project's risk profile may be non-stationary and continuous, the practical ability to respond in real time to changes in risk is not and is inherently discrete in nature. As such, there will always be a disjunct between the application of risk mitigation measures and the realised risk exposure at anyone point in time under a non-stationarity risk profile. Consequently, the issue then becomes a question of what is an acceptable level of risk differential to be incurred until further mitigation is implemented. This issue and its practical outworking are discussed further in Section 6.

6. Recommendations

The adoption of suitable Flood Design Standards for infrastructure and planning projects should reflect, as relevant:

- The characteristics of the existing environment;
- The potential economic consequences of flooding as a result of the proposed development;
- Potential changes to the existing over the project's Effective Service Life;
- Potential changes to the consequence fo flooding as a result of the proposed development over the project's Effective Service Life; and
- The risk preference profile of the relevant project determining authority.

The following sections provide a mechanism through which a **new infrastructure or planning project** may include appropriate consideration of the above factors in the selection of Flood Design Standards. The mechanism, undertaken by the project developer/proponent, progresses through a three stage process:

1) Initial Project Evaluation;
2) Risk Assessment:
    a. Stationary Risk;
    b. Non-Stationary Risk; and
3) Application of Design Standard and Adaptation.

To facilitate this process it is important that the relevant approval authority has a strong understanding of their own risk profile as to what level of risk may be acceptable or tolerable, and what would be considered intolerable. As this may vary between authorities it is also the case then that required Flood Design Standards that the project developer/proponent must adhere to may also vary.

Guidance for approval authorities to determine their risk profile is provided in Section 6.1 and a flow chart outlining the mechanism for subsequently determining the appropriate Flood Design Standard is provided in Figure 6-1.

For developments which are focussed on **mitigation of flood impacts, protection or maintenance of existing infrastructure** it is recommended that an ALARP principle be adopted in determining the design level to be adopted.

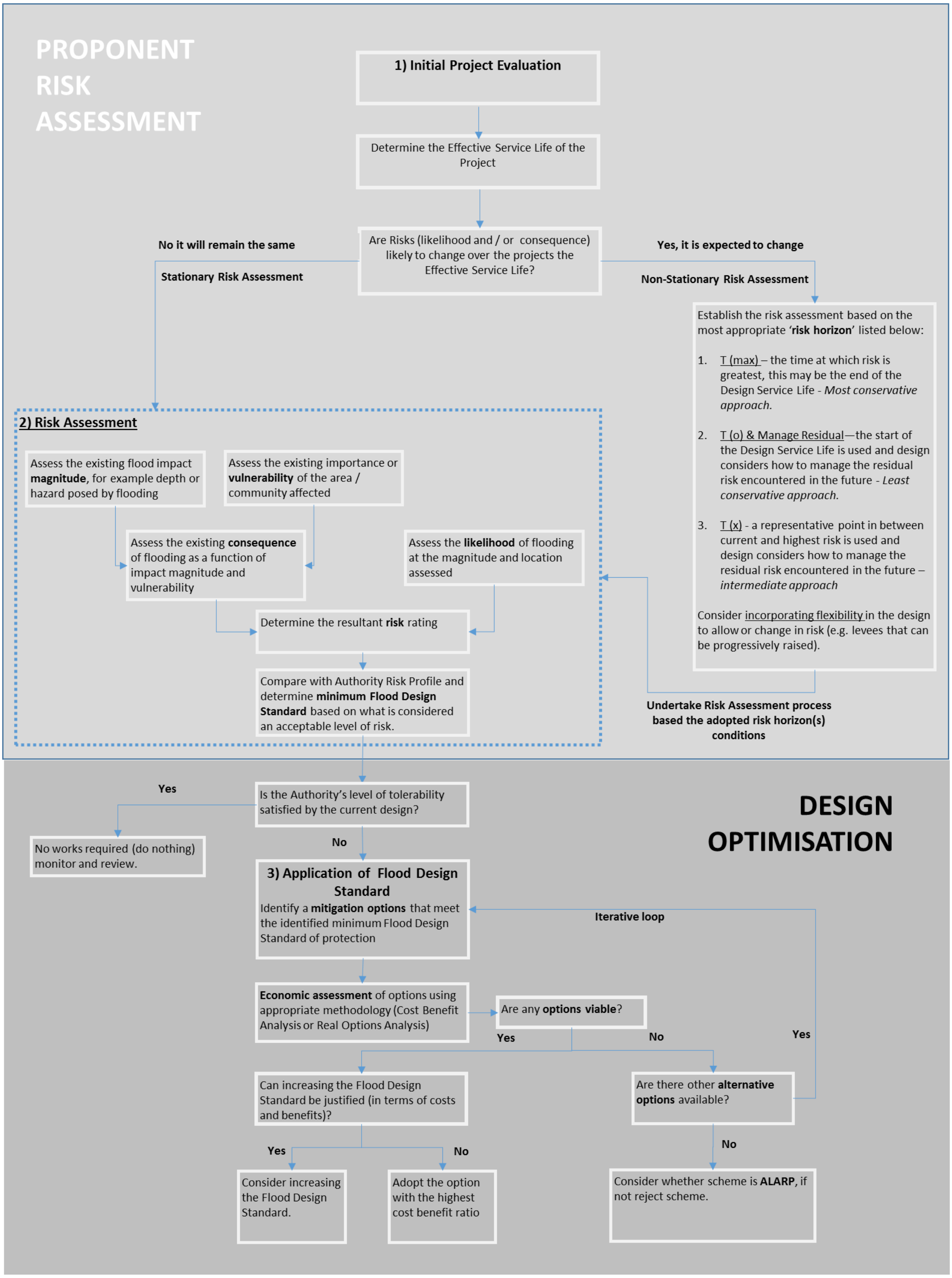


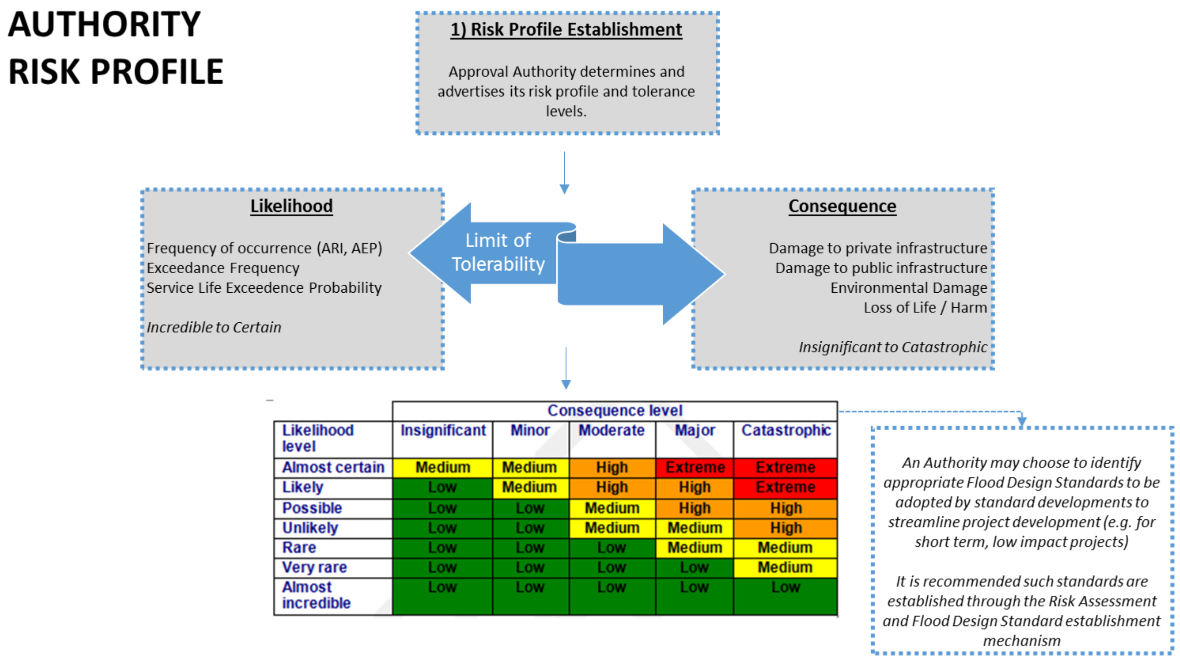
Figure 6-1 Flood Design Standard establishment mechanism

6.1. Authority Risk Profile

6.1.1. Why Authorities should establish a Standard Risk Profile

Risk is subjective in nature; what may be determined to be an appropriate level of flood protection to one agency may be considered to be overly cautious to another. Due to this subjectivity, it is useful for agencies (i.e. approval authorities) to determine a standard risk profile(s) that is appropriate based on their organisations specific responsibilities and objectives. This risk profile clearly defines what an authority determines to be acceptable, tolerable and unacceptable, allowing for greater transparency in decision making. Such a standard risk profile may be rolled out widely across various projects and should be used as the basis for project developers / proponents to select appropriate Flood Design Standards.

