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WAGGA WAGGA LEVEE UPGRADE

FLOOD FREEBOARD

Report Number: DC 10096

Thursday, November 04, 2010

Wagga Wagga City Council

City of Wagga Wagga

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1. Introduction

This report addresses the freeboard requirements for the proposed Wagga Wagga Levee upgrade works. The freeboard allowances contribute to the overall Design Levee Levels (profile) for the entire length of the levee systems at Wagga Wagga (Main Levee) and North Wagga Wagga (North Wagga Levee).

The City of Wagga Wagga is situated on the south bank of the Murrumbidgee River and North Wagga Wagga is on land enclosed between the Northern flood plain and the river. North Wagga Wagga is only slightly higher than the surrounding flood plain. The Murrumbidgee River is a major tributary of the Murray River system and drains some 100,000 km^2 in the southern inland area of New South Wales. Rising on the western slopes of the Snowy Mountains, the Murrumbidgee River has a catchment area of some 26,400 km^2 at the city of Wagga Wagga.

The Main Levee currently provides protection from inundation up to a level of approximately equivalent to the August 1974 flood event plus a freeboard of 1 metre. Temporary levees have been constructed around the village of North Wagga Wagga since at least the mid 1930's. The North Wagga Wagga levees were formalised as more permanent structures in 1990 so as provide protection up to approximately 0.5 to 1 metre below the level of the August 1974 flood event. Refer to Attachment 1 for the height of the existing Wagga levee system crest levels.

The existing Main Levee consists of a 9km long levee constructed generally as an earthfill embankment, with a portion consisting of a reinforced concrete wall type levee. Levees at North Wagga Wagga (with inclusion of Bank Two) total approximately 5.8km in length. These levees are of the earthfill embankment type.

The design flood levels, with appropriate freeboard allowance, are assigned in accordance with flood levels determined for a range of ARI events, as provided in the flood study (and its addendum) completed by Webb, McKeown and Associates in 2004 and 2009 respectively. The design levels as depicted in Figure 1 are superimposed onto the length of the existing/extended levee alignment of the Main Levee and North Wagga Wagga Levee to determine the degree of levee rising required at each particular location. This will influence the type of levee option to be considered in the proposed option study. The design levee profiles will be determined using the following design flood events:-

- Main Levee – 100 year ARI flood event; and
- North Wagga Wagga Levee – 20 year ARI flood event.

Additional to these design flood levels, appropriate freeboard allowances will be added. This report details the determination of the appropriate freeboard allowance and the recommended freeboard values for each levee.

2. Freeboard

Freeboard is incorporated into the final design height of the levee and is expressed as the incremental difference in height between the level of the flood the levee is designed to protect against, and the design crest level of the levee.

The purpose of freeboard is to provide a reasonable certainty that the risk exposure associated with a particular design flood is actually provided. Generally, freeboards are added to levee crest levels to allow for:-

- Uncertainties in the estimates of flood levels, such as inadequacies in the historical data;
- Increases in flood level as a result of wind and wave action;
- Differences in flood levels due to 'local factors' such as local water surge;
- Post construction settlement, which effectively reduces the long term level of the levee;
- Reduction in crest level due to defects in the levee and surface erosion, plus effects of vehicle, animal or pedestrian crossings and lack of levee maintenance;
- Potential changes in rainfall patterns as a result of climate change; and
- Computational uncertainties, inadequacies in survey data and other sources of error.

It has been common practice to adopt a freeboard of 1 metre for typical earth embankment type levees, and 0.6 metres for retaining wall type levees or levees constructed as sealed roads, however the freeboard allowance factors listed above can differ substantially for different sections of a single levee, according to such factors as type of levee, exposure to wave action etc. Thus applying a standard freeboard allowance for a levee is considered simplistic, and in many instances, overly conservative.