An authority may want to develop multiple profiles to provide more detailed guidance for specific project circumstances (e.g. short term risk profiles may be better expressed in terms of exceedence frequency than event likelihood). Similarly, they may want to separate out different types of consequence (e.g. a risk to life profile, an infrastructure damage profile) to enable more detailed consideration of key risks. Figure 6-2 outlines the process by which an agency may establish its standard risk profile and the following sections further detail this process.



Likelihood level	Consequence level: Insignificant	Minor	Moderate	Major	Catastrophic
Almost certain	Medium	Medium	High	Extreme	Extreme
Likely	Low	Medium	High	High	Extreme
Possible	Low	Low	Medium	High	High
Unlikely	Low	Low	Medium	Medium	High
Rare	Low	Low	Low	Medium	Medium
Very rare	Low	Low	Low	Low	Medium
Almost incredible	Low	Low	Low	Low	Low

Figure 6-2 Establishment of Authority Risk Profile

6.1.2. Expressing the Authority's Standard Risk Profile

If agencies accept / tolerate a broad range of risk likelihoods or risk consequences, they are classed as more 'risk accepting' than 'risk averse' agencies which tolerate a smaller range. Tables 6-1 and 6-2 demonstrate sample risk profiles and use AEP as measure of likelihood. Establishing a standard risk profile allows Authorities to express:

- The level of risk which results from a particular combination of likelihood and consequence; and
- What level of risk is determined to be acceptable, tolerable or intolerable.

Table 6-1 Example *risk averse* matrix (green = acceptable, yellow = tolerable, orange = intolerable)

Likelihood (AEP)	Consequence				
	Minimal	Minor	Moderate	Major	Catastrophic
0.1	Negligible	Negligible	Negligible	Low	Medium
0.5	Negligible	Negligible	Low	Medium	Medium
1	Negligible	Low	Low	Medium	High
10	Low	Low	Medium	High	High
20	Low	Medium	High	High	Extreme
50	Low	Medium	High	Extreme	Extreme
100	Medium	High	Extreme	Extreme	Extreme

Table 6-2 Example *risk accepting* matrix (green = acceptable, yellow = tolerable, orange = intolerable)

Likelihood (AEP)	Consequence				
	Minimal	Minor	Moderate	Major	Catastrophic
0.1	Negligible	Negligible	Negligible	Low	Low
0.5	Negligible	Negligible	Low	Low	Medium
1	Negligible	Negligible	Low	Medium	High
10	Negligible	Low	Medium	High	High
20	Low	Medium	High	High	High
50	Low	Medium	High	High	Extreme
100	Low	High	High	Extreme	Extreme

Consequence can be broken down into magnitude and sensitivity components to help determine overall consequence rating (Section 3.3.1). To provide developers with as much guidance as possible, Authorities can supply detailed information as to how consequences may be evaluated (e.g. can loss of life be assigned a dollar value?) and what impacts are considered tolerable / intolerable (e.g. is loss of life considered to be catastrophic and intolerable under all scenarios?). Table 6-3 provides an example of how risk profiles can be generated to separate out different types of risk.

Table 6-3 Example risk matrix of Damage to Infrastructure and Loss of Life

Likelihood (AEP)	ARI	Consequence						
		Damage to Infrastructure			Loss of Life			
		Roads Flooded	Roads & properties Flooded	Building floors flooded	Almost Incredible	Rare	Possible	Likely
0.01	10000	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable	Unacceptable
0.5	200	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable	Tolerable	Unacceptable
1	100	Acceptable	Tolerable	Unacceptable	Acceptable	Acceptable	Tolerable	Unacceptable
10	10	Tolerable	Unacceptable	Unacceptable	Acceptable	Tolerable	Unacceptable	Unacceptable
20	5	Unacceptable	Unacceptable	Unacceptable	Acceptable	Tolerable	Unacceptable	Unacceptable
50	2	Unacceptable	Unacceptable	Unacceptable	Acceptable	Tolerable	Unacceptable	Unacceptable
100	1	Unacceptable	Unacceptable	Unacceptable	Acceptable	Tolerable	Unacceptable	Unacceptable

Authorities may wish to generate specific service life based risk profiles if they prefer utilising an SLEP (Table 6-4) or Exceedence Frequency based approach. For example they may use Exceedence Frequency (i.e. number of exceedence events) in place of likelihood and generate a risk matrix and acceptability levels which could be applied for in evaluation of temporary / short term infrastructure. This report recommends that this approach to risk analysis is best practiced for short-term projects (i.e. those with an Effective Service Life of less than one-year). Beyond this, the use of annual occurrence frequencies may provide a more readily comprehendible approach to evaluation.

Table 6-4 Example risk matrix utilising Exceedance Frequency of Flood Design Standards
(green = acceptable, yellow = tolerable, orange = intolerable)

Service Life Exceedence Probability	Consequence				
	Minimal	Minor	Moderate	Major	Catastrophic
1%	Negligible	Negligible	Negligible	Low	Low
2%	Negligible	Negligible	Low	Low	Medium
5%	Negligible	Negligible	Low	Medium	High
10%	Low	Low	Medium	High	High
20%	Low	Medium	High	High	High
50%	Medium	Medium	High	High	Extreme
100%	High	High	High	Extreme	Extreme

The standard risk profile established by a determining Authority will form the basis of the risk appraisal to be adopted by the project developer/proponent (Figure 6.1) detailed in the following sections. A determining authority may wish to stipulate what level of risk is to be achieved for certain projects. Under the ALARP principles, this may include:

- Requiring all new developments to attain “acceptable” levels of risk;
- Requiring all modifications to new developments to attain “tolerable” levels of risk; or
- Require any projects with potential risk to life to obtain an “acceptable” levels of risk.

It is also noted that asset owners may develop their own risk profiles as the financial or corporate risks faced by the proponent of a project may differ to the economic risks faced by a determining authority. Where there is a difference in the perceived level of risk associated with a particular combination of likelihood and consequence, or what is considered tolerable / intolerable then the more conservative standard of tolerability would be adopted as the basis for determining Flood Design Standards.

The steps to be undertaken as part of determining the Flood Design Standards for a specific project will depend upon a Standard Risk Profile being prepared by the relevant authority. Details of how a Standard Risk Profile would be utilised by a project developer / proponent are provided below.

6.2. Stage 1 - Initial Project Evaluation

6.2.1. Overview of the Initial Project Evaluation

All projects, regardless of the likelihood and consequence of impacts should undertake a risk assessment of some form. The level of detail and technical support required as part of the risk assessment may vary between authorities depending on the characteristics of the project. The following sections detail a process and potential screening tools to streamline the risk assessment requirements that may be adopted.

The Initial Project Evaluation (IPE) determines whether the risk assessment to be undertaken should be a:

- Stationary Risk Assessment; or
- Non-Stationary Risk Assessment

Risk assessment can be undertaken assuming either stationary or non-stationary environment. In general, uncertainty in risk likelihood and consequence increases with the Effective Service Life (Section 6.2.2). As noted in Section 5.2, factors contributing to non-stationarity developing over time, include:

- Likelihood change:
    - Seasonality;
    - Climatic Variability;
    - Catchment or flood mechanism changes;
    - Evolving hydrological / hydraulic estimates;
    - Climate Change;
- Consequence change:
    - Land-use change;
    - Economic changes such as inflation; and

- Changes to the community exposed to risk (demographic shift, education, seasonality).