There are no formal freeboard standards adopted in Australia, and estimates of acceptable freeboard for the Wagga Wagga Levee are made based on a Joint Probability Analysis. This consists of matrix of design variables and associated probabilities. The exercise indicates that the commonly adopted freeboard could be reduced without significantly affecting the risk of providing protection for Wagga Wagga against the selected design flood.

3. Freeboard Components

The flood freeboard is calculated from a number of specific components, each of which can be determined with some precision or reasonably estimated from past performance. Each of these components are described below.

3.1 Wave Action

Where the levee face is exposed to a large expanse of flood water, significant waves can be generated under windy conditions. These waves, when superimposed onto the design flood level, may overtop the levee.

The design wind and wave action estimation carried out in this study have been based on the Australian Wind Loading Standard - AS/NZS1170.2 (2002) - and guidelines for estimation of waves for shallow water reservoirs - USBR (1992).

3.1.1 Fetch

Fetch is the distance a wave is assumed to travel from the point of origin to a point of impact. The distance is limited by the land surrounding the body of water. The fetch in turn, determines the extent of exposure to wind that a wave will have such that the longer the fetch, the greater will be the wave height.

As the extent of flood water is limited by the irregular “shoreline”, an effective fetch (F) must be calculated to determine an average horizontal distance in the general direction of the wind over water, corrected for flood geometry over which a wind acts to generate the waves. The method determines an effective fetch for a single point on the levee from various points on the “shoreline”, where waves can originate. Distances are calculated for a 90^{o} arc from the nominated point on the levee. The effective fetch is used to calculate wave properties.

Determining the longest effective fetch is a trial and error process, whereby a number of positions on the levee are selected and the calculation of maximum effective fetch carried out using the following equation :-

$$F = \frac{\sum x_i \cos \alpha_i}{\sum \cos \alpha_i}$$

where :-

F = Effective fetch (km)

X_i = length of projection of radial (i) on the central radial

α_i = angle between the central radial from the dam and radial (i).

It has been assumed that the design wind can originate from any direction.

An example of the method of calculation is shown in Figure 4.

Effective fetch for the Wagga Wagga levees has been determined for each of the two levees and corresponding design flood events, ie :-

- Main Levee – 100 yr ARI flood event
- North Wagga Wagga Levee – 20 yr ARI flood event.

In the case of the Main Levee, it is assumed that the area within the North Wagga Wagga Levee is inundated such that fetch distances to the north of the Main Levee are extended to the perimeter of the inundation area. In the case of the North Wagga Wagga Levee (20 yr ARI design flood event) the Main Levee will offer some protection to the south of the North Wagga Wagga Levee.

In each case, three representative points on the levee were assessed as potential maximum effective fetch locations and effective fetch distances calculated. These are shown on Figure 2 (Main Levee) and Figure 3 (North Wagga Wagga Levee) and are denoted as fetches A, B and C. The calculated fetch distances are given in Table 3.1.

Table 3.1 Effective Fetch

Levee	Flood Event	Fetch (km)
Main Levee	100 yr ARI (see Figure 2)	A = 6.28 km B = 4.25 km C = 4.27 km
North Wagga Levee (incl. Bank 2)	20 yr ARI (see Figure 3)	A = 1.87 km B = 3.01 km C = 1.83 km

3.1.2 Design Wind

The height of waves generated for a given wind speed are limited by wind duration and fetch distance. Wave heights progressively increase under constant wind action, as they move along the fetch, until a maximum limiting value is reached. A certain duration of wind is required to generate waves over the given fetch distance.

For the maximum design flood levels (ie 100 yr ARI and 20 yr ARI respectively) a moderate wind is proposed – one that can be reasonably expected to occur concurrently with the maximum flood levels. This moderate wind is adopted as the 1 year ARI wind.

Values for maximum design winds at Wagga Wagga, for a range of ARI events, are given in Table 3.2 This design wind speed information was obtained from Section 3 of the Australian Wind Loading Standard – AS/NZS-1170.2 (2002).

Table 3.2 Design Wind Speeds

Wind Event (ARI)	Design Wind Speed (m/sec)
1	17
10	22
100	26

3.1.3 Wave Height

Wave heights are function of the water depth, wind speed, wind fetch length, river velocity and current influences.

A significant wave, which defines the design wave height, is defined as a fictitious wave with a height and period equal to the average height and period of the highest one-third of the actual waves that pass a fixed point. The height of this wave is a major component used in determining the required freeboard value. The period and height of this wave are termed significant wave period (Ts) and significant wave height (Hs), respectively.

The following equations from Saville, are used to determine the significant wave height and the corresponding significant wave period :-

$$\mathbf{gH_s/U^2 = 0.0026\ (gF/U^2)^{0.47}}$$

$$\mathbf{gT^2/U = 0.46\ (gF/U^2)^{0.28}}$$

where

H_s = significant wave height (feet)

T = significant wave period Ts (seconds)

F = effective fetch Fe (miles)

g = acceleration due to gravity (79,036.36 miles/hr2)

U = <u>average</u> integrated wind velocity over water (miles per hour)

These equations can be used for developing graphical diagrams for forecasting wave heights and wave periods. The wave period (T) can be determined from Figure 6 (Ref 9).

The wave length can be determined from the following deep water equation :-

$$\mathbf{L = 1.56\ T^2}$$

where

L = wave length (metres)

T = wave period (seconds)

In the case of significant flooding at Wagga Wagga, the flooded areas are deemed to be sufficiently deep to permit the development of deep water waves. The body of water is assessed to be "deep" compared to the wave length when water depth exceeds 0.5L.

Estimated wave heights and wave periods for the Wagga Wagga levee, at the design 1 year ARI wind speed, are given in Table 3.3 and Attachment 2.

Table 3.3 Wagga Wagga Levee – Wave Heights

Levee	Effective Fetch (km)	Hs (m)	T(sec)
Main Levee	A = 6.28	0.88	3.2
(100 yr ARI flood event)	B = 4.25	0.73	2.85
	C = 4.72	**0.91**	**3.2**
North Levee	A = 1.87	0.48	2.3
(20 yr ARI flood event)	B = 3.01	**0.59**	**2.5**
	C = 1.83	0.53	2.5

3.1.4 Wind Set-up

When wind blows over a water surface it exerts a horizontal shear stress on the water, driving it in the wind direction. This results in water piling up on the leeward end and a lowering of the water on the windward side. The effect is defined as wind set up (S).

Wind set up is calculated from the Zuider Zee equation :-

$$\mathbf{S = U^2F/1400D}$$

where

S = wind set-up or height above still water (feet)

U = integrated average wind velocity over water (miles/hr)

F = wind fetch (miles)

D = average water depth (assumed to be 16 feet (5 metres))

Wind set-up is added as a component of the minimum freeboard required. Values of wind set-up for the Wagga Wagga Levees are given in Table 3.4

Table 3.4 Design Wind Set-up

Wind Event (ARI)	Main Levee Wind Set-up (m)	North Wagga Levee Wind Set-up (m)
1	0.07	0.04
10	0.12	0.06
100	0.18	0.09

3.1.5 Wave Run-up

When a wave reaches a sloping embankment (e.g. levee) it will break on the embankment and run up the slope. The height it runs up the slope is governed by the angle of the slope, the roughness and permeability of the surface and wave characteristics. This vertical height is called wave run-up (**R**) and is the maximum height that the water reaches <u>above the still water flood level</u>.

Rockfill protected slopes act as wave energy dissipators, thereby reducing the extent of run-up. Well vegetated slopes also offer enhanced protection. Smooth slopes provide less resistance, thereby increasing the run-up extent. Vertical (or near vertical) walls prevent wave run-up.

To determine the maximum extent of wave run-up, the wave run-up ratio (**R/Ho**) is derived from work completed by Saville and others (Ref 10), such that wave run-up can be calculated from the formula:-

R = Ho * (R/Ho)

where

R = wave run-up on an embankment (vertical height)

Ho = wave height, Refer to Figure 5.