The rate at which these factors may change over time will differ between locations and projects. For example, the current rate of change in precipitation levels due to global warming may increase in some areas and decrease in others. Within Australia, the rate at which an average increase precipitation may occur (2 – 8% by 2090) (BoM, 2014) is sufficiently low that precipitation increases over the next 20 years are unlikely to result in flood risk profiles that significantly differ to the existing scenario. In contrast, a temporary project being undertaken in a tourist beach resort, may face significantly lower risks (e.g. risk to life) in winter than in summer.

In general, for medium to long term infrastructure (i.e. with Effective Service Life of greater than 5 years), it is suggested that:

- If the Effective Service Life is less than 20 years a Stationary Risk Assessment should be undertaken;
- If the Effective Service Life is greater than 20 years but less than 50 years it is recommended that a Non-Stationary Risk Assessment is undertaken, except in areas in which the likelihood of change in local and regional land uses is minimal; and
- If the Effective Service Life is greater than 50 years a Non-Stationary Risk Assessment should be undertaken.

For short-term infrastructure (<5 years) it is likely that a Stationary Risk Assessment would be required.

The above is a general guidance, and does not take into account project specific issues. For both short-term and long-term infrastructure it is recommended that an initial review be undertaken that evaluates whether or not changes in Likelihood and/or Consequence (as listed above) are likely to occur over the Effective Service Life of the project and considering whether such changes would impair the project's ability to perform its intended function.

It is also noted, that the scope of risk assessments (Section 6.3) should not unnecessarily burden themselves with future risks associated with catchment and land-use changes. For the majority of infrastructure, it is the responsibility of future developments affected by the original project to meet appropriate Flood Design Standards, not the responsibility of the original development. Exceptions to this include significant and / or planning related infrastructure (e.g. the development of a large dam which may significantly limit downstream development, or a flood levee that is intended to protect future development).

It is also recognised that an Authority may want to adapt the IPE process to assist in setting Flood Design Standards for projects that are considered of sufficiently low risk as not to warrant any form of risk assessment, based on project characteristics. Where an Authority wishes to adopt such a system, it is recommended that the Authority utilise a Stationary and/or Non-Stationary

Risk Assessment in determining its designated Flood Design Standards.

6.2.2. Determination of Effective Service Life

The Effective Service Life of a particular project may be difficult to estimate. However, it is noted that the following conditions are likely to potentially lead to the Effective Service Life extending past the Design Service Life:

- Magnitude of infrastructure – very large infrastructure projects are more likely to remain in place than smaller projects (e.g. bridges, dams);
- High decommissioning or replacement costs – where decommissioning or replacement costs are high there may be strong economic incentives to continue utilisation of the project (e.g. buried pipes within an urban environment); or
- Integrated development – where the project forms part of a broader piece of infrastructure or on-going service there may be economic incentives to continue utilisation of the project, particularly where a change to one component would require a change to others (e.g. road alignment – a road may be reconstructed/ rehabilitated over time, but due to other constraints, will not be able to be changed in terms of elevation or geometry).

Determining the Effective Service Life of infrastructure is complex as it is a product of infrastructure design, materials, environment, maintenance and rehabilitation regime and use. For example, exposed infrastructure (eg. roads) typically has a lower service life in tropical climates than in sub-tropical climates. Similarly, pipes that lie below a water table typically have shorter service lives than pipes that lie above a water table. The rate of degradation of construction material (e.g. metal, plastic pipes) will also vary with circumstance (e.g. saline vs non-saline conditions). Maintenance and rehabilitation of infrastructure may also seek to extend a project's expected service life (for example, a lining installed in a stormwater pipe). Table 6-5 summarises some of the typical life expectancies (and range in life expectancies) for various infrastructure types.

Table 6-5 Infrastructure types and potential Effective Service Life[1]

Infrastructure	**Effective Service Life expectancy**
Water Treatment Plants	20 - 50 years
Concrete Kerb and Gutters	40 - 70 years
Stormwater Pipes	80 -100 years
Wastewater Systems	50 – 80 years
Residential buildings	40 - 95 years
Roads	35 -110 years
Commercial buildings	15 -150 years
Open stormwater channels	10 – 100 years

[1] Data represents a synthesis and interpretation of a number of reports including: IPART (2012), Cardno (2014), USEPA (2014), International Transport Forum (2013), Tonkin (2009).

Locks and Weirs	40 – 200 years
Dams	50 – 500 years

As can be seen from Table 6-5 the range within and between infrastructure is high. Within Australia, data for long-lived assets is limited to determine as much infrastructure has not yet reached its design life. It is recommended that, in determining the likely Effective Service Life, a project owner should use a standard Design Service Life of the asset as a starting point and then seek to contextualise these estimates through consultation with local Authorities and comparison with other similar infrastructure.

6.3. Stage 2 – Risk Assessment

This section details the process to be followed for Stationary or Non-Stationary risk assessments as determined by the IPE.

6.3.1. Stationary Risk Assessment

Stationary risk assessments assume there will be no change in the likelihood or consequence of flood events over the Effective Service Life of a project. The likelihood and consequence of the risk horizon year are calculated and considered to persist throughout the Effective Service Life.

Consequence and likelihood can be estimated quantitatively or qualitatively (Section 3.3). It is recommended that for short term projects or projects in which the perceived risk of flooding impacts is evidently negligible a qualitative risk assessment is undertaken. However, where possible, quantitative metrics are encouraged to be utilised.

The estimated consequences, for each likelihood, are then estimated and compared with the Authority risk profile.

Where evaluated consequence is greater than the maximum acceptable (or tolerable) level identified, then any development should adopt a Flood Design Standard (or alternative management measure) that results in an improvement to the consequences associated with event likelihood (e.g. that given ARI event). These may act as initial flood-related design requirements to be considered in establishing a preliminary project design. The preliminary project design should also consider design elements related to:

- Purpose of the project;
- Initial flood-related design requirements;
- Potential for non-infrastructure based methods to lower consequence (e.g. emergency response plans);
- Consequences of failure; and
- Potential for cost of upgrade or adaptation in regards to flooding.

Once a project design has been firmly established it is recommended that the risk assessment is re-run to confirm that it suits the relevant Authority's Standard Risk Profile.

The decision as to how best meet Flood Design Standards should be informed through economic assessment of potential design options (Section 6.4). A worked example of this process is provided in Section 7.

6.3.2. Non-Stationary Risk Assessment

Where a non-stationary risk assessment is identified by the IPE as required a similar process to that identified above should be undertaken. However, the non-stationary nature of the risks present will influence the design horizon over which the assessment is undertaken. Primarily there are three approaches able to be adopted:

1) **Undertake risk assessment based on the existing environment (T_0) and commit to managing residual risk as it arises:** This approach will require periodic reassessment of risks associated with the project at agreed points in time (e.g. re-evaluation of risks every 10 years may be considered appropriate). This approach may lead to under-engineering towards the end of the re-evaluation period and is considered the least conservative approach (Figure 6-3).
2) **Undertake risk assessment at the point in time of highest overall risk (T_{max})**: Typically, this may be at the end of the project's Effective Service Life, assuming risks are increasing over time. By applying the risk assessment process detailed in Section 6.4.1 at T_{max}, and determining appropriate design criteria for this point, the proponent will effectively design its infrastructure to be acceptable at all points of its Effective Service Life. This is considered to be the most conservative approach and will lead to relative over-engineering of infrastructure at some points of its life (Figure 6-4).
3) **Undertake risk assessment at a representative point in the projects Effective Service Life (T_x) and commit to managing residual** : This approach will likely lead to over-engineering in the initial (pre – T_x) period, after which it will require periodic reassessment of risks associate with the project at agreed points in time. This approach is a hybrid of approaches 1) and 2) (Figure 6-5).

These three approaches typically assume that the Authority's standard risk profile (which reflects views as to what is acceptable / tolerable / intolerable) does not change over time. However, approaches 2 and 3 do also allow for changes in an approval Authority's standard risk profile to be incorporated at periodic reassessment.

An important component of Non-Stationary Risk Assessment is the identification of an Authority's Limit of Tolerability (LoT). The LoT will define the relationship between consequences and the frequency at which they may arise. If the LoT is able to be established by an Authority for a range of potential consequences (e.g. loss of life, damage to residential property), then based on anticipated rate of change in the likelihood or consequence of flood events over time, it may be possible to approximate the time at which the LoT will be exceeded for any one consequence. Beyond this point, flooding in association with a given project, would be considered to generate unacceptable consequences. Such turning points may be utilised as points at which management measures or infrastructure adaptations are implemented under approaches 2 or 3.

For example, a project is designed within the acceptable range under existing conditions. In 10 years it will move into the tolerable range due to non-stationary factors, and then into the unacceptable range in 20 years (Figure 6-3). This could then serve as the trigger point for modification to the infrastructure to bring it back to the tolerable or acceptable range.

Section 6.5 discusses how a project may determine which approach to utilise.

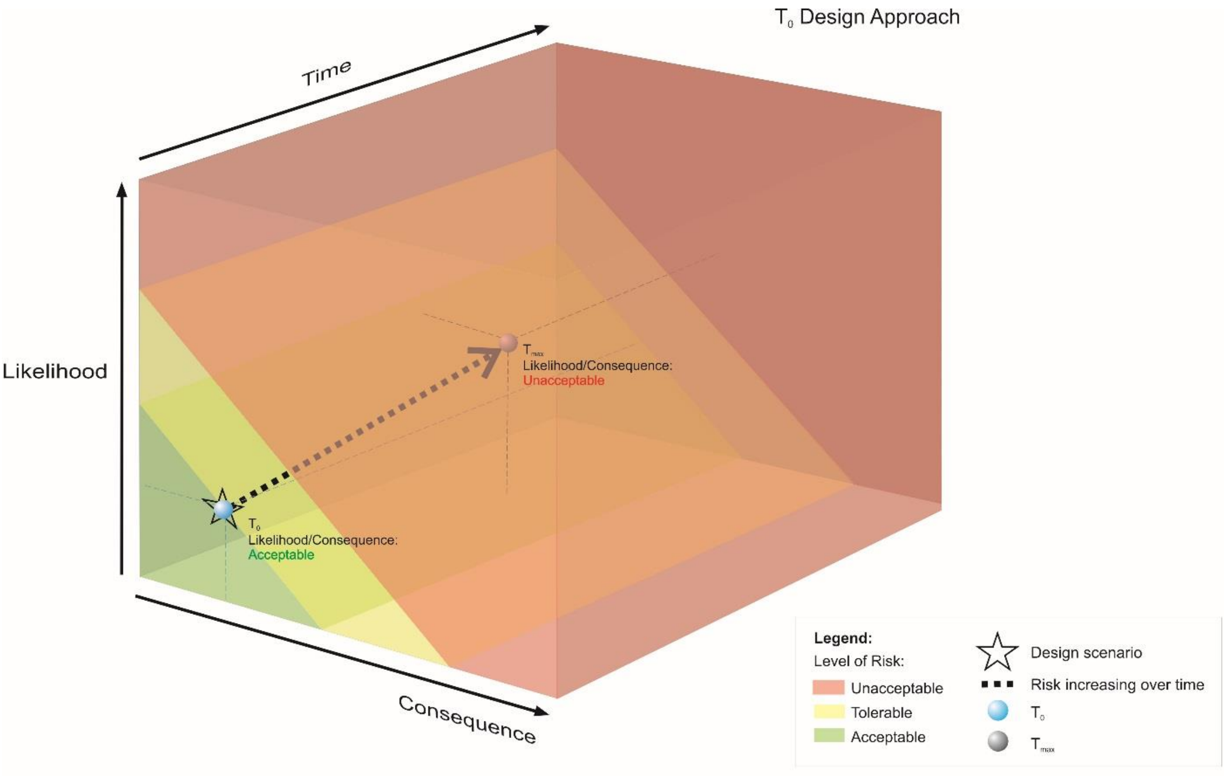


Figure 6-3 Change in realised risk from adopting a T0 design approach

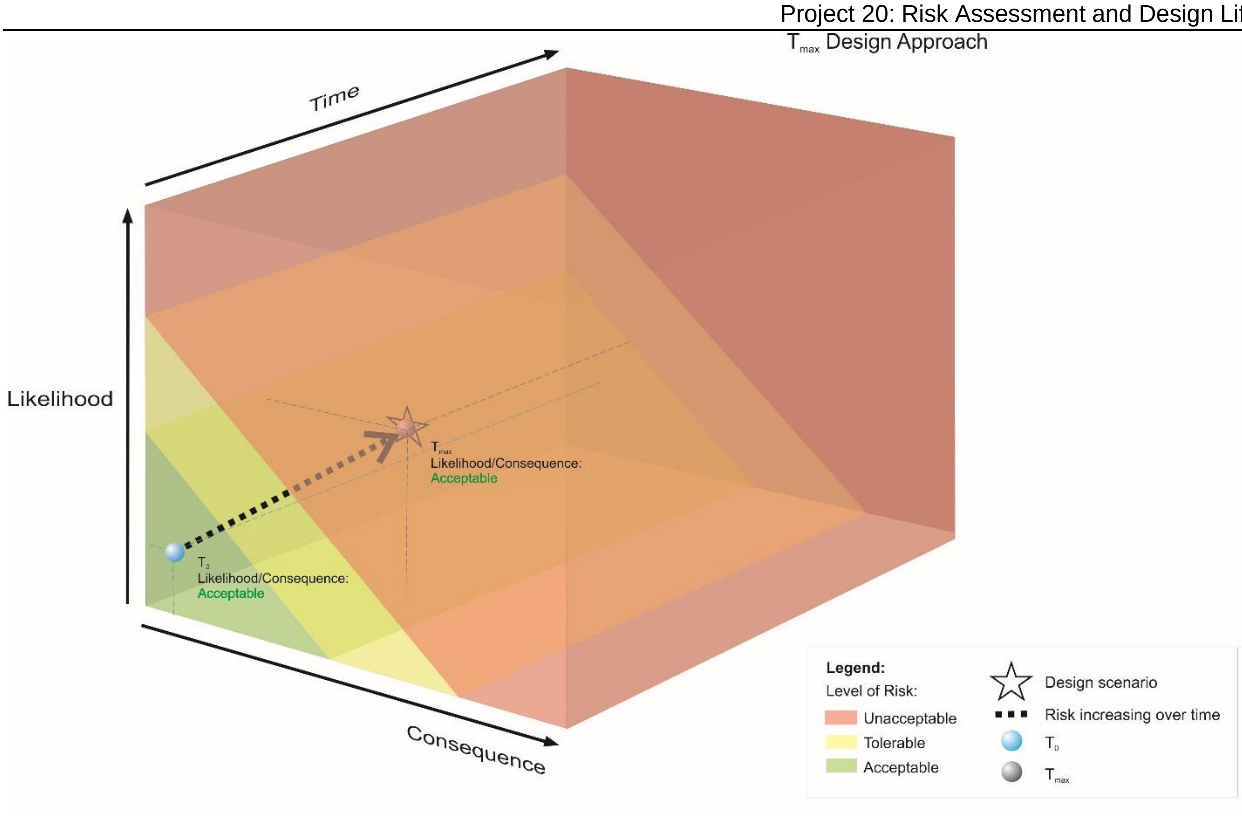


Figure 6-4 Change in realised risk from adopting a Tmax design approach

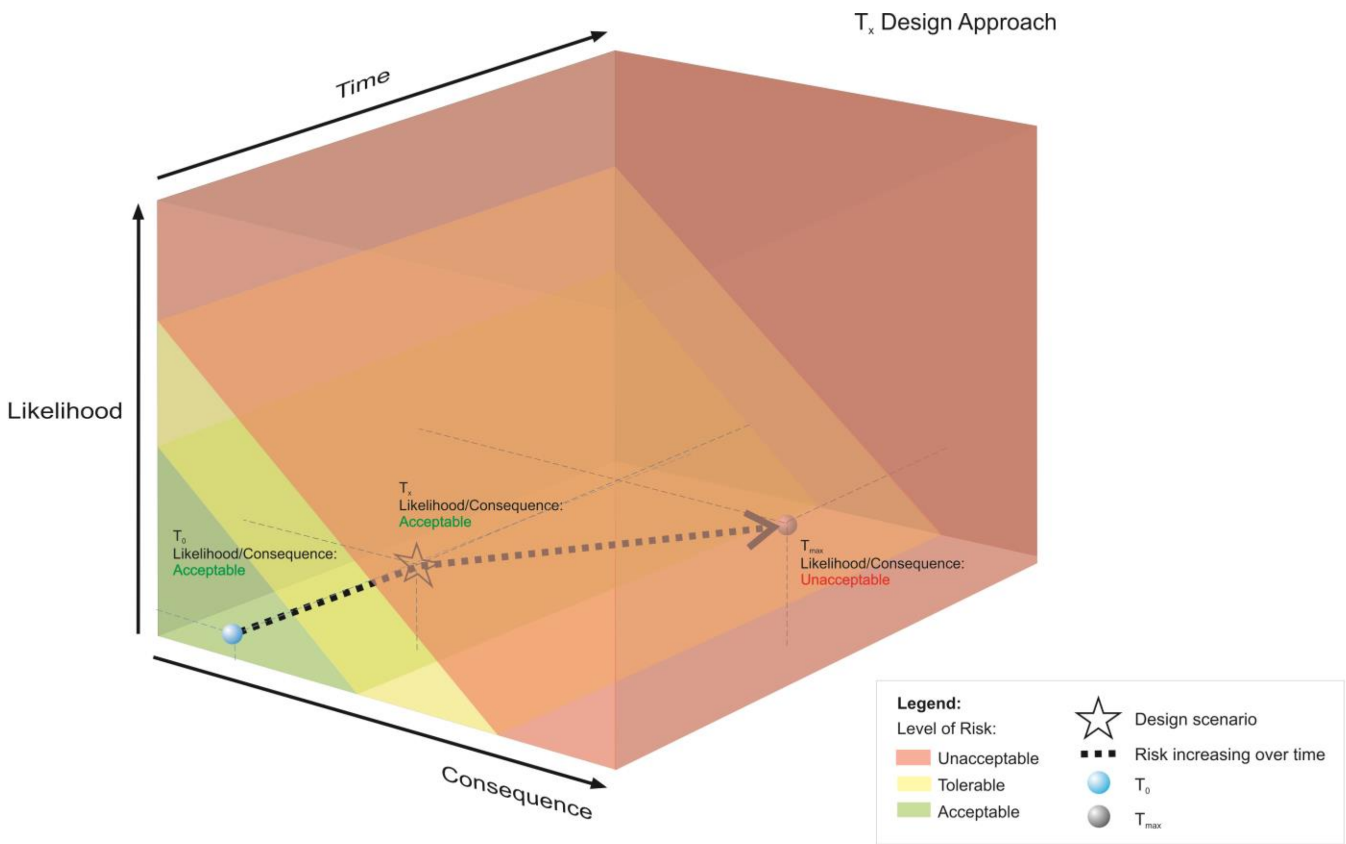


Figure 6-5 Change in realised risk from adopting a T_x design approach

6.4. Stage 3 – Application of Design Standard and Adaptation

The risk assessment process outlined in Sections 6.3 and 6.4 will identify appropriate Flood Design Standards consistent with an approval Authority's, and/or the proponent's, risk profile. However, in both stationary and non-stationary environments the options by which an acceptable level of risk can be achieved may be numerous. It is recommended that economic analyses be undertaken to determine the preferred approach.

6.4.1. Economic Analysis in Stationary Risk Assessment

In a stationary environment, the risk present at the start of the project will be the same as the risks present at the end of the project's Effective Service Life. As such, the Flood Design Standards to be met will also remain constant.

Design options provided to achieve these criteria are best assessed through comparative Cost Benefit Analysis (CBA) of the identified options. Based on the comparative present costs and benefits associated with the options (it is possible the certain options may provide additional benefits to the project beyond flood protection), standard economic measures of Net Present Value, Benefit Cost Ratio (BCR), Internal Rate of Return, etc. can be determined.

Typically the value with greatest BCR is likely to be identified as the preferred option. Where no options are seen to be economically viable (i.e. BCR < 1), it should be assessed whether:

- There are further alternatives available;
- The scope of the economic analysis is sufficient to determine overall project viability; and
- The Flood Design Standards are consistent with ALARP.

It is recommended that a sensitivity analysis on the CBA is also undertaken, looking at the potential for changes in key variables to affect the BCR outcome. Specifically, sensitivity analysis should consider increasing the level of flood protection afforded (and any associated costs) to determine whether there are net benefits gained from adopting higher than necessary Flood Design Standards or whether the Flood Design Standard may be lowered based on provision of more effective risk management measures. This may be beneficial in circumstances where there is uncertainty in estimating a project's Effective Service Life. Similarly, although adaptability is typically not required within stationary risk environments, where there is uncertainty regarding Effective Service Life, the CBA options analysis could consider options which incorporate elements of adaptability. To minimise assessment and evaluation costs for less complex projects, authorities may simply require adherence solely to the initially identified Flood Design Standards; any CBA undertaken would then be solely for the purpose of the proponent to aid in identification of preferred design options.

6.4.2. Economic Analysis in Non-Stationary Risk Assessment