R/Ho = run-up ratio.

The wave run-up ratio can be calculated from Figure 11 (Ref 2) which represents the relationships between wave run-up ratios (**R/Ho**), wave height (**Ho**), wave period (**T**) and slope of embankment. A copy of this figure is included, as Figure 7, in this report.

Two sets of curves are included in the figure, representing relatively permeable rubble mounds (e.g. rockfill embankments) and smooth slopes (e.g. bare earth slopes).

In the assessment of freeboard for the Wagga Wagga Levees, the following interpolations have been adopted :-

- Very well vegetated slopes, with some shrub and/or tree protection are estimated to be similar to rubble mound (rockfill) slopes.
- Moderately vegetated grassed slopes are estimated to be mid-way between rockfill slopes and smooth slopes

Levees at Wagga Wagga are likely to consist of either well or moderately well vegetated slopes or vertical walls. Calculated run-up values for these levee types at Wagga Wagga Levees are given in Table 3.5.

Table 3.5 Typical Wave Run-up Values

Levee	Levee Type	Slope	Wave Height Ho (m) (1)	Ho/T^2 (m/sec^2) (2)	R/Ho	R (m)
Main Levee	Earthfill, well vegetated	4:1	0.91	0.089	0.53	0.48
		3:1	0.91		0.62	0.56
	Earthfill, moderate veg.	4:1	0.91		0.75	0.68
	Rockfill	2:1	0.91		0.72	0.66
	Retaining wall	Vert.	0.91		0.5 (3)	0.46
North Wagga Levee (incl. Bank 2)	Earthfill, well vegetated	4:1	0.59	0.094	0.52	0.31
		3:1	0.59		0.60	0.35
	Earthfill, moderate veg.	4:1	0.59		0.72	0.42
	Rockfill	2:1	0.59		0.69	0.41
	Retaining wall	Vert.	0.59		0.5 (3)	0.30

(1) Maximum wave height from Table 3.3

(2) Wave period (T) corresponding to maximum wave height

(3) No wave run-up. Wave breaks against wall.

It can be seen from the wave run-up values in Table 3.5 that there can be considerable benefit in selecting levee types, at particular locations, which act to minimise wave run-up.

3.2 Local Water Surge

When water velocities and flow directions change locally, such as at a levee alignment which is oblique to the direction of flow or as a result of local blockages in the channel, local flood water levels can be higher than the general flood level. These changes can be difficult to predict under flood conditions, however flood modelling results can be used to assess likely surge heights.

The flood report (Ref 15) presents local velocity data for both design floods (100 yr ARI and 20 yr ARI) and surge heights can be determined from the relationship :-

$$\mathbf{h_s = v^2/2g}$$

where

$\mathbf{h_s}$ = surge height (m)

$\mathbf{v}$ = local velocity (m/sec)

Maximum surge heights, at selected oblique levee locations, are given in Table 3.6

Table 3.6 Local Surge Heights

Levee	Location	Velocity (m/sec)	Surge Height (m)
Main Levee (100yr ARI flood event)	Ch 8150-8880 Ch 5500-5800	0.7 1.3	0.025 0.086
North Wagga Levee (incl. Bank 2) (20yr ARI flood event)	Eastern face	0.6	0.018

Similar local surge effects could be expected due to blockages in the flood channel, adjacent to the levee (eg fallen trees).

A conservative 100mm local surge allowance is proposed. This surge allowance will allow not only for oblique levee alignments, but also isolated features and events that may act to promote local surge effects.