The introduction of non-stationary risk significantly alters the decision making process regarding selection of project Flood Design Standards and, consequently, selection of appropriate project options.

Section 6.4.2 outlines three broad approached to non-stationarity (T_{max}, T_0 and T_x). All three of these revolve around the choice between conservatively over-engineering to ensure risk levels are satisfied, against programs of continuous upgrades in which changes in risk are responded to through adaptation in design.

In general the T_{max} approach may be identified as the preferred approach where:

- The magnitude of change in risk is well known and likely to be small;
- A project's Effective Service Life is certain;
- The costs of over-engineering are low; or
- The potential for retro-fitting / incorporating adaptability is low.

In contrast, The T_0 and T_x approaches are more likely to be favourable where:

- The potential change is risk is high or uncertain;
- The projects Effective Service Life is uncertain;
- The costs of over-engineering are high; or
- The potential for incorporating adaptability is high.

It is noted that any option based around the future upgrade of infrastructure poses potential legal and commercial risks to both proponents and approval Authorities. Given the extent of timeframe over which the infrastructure may be in place, the responsibility (and cost) of re-evaluation and upgrade in the future may change between individuals and there is the potential that the decision to upgrade at that time is not viable. In such circumstances the project may be decommissioned (these costs should be considered in any economic analysis).

A potential framework by which the appropriate approach (and design options) can be determined is through use of Real Options Analysis (ROA) (Section 6.4.2.1). Where ROA is not applicable, it is recommended that standard CBA evaluation of options, incorporating variable option implementation timing is adopted (i.e. run CBA scenarios in which the project is developed in different phases over time). For example, if we pay to construct a levy now to protect against climate change, then the cost is incurred in the present, but no real benefit may be realised for twenty years, when climate change has a measurable effect. When the time value of money is considered in this scenario, it may be worth not investing in the levy until twenty years have passed. A CBA analysis could assess a range of scenarios (including staged scenarios) that capture this changing nature of costs and benefits over time.

6.4.2.1. Real Options Analysis

ROA is a recognised approach to address the uncertainties of future conditions in flood risk management by accounting for flexibility in investment decision (World Bank, 2010; Short et al. 2012; Park et al. 2014, HM Treasury & DEFRA, 2009). The standard CBA approach is a relatively coarse mechanism in which costs and benefits assessed are considered as a whole and do not allow for discernment of the manner in which they accrue (e.g. changes in the rate at which benefits are received may not justify development of all project components as part of initial project construction). Neither does the analysis recognise that estimates of cost, benefit and risk into the future are inherently uncertain. As such, deferring decisions on infrastructure investment until a later date when more information is available may be the preferred approach. ROA allows the value of deferring investment decisions to be assessed.

In ROA, “options” represent predefined choices over a project’s Effective Service Life that strategically or operationally affects the course of the project. For example, a project may be to build a levy. If we build the levy in such a way that it is possible for it to be upgraded at a later date, a Real Option may be to increase levy height by 0.5m. The analysis defines decision points at which these choices are made (e.g. T_x). The decision points can be points may be fixed in time or variable and triggered by internal or external events (e.g. occurrence of a 1% AEP event). Based on the Black-Scholes model utilised in financial options analysis, ROA utilises estimates of volatility (i.e. the likelihood of a particular flood event or level of damage occurring in one year) to evaluate expected values/damages that are likely to be incurred over the Effective Service Life. The establishment of appropriate volatility measures is critical to ROA, and not all systems will have readily discernible volatilities.

For example, a flood levy may be required and it is known that currently it needs to be built to a 20% AEP in order to maintain an acceptable level of risk. However, it is also forecast that due to climate change, over 50 years, the magnitude of the 20% AEP event will be equivalent to the magnitude of the current 10% AEP event and that levy would need to be increased by one metre height to provide the same level of risk. Assume, also that the volatility is such that there was 50% chance that the cost of flooding would increase by 5% per year and a 50% chance that the cost of flooding would increase by 1% per year. Utilising a numerical method for the pricing of options (e.g. the Binomial Method, Black-Scholes Model), and based on this volatility year on year, it would be possible to estimate the value of implementing an option in a given year (i.e. the value of waiting to make a decision on investing until more information is available). For example, if it turns out that by year 10 that there have been 10 consecutive 5% increases, then the benefits of increasing the height of the levy at that point will be significantly greater than if there had been 10 consecutive 1% increases per year.

Other common decision-under-uncertainty making tools which may be utilised include Laplace’s Principle of Insufficient Reason or Walds Maximin Model.

7. Case Study

7.1. Case Study 1 – Construction

Smart Developments intends to build a large shopping centre complex. As part of the construction, a basement and foundations will result in an excavated pit during construction. The construction site is located within the floodplain of the Snake River and is part of the Greater Cobra Council Local Government Area. Once completed, the resulting development and basement will be protected against flooding. However, during construction, if flooding occurs, then the excavated basement will be inundated, resulting in a risk to life and construction equipment.

Key information about the development:

- The construction period for the basement will last for approximately 6 months;
- It is estimated that the basement will be inundated in a 2 year ARI and larger;
- The river rises rapidly, with the inundation of the basement expected to occur within 5 hours of the start of rainfall;
- At any time of the day during construction, there will be equipment that is estimated to be around $1 million in value in the excavated area; and
- For 10 hours every day, there will be around 10 people working in the excavated area during construction.

7.1.1. Authority Risk Profile

Cobra Council has derived an acceptable risk profile for developments. This risk profile is provided in the following table.

The Cobra Council Risk Profile economic factors focus on impacts to residential developments, and not to construction economic costs.

In addition, Smart Developments have their construction insurance with Happy Insurance Ltd. Happy Insurance Ltd have a simple risk profile, where damages will be covered up to $1 million for events larger than a 5 year ARI.

Table 7-1 Cobra Council Risk Profile

Likelihood (AEP)	ARI	Consequence						
		Economic Damage			Loss of Life			
		Roads Flooded	Roads & properties Flooded	Building floors flooded	Almost Incredible	Rare	Possible	Likely
0.01	10000	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable	Unacceptable
0.5	200	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable	Tolerable	Unacceptable
1	100	Acceptable	Tolerable	Unacceptable	Acceptable	Acceptable	Tolerable	Unacceptable
10	10	Tolerable	Unacceptable	Unacceptable	Acceptable	Tolerable	Unacceptable	Unacceptable
20	5	Unacceptable	Unacceptable	Unacceptable	Acceptable	Tolerable	Unacceptable	Unacceptable
50	2	Unacceptable	Unacceptable	Unacceptable	Acceptable	Tolerable	Unacceptable	Unacceptable
100	1	Unacceptable	Unacceptable	Unacceptable	Acceptable	Tolerable	Unacceptable	Unacceptable

7.1.2. Initial Project Evaluation

Effective Service Life

The effective service life is estimated as 6 months, based on the period of construction.

IPE

With the Effective Service Life of 6 months, and that the consequences relate to construction activities, a stationary risk assessment has been identified as appropriate.

7.1.3. Stationary Risk Assessment

The analysis by Smart Developments suggest that the construction area is likely to be inundated in a 2 year ARI. This inundation will represent a likely loss of life due to the 10 construction personnel in the excavation area. In addition, it is estimated that around $1 million in construction equipment would be damaged.

The likelihood that a 2 year ARI would occur over the 6 month effective life is in the order of 25 to 30%. Based on the risk profile provided above in Section 7.1.1, this can be conservatively rounded to a 20% AEP.

At this level, a likely loss of life is not acceptable based on Cobra Council's risk profile. Furthermore, the damages to the construction equipment exceed the risk profile of Happy Insurance Ltd.

7.1.4. Application of Flood Design Standard

Based on the above analysis, the proposed construction is not acceptable. Therefore, design solutions are required in order to meet the risk profiles for both Cobra Council and Happy Insurance Ltd.

There are two alternative design options that the company are considering:

- Option 1 - Construction of a levee around the excavation, with a flood level protection of 10 year ARI

- Option 2 - Construction of a levee around the excavation at the 10 year ARI. Development of a flood evacuation plan and flood warning system that will allow for the construction team to evacuate safely.

Under Option 1, the risk to life is reduced to occurring only during a 10 year ARI. This has a probability of around a 5% chance of occurring during the 6 month effective design life. Based on Cobra Council's risk profile, this is still an unacceptable risk to life.

Under Option 2, an evacuation plan is put in place that will minimize the risk to life for construction personnel. It is estimated that during a 10 year ARI event, the likely loss of life for construction personnel would be rare. The chance of a 10 year ARI event occurring during the 6 month effective life is approximately 5%. At this probability, Cobra Council's risk profile is that this is tolerable.

Based on this assessment, Smart Developments adopts Option 2. However, following an economic assessment they identify that the additional cost for achieving a 20 year ARI levee is minimal in comparison to the benefits and reduction in risk to life. Therefore, they adopt Option 2 with a 20 year flood levee to provide additional protection.

7.2. Case Study 2 – Stormwater Policy

Diamond Council is reviewing their stormwater policy, and in particular the drainage capacity for new developments. Their current policy is:

- Minor drainage – 5 year ARI; and
- Major drainage – 100 year ARI.

The effect of their current policy is that all stormwater is conveyed in drainage systems up to the 5 year ARI, with minimal impact on the community. Above the 5 year ARI and up to the 100 year ARI, overland flows are conveyed along roads and parks. The policy ensures that this does not impact on properties, but results in some minor damages to vehicles. The current policy requires that overland flows are low hazard, and therefore the risk to life from overland flows is low.

Diamond Council decide to undertake a risk assessment across the entire LGA, to allow them to determine appropriate design standards and simplify the process for developments.

7.2.1. Authority Risk Profile

Diamond Council has previously established a risk profile for flooding and drainage. This risk profile is provided below.

Table 7-2 Diamond Council Risk Profile

Likelihood (AEP)	ARI	Consequence						
		Economic Damage			Loss of Life			
		Roads Flooded	Roads & properties Flooded	Building floors flooded	Almost Incredible	Rare	Possible	Likely
0.01	10000	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable	Unacceptable
0.5	200	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable	Tolerable	Unacceptable
1	100	Acceptable	Tolerable	Unacceptable	Acceptable	Acceptable	Tolerable	Unacceptable
10	10	Acceptable	Unacceptable	Unacceptable	Acceptable	Tolerable	Unacceptable	Unacceptable
20	5	Tolerable	Unacceptable	Unacceptable	Acceptable	Tolerable	Unacceptable	Unacceptable
50	2	Unacceptable	Unacceptable	Unacceptable	Acceptable	Tolerable	Unacceptable	Unacceptable
100	1	Unacceptable	Unacceptable	Unacceptable	Acceptable	Tolerable	Unacceptable	Unacceptable

7.2.2. Initial Project Evaluation

The proposed policy will apply to new developments, and in particular, the stormwater drainage infrastructure. The design life for the majority of the stormwater structure is in the order of 50 years. However, a review of Council's existing stormwater infrastructure suggest that the effective service life is generally much longer, with some of the existing stormwater pipes being in the ground for longer than 100 years.

Based on this, Council estimates that the effective service life of any stormwater infrastructure is in the order of 100 years.

Based on this long Effective Service Life, Diamond Council identifies the need for a non-stationary risk assessment.