3.3 Uncertainties in Flood Levels

3.3.1 General

Uncertainties in the determination of flood levels typically consists of being unsure about the value of some of the parameters used in computation. Consequently these uncertainties can have localised or cumulative effects on the accuracy of hydrologic and hydraulic modelling. Confidence in the computed flood levels may be compromised due to the following:-

- How well the theoretical ARI-Discharge curve fits known flood levels;
- Availability of detailed survey and other topographic data;
- Reliability of the historical flood data;
- The calculation of the slope or flood profile along the length of the levee can be prone to error as the precise direction of flood flow in a wide flood plain can not always be predicted accurately; and
- Estimated parameters can contain some degree of uncertainty e.g. afflux, surface roughness, evapotranspiration loss, rainfall pattern etc.

3.3.2 100 year ARI Design Flood

The order of accuracy of the design flood levels was originally estimated to be ±0.5m in the 2004 flood study. This level of accuracy is based on two factors, the first being the lack of detailed topographic information and the second being the limited availability of historical flood information. The order of accuracy of design flood levels was increased to ±0.3 m in the 2009 flood study, as more detailed topographic information was made available for the study area.

3.3.3 20 year ARI Design Flood

The order of accuracy of the 20 year ARI design flood levels was suggested to be ±0.3 m in the 2009 flood study. However, long lengths of good quality flood height data are available for 20 year ARI flood event in contrast to 100 year ARI flood event. In areas where more detailed topographic information in addition to historical flood information are available, a better confidence level of the 20 year ARI flood level can be achieved.

It is proposed that the order of accuracy for the 20 year ARI flood event be adopted as ±0.25m

3.4 Levee Settlement

Levee type is an important element affecting freeboard requirements. The levee type may vary along the length of the levee according to land availability, ease of construction, construction resources and social considerations.

Some of the different types of levees likely to be used at Wagga Wagga, and typical estimates of settlement considerations include :-

- <u>Earthfill Embankment</u> – The structural integrity of an earthfill embankment depends on the age of the embankment, embankment design and material types, construction methods, and on-going maintenance program. In most cases settlement of earthfill embankments can be attributed to normal post construction settlement plus effects of drying, shrinkage and cracking etc.

  Well constructed embankment dams with a specified high degree of compaction and good construction quality control are expected to experience a post construction settlement of up to 0.5% of their constructed height. Levees are usually constructed with at least a reasonable degree of compaction and normal post construction settlement may be expected to be in the order of 1% of the height of the levee.

  Based on the above, settlement of the Wagga Wagga levee could be expected to be of the order of 0.02 – 0.05 metres, assuming that the entire levee section is re-constructed. In the case of the Wagga Wagga levees, where augmentation works could be expected to retain most of the existing levees which have been in place for many years, most post construction settlement will have finished. Settlement would therefore only be attributed to the newly constructed raised portion of the levee, plus some minor settlement of the existing levee due to the increased loading.

  A post construction settlement allowance for earthfill embankments for the raised Wagga Wagga Levee is therefore proposed as 0.025 metres. Should a new levee be required this settlement allowance should be revised.

- <u>Retaining Walls</u> – Correctly designed and constructed retaining walls (eg concrete cantilever walls, sheet pile walls, rockfill gabion baskets etc) are not expected to experience any significant settlement. No post construction settlement allowance is proposed.

3.5 Defects in Levee

3.5.1 Erosion

The degree of erosion depends on the condition of levee, level of compaction, type of materials, quality of protection (e.g. grass cover on batters, gravel crest etc) and quality control during construction. Some bare earth levees have been known to erode at a rate of 100mm/ year.

3.5.2 Holes

Holes can appear in levees due to burrowing animals, dispersion cavities etc. These holes may foster piping through the levee

Low points in the levee crest can result from concentrated traffic from animals, pedestrians and vehicular traffic.

Regular maintenance of the levee will address these problems.

3.5.3 Cracking

The extent of cracking of levee earthfill materials depends on the material used, the construction methods, subsequent maintenance and moisture content. Lateral cracks up to 2 metres depth can occur, leading to a risk of piping though the levee bank during a flood event.