7.2.3. Risk Assessment

T(0) Risk Assessment

A risk assessment has been undertaken based on existing conditions by Council for their current policy. The results of this assessment are represented in graphical form in the following. As identified, their current policy identifies that the policy meets with the current profile.

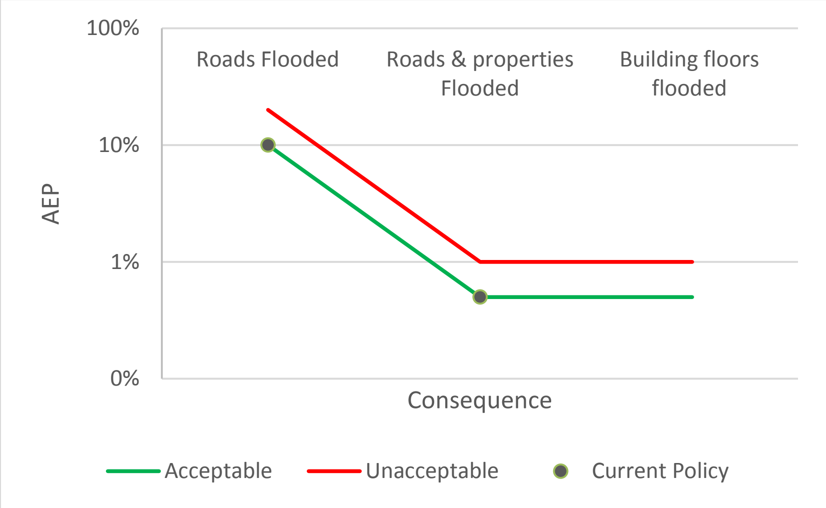


Figure 7-1 T(0) Risk Assessment

T(max) Risk Assessment

An assessment of climate change by Diamond Council suggests the following:

- The current 5 year ARI will be equivalent to roughly a 2 year ARI in 2100; and
- The currently 100 year ARI will be equivalent to a 200 year ARI in 2100.

The stormwater policy applies to new developments. Council's planners have advised that within the next 100 years, it is not expected that any new developments will significantly increase in density. Therefore, the only change to the risk profile is through the change in likelihood.

An assessment of their policy, in comparison with their risk profile, for 2100 is provided in Figure 7-2. It identifies that in 2100, stormwater infrastructure that is built under current conditions will not be acceptable in terms of both road flooding and also inundation of properties. Furthermore, as it is likely that the stormwater infrastructure may be in existence for potentially beyond 2100, this is expected to extend further into the unacceptable range.

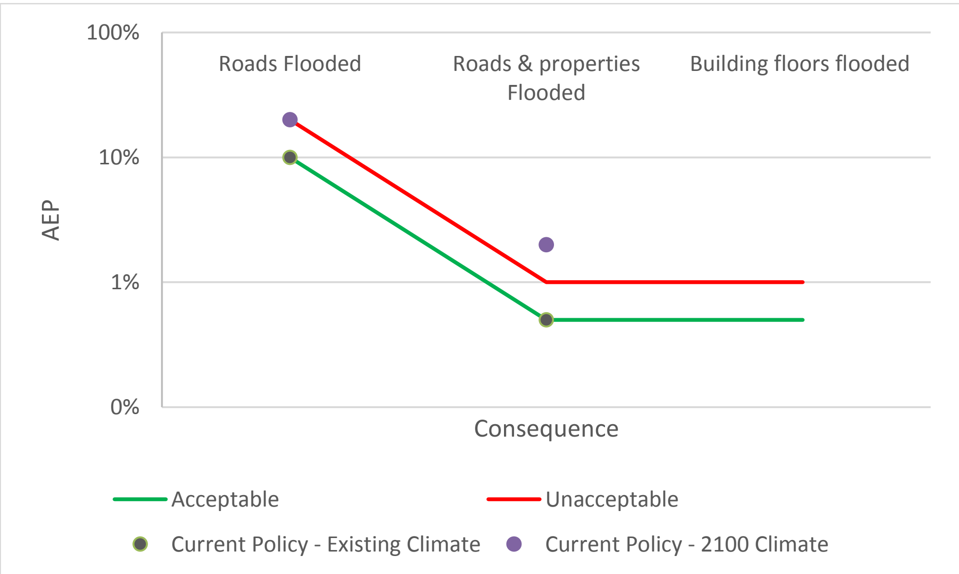


Figure 7-2 T(max) Risk Assessment

7.2.4. Design Standard

Council have reviewed the options that are available to them. The existing policy is unacceptable to them because stormwater infrastructure will not be within the acceptable range on their risk profile for very long during the effective service life. Some initial estimates, based on current projections of climate change, suggest that the stormwater infrastructure under the policy will reach the unacceptable range by around 2050. With an effective service life greater than 100 years, a large part of the effective service life will be within the unacceptable range.

Council therefore chooses to modify their stormwater policy. The policy adopts the following:

- Design for the 2050 climate predictions at present, but ensure that the infrastructure is designed to allow adaptability in the future to accommodate the expected increases in flow. This adaptability will need to be demonstrated in the design; or
- Design for the 2100 climate predictions at present.

While the effective service life may extend beyond 2100, Council believes that the residual risk is suitably small.

In order to ensure that the policy is appropriately updated, a review has been allowed for every 5 years.

7.3. Case Study 3 – Sub-division

TopLand Developers are undertaking a 1000 lot subdivision adjacent to the existing township of Star. Star itself has a history of flooding from the River Styx, and a number of years ago constructed a ring levee at a 100 year ARI level to protect the town from flooding. However, the proposed development is outside the protection of this ring levee.

The proposed land for development, currently farmland, is higher in elevation than Star Township and is inundated in events greater than the 100 year ARI. However, modelling of the 2100 climate change scenario suggests that flooding will be nearly 1 metre deep in the 100 year ARI, which will result in overfloor flooding in most of the dwellings and a risk to life from difficulties with evacuation.

7.3.1. Authority Risk Profile

Star Council has previously established a risk profile for flooding and drainage. This risk profile is provided below.

Table 7-3 Diamond Council Risk Profile

Likelihood (AEP)	ARI	Consequence						
		Economic Damage			Loss of Life			
		Roads Flooded	Roads & properties Flooded	Building floors flooded	Almost Incredible	Rare	Possible	Likely
0.01	10000	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable	Unacceptable
0.5	200	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable	Tolerable	Unacceptable
1	100	Acceptable	Tolerable	Unacceptable	Acceptable	Acceptable	Tolerable	Unacceptable
10	10	Acceptable	Unacceptable	Unacceptable	Acceptable	Tolerable	Unacceptable	Unacceptable
20	5	Tolerable	Unacceptable	Unacceptable	Acceptable	Tolerable	Unacceptable	Unacceptable
50	2	Unacceptable	Unacceptable	Unacceptable	Acceptable	Tolerable	Unacceptable	Unacceptable
100	1	Unacceptable	Unacceptable	Unacceptable	Acceptable	Tolerable	Unacceptable	Unacceptable

7.3.2. Effective Life

Following approval of the sub-division, development is expected to occur over an approximate 10 year period. Topland Developers will construct the road and services for the development in a staged release, and then on-sell the land for development by individuals. The final houses are not expected to be built until after 10 years.

The houses themselves are built with a design life of 50 years. However, in reality, based on other similar developments in the area, it is expected that the effective life will be closer to 80 years. Together with the construction and development period, this leads to a time horizon in the order of 90 years.

A non-stationary analysis has been adopted, as:

- Climate change is expected to be relatively significant over effective service life;
- During the first 10 years of the project, there will be a significant change in the land-use as properties are developed.

7.3.3. Risk Assessment

TopLand Developers and Star Council agree to base the land-use on the houses that will be present at the end of the construction and development period (i.e. 10 years). Within that period, it is not expected that climate change will be significant for the area.

As the land gradually rises away from the floodwaters, Topland has established a flood evacuation plan and ensured that there is rising road access to appropriate shelter, and hence the key consideration is economic damage to structures.

With the much larger flooding expected in 2100, TopLand Developers wants to investigate two alternatives:

1. Construction of a levee at the 2100 1% AEP flood level. 2100 represents the approximate

overall effective service life period, and hence this is a T(max) approach.

2. Construction of a levee at the 2060 1% AEP level, and then managing the risk past that point. This levee is approximately 0.5 metres lower than the scenario 1 levee. This represents a T(x) approach.

Under Scenario 1, all properties are protected throughout their effective service life up to the 1% AEP event. Based on Council's risk profile, this design meets the risk profile throughout its effective service life.

Under scenario 2, all properties are protected to the 1% AEP level up to 2060. Additional modelling that has been undertaken identifies that:

- by 2080, overtopping of the levee in the 1% AEP will cause inundation of roads and property, but no overtopping of floor levels within the development. This is identified as tolerable in Council's risk profile;
- by 2100, overtopping of the levee in the 1% AEP will cause inundation of roads and property, together with overtopping of floor levels within the developments. This is identified as unacceptable in Council's risk profile.

7.3.4. Design Standard

Following a review and further discussion with Council, TopLand Developers decide to adopt Scenario 2. A levee will be constructed that allows for retrofitting in the future to increase the height of the levee by 0.5 metres in the future.

Based on the analysis, it is expected that the levee will not need to be upgraded until around 2080, when the level of protection goes beyond Council's level of tolerability. However, given the uncertainties of climate change, TopLand and Council decide to use this as a trigger level more than a specific date.

8. References

ANCOLD (Australian National Committee on Large Dams Incorporated), 2000 - Guidelines for Selection of Acceptable Flood Capacity for Dams

Aubrecht, Freire, Neuhold, Curtis and Steinnocher, 2012 - Introducing a Temporal Component in Spatial Vulnerability Analysis http://www.researchgate.net/profile/Christoph_Aubrecht/publication/231179667_Introducing_a_temporal_component_in_spatial_vulnerability_analysis/links/0c9605178db1f0b2ae000000

Australian Greenhouse Office (Department of the Environment and Heritage), 2006 - Climate Change Impacts & Risk Management A Guide for Business and Government http://www.climatechange.gov.au/sites/climatechange/files/documents/03_2013/risk-management.pdf

AUSTROADS, 1994 - Waterway Design, A Guide to the Hydraulic Design of Bridges, Culverts and Floodways

Cardno, 2014 – Efficiency Review of Murray Operations capital and operating expenditure. Prepared on behalf of the Commonwealth Department of Environment

CSIRO (Commonwealth Scientific and Industrial Research Organisation), 2000 – Floodplain Management in Australia: Best Practice Principles and Guidelines

CSIRO and Australian Bureau of Meteorology, 2014, Climate Change in Australia, Technical Report. Melbourne Australia, October 1014.

DEPI (Department of Environment and Primary Industries formerly known as Department of Sustainability and Environment) 2012 - Guidance Note on Dam Safety Decision Principles

https://www.google.com.au/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0CB8QFjAA&url=http%3A%2F%2Fwww.depi.vic.gov.au%2F__data%2Fassets%2Fpdf_file%2F0006%2F176946%2FFINAL-Guidance-Note-4-June2012.pdf&ei=enaTVKGEIeS4mwWqj4KYDw&usg=AFQjCNHT4Q8o2X3FjZdGFX9pDqjXB4rWIg&sig2=SV_mh4OZ6UqT8w2dnHdqNA&bvm=bv.82001339,d.dGY

DPWH (Department of Public Works and Highways), 2002 - Technical Standards and Guidelines for Planning and Design Volume 1 Flood Control

http://www.jica.go.jp/project/philippines/0600933/04/pdf/Technical_Standards_and_Guidelines_for_Planning_and_Design.pdf

Emergency Management Australia, 2002 - Disaster Loss Assessment Guidelines: Australian

Emergency Manuals Series (Manual 27, Part III - Emergency Management Practice Volume 3 Guidelines Guide 11)

http://www.em.gov.au/Documents/Manual27-DisasterLossAssessmentGuidelines.pdf

Emergency Management Australia, 2004 - Emergency Risk Management – Applications Guide (Emergency Management Practice, Manual 5)

https://www.em.gov.au/Documents/Manual%2005-ApplicationsGuide.pdf

Environment Agency, 2010 - Flood and Coastal Erosion Risk Management appraisal guidance

http://webarchive.nationalarchives.gov.uk/20131108051347/http://a0768b4a8a31e106d8b0-50dc802554eb38a24458b98ff72d550b.r19.cf3.rackcdn.com/geho0310bsdc-e-e.pdf

Environment Agency, 2011 - Adapting to Climate Change: Advice for Flood and Coastal Erosion Risk Management Authorities

https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/297379/geho0711btzu-e-e.pdf

Fleming (2002) Flood Risk Management, Thomas Telford Ltd, London

http://trove.nla.gov.au/goto?i=x&w=x&d=http%3A%2F%2Fbooks.google.com%2Fbooks%3Fid%3DQoabWTHA2ccC%26printsec%3Dfrontcover%26source%3Dgbs_ViewAPI

Floodplain Regulations Committee (Association of State Floodplain Managers), 2010 - A Guide for Higher Standards in Floodplain Management

http://www.floods.org/ace-files/documentlibrary/committees/Insurance/ASFPM_Higher_Standards_Reference_Guide_1010.pdf

Green, J. et al. 2012, The revised intensity-frequency-duration (IFD) design rainfall estimates for Australia – An overview, 34th Hydrology and Water Resources Symposium, 19-22 November, 2012, Sydney Australia.

Institute for Water Resources, 2011, Flood Risk Management Approaches: As being practiced in Japan, Netherlands, United Kingdom and United States. IWR Report No: 2011-R-08.

International Transport Forum, 2013 – Understanding the value of transport infrastructure: Guidelines for macro-level measurement of spending and assets. Prepared for the OECD.

Independent Pricing and Regulatory Tribunal, 2012 – Review of prices for Sydney Water

Corporation's water, sewerage, drainage and other services.

Jonkman, van Gelder, Vrijling, Journal of Hazardous Materials, 2002 - An overview of quantitative risk measures for loss of life and economic damage

https://portal.uni-freiburg.de/empiwifo/lehre-teaching-1/summer-term-09/materials-seminar-in-risk-management/acceptable_risk9_jonkman.pdf

McLuckie, D, 2015, Linking design flood estimation to decision making. In Australian Rainfall and Runoff Guideline (revision draft). Engineers Australia, 2015.

May, Ackers, Kirby, 2002 - Manual on scour at bridges and other hydraulic structures, CIRIA

http://umusebo.com/wp-content/uploads/2012/07/manual-on-scour-at-bridge-&-other-hydraulic-structures-ciria.pdf

Melbourne Water Corporation, 2010 - Flood Risk Assessment: How flood impacts are assessed in the Port Phillip and Westernport region

http://www.melbournewater.com.au/whatwedo/manageflooding/Documents/Flood_Risk_Assessment_Summary.pdf

Merz, Hall, Disse, Schumann, 2010 – Flood Risk Management in a Changing World

http://www.nat-hazards-earth-syst-sci.net/10/509/2010/nhess-10-509-2010.pdf

National Emergency Management Committee, 2010 - National Emergency Risk Assessment Guidelines

http://www.em.gov.au/Documents/National%20Emergency%20Risk%20Assessment%20Guidelines%20October%202010.PDF

Passey, Bennett, Zielinski, Donnelly, 2014 (Canadian Dam Association) - Dam Safety Management Plans: A Conceptual Framework For Risk-informed Decision Making In Ontario

http://www.researchgate.net/profile/C_Richard_Donnelly/publication/265206945_DAM_SAFETY_MANAGEMENT_PLANS_A_CONCEPTUAL_FRAMEWORK_FOR_RISK-_INFORMED_DECISION_MAKING_IN_ONTARIO/links/540491050cf23d9765a6637c

Sayers, Hall, Meadowcroft, 2002 (Proceedings of the Institute of Civil Engineers) Towards risk-based flood hazard management in the UK.

Tonkin, 2009 – Infrastructure Asset Useful Lives: SA Council's Current Practices. Prepared on behalf of the SA Local Government Association.

United States Environmental Protection Authority, 2014 – Sustainable Infrastructure for Water and Wastewater

http://www.epa.gov/waterinfrastructure/basicinformation.html#fiv