3.5.4 Maintenance

Regular maintenance works will reduce or eliminate the risk of levee progressive failure from defects. Settlement of earthfill embankments can also be compensated by effective maintenance and follow up works.

3.5.5 Defect Allowance

The impact of defects in the levee can be mitigated by regular and effective maintenance. Levees which are neglected should allow a freeboard component of up to 0.5 metres to cater for defects. In the case of Wagga Wagga earthfill levees, which appear to be well maintained, a component freeboard allowance of 100mm is considered appropriate.

No defect allowance is considered necessary for a retaining wall type levee that is well maintained.

3.6 Climate Change

The Floodplain Development Manual indicates that climate change should be considered in developing and implementing Floodplain Risk Management plans. Climate science advises a range of trends in changes to the environment that will continue to impact on flood risk, irrespective of the effectiveness of climate change mitigation strategies.

Short to medium term climatic changes may influence the flood record. The impacts of climate change on sea levels and flood producing rainfall events will have a flow on effect on flood behaviour which may result in key flood levels being reached more frequently and floods of the same ARI, being of a larger magnitude. This is an emerging field that has the potential to have a significant bearing upon design flood estimation and its accuracy. The climate change factors influencing flood behaviour and their ramifications to the community will vary with the location.

The freeboard allowance required to cater for the climate change is greatly affected by the uncertainties in future model projections. The major constraints for correct projection are listed as follows :-

- Australian rainfall is highly variable on an annual timescale. The challenge is to separate climate variability from any longer term trends that relate to anthropogenic climate change;
- Historical data is insufficient to represent the full range of decadal scale variability in our climate;
- The decadal patterns of rainfall variability can be related to the Inter-decadal Pacific Oscillation, an ocean circulation operating over a longer time scale. Given the very high variability of rainfall in Australia it is harder to attribute recent rainfall patterns to human-induced climate change;

- One of the impediments to adaptation to climate change and reduced water availability has been the high uncertainty over future climate change. This uncertainty goes beyond scientific uncertainty in the global climate models to uncertainties in future greenhouse gas emissions; and
- Projections of climate change are based on global circulation models, which represent the atmospheric and oceanic processes across the globe. While the models are very detailed and advanced they do represent the globe and by necessity they only show conditions averaged over a large area. Individual runoff generating storms and hydrology operate at smaller scales and locally there can be much more extreme conditions than is suggested by the average.

Assignment of a freeboard allowance for the Wagga Wagga levee, to account for climate change, is therefore somewhat of an estimation. At the local level, such allowance may even be negative. We can expect that over time the impact of climate change will be reflected in flood records and climate data in general.

Notwithstanding the above, it is proposed that a climate change component be included in the total freeboard allowance for the Wagga Wagga Levees.

Current science suggests that whilst the region will become drier on average due to climate change, the frequency and intensity of the climate extremes such as storms, floods and droughts will increase (ie large storm events will occur more often and be greater in magnitude). The current science provides some guidance on the likely drying of the region by 2030 and 2070 however the guidance on the likely changes in extremes such as storms and resultant floods is limited.

The work of Hennessey et al suggests that for the region by 2030 there will be no significant increase in the 40 year ARI 24 hour and 72 hour rainfalls however there will be increases in both events of between 15% and 10% respectively, by 2070. Whilst it is more than likely that such increases in extreme rainfalls will translate to increased flood flows, it is currently difficult to quantify the likely nature and extent of these increases.

More recent work by the CSIRO suggests that the greatest increases in extreme rainfall intensities due to climate change will be for the shorter duration storm events (ie less than 6 hours) and that there will be a tendency for the rainfall to occur earlier in the storm event. The tendency will be for increases in storm intensities to decrease with increasing storm duration. This has more implications for small urban areas, where flash flooding is the dominant source of flooding, rather than say flooding in the Murrumbidgee River which results from longer duration storm events.

There is also uncertainty in how these changes in rainfall extremes due to climate change will translate to flood peaks. Little to no information has been provided on such factors as the wetness of the catchment prior to such storms (ie changes in rainfall losses) or the resultant catchment runoff and storage routing characteristics. A conservative worst case scenario of increased flooding from the Murrumbidgee River could be that by 2070 a 10% increase in extreme rainfall intensities (Ref 18) translates fully to an increase in flood peaks of 10%. The rating curve at Wagga Wagga reflects a 0.15 metre flood height increase (at Hampden Bridge) corresponding to this 10% increase in flood peak.

It is therefore proposed to include a 0.15 metre component in the flood freeboard allowance for the Wagga Wagga levees for both the 20yr ARI and 100 yr ARI flood events.

4. Freeboard Allowance

4.1 General

The freeboard allowance contributes to the overall Design Levee Levels (profile) for the entire length of the levees at Wagga Wagga (Main Levee) and North Wagga Wagga (North Wagga Levee). The Main Levee will be designed for the 100 year ARI flood event and North Wagga Levee for the 20 Year ARI flood event.

Levee Freeboard components, which are discussed in Section 3 of this report, are summarised in Table 4.1.

Table 4.1 Levee Freeboard Components

Freeboard Item	Maximum Height Allowance (m)	
	Main Levee	North Levee
Wave action		
• Run-up (including wave height [(1)])		
o Embankment (4:1, well grassed)	0.48	0.31
o Retaining wall	0.46	0.30
• Set-up	0.07	0.04
Local water surge [(2)]	0.1	0.1
Uncertainties in Flood Levels	0.30	0.25
Levee Settlement		
• Embankment	0.025	0.025
• Retaining walls	0	0
Defects in Levee		
• Embankment	0.10	0.10
• Retaining walls	0	0
Climate Change	0.15	0.15

(1) Wave height above still water flood level.
(2) Localised impact only.

4.2 Joint Probability Analysis

As a flood risk is rarely a function of just one source variable (e.g. waves, river velocity, wind speed etc), Joint Probability analyses is used to address the chance of two or more conditions occurring at the same time.

Joint Probability Analysis recognises that design flood characteristics could result from a variety of combinations of flood producing factors, rather than from a single combination. Thus, Joint Probability Analyses is used to take account of the dependence between input variables, as well as the distribution and extremes of the individual variables. It can increase the accuracy of failure probability estimation as it uses the input information more effectively. This approach, which considers the outcomes of events with all possible combinations of input values and their correlation structure, will lead to a better estimate of flood freeboard.

In general, and unless there is readily available alternative data, it is suggested that probability classification guidelines be adopted as set out in Table 4.2. These would be combined with freeboard component factors as relevant, to determine the design freeboard for the levee.

Table 4.2 Probability Classifications (Ref 13)

Description	Probability
Virtually certain	0.999
Very likely	0.99
Likely	0.9
Neutral	0.5
Unlikely	0.1
Very unlikely	0.01
Virtually impossible	0.001

4.3 Main Wagga Wagga Levee Freeboard Allowance

The required freeboard allowance for the Main Levee has been summarised in Table 4.3 and Table 4.4. The calculations have assumed that the levee consists of well grassed earthfill embankment levees and retaining wall levees respectively.

Table 4.3 Main Levee – Freeboard Allowance (Earthfill Embankment)

Freeboard Item	Allowance (m)	Probability (1)	Joint Probability Component (2)
Wave action			
• Run-up (incl. wave height)	0.48	0.5	0.24
• Set-up	0.07	0.5	0.035
Local water surge	0.1	1	0.1
Uncertainties in Flood Levels	0.30	1	0.30
Levee Settlement	0.025	0.5	0.012
Defects in Levee	0.10	0.5	0.05
Climate Change	0.15	1	0.15
Total			0.887
Freeboard Allowance			**0.90**

(1) Probability of the typical height occurring at location during flood.

(2) Probability weighted positive variation for this component

Table 4.4 Main Levee – Freeboard Allowance (Retaining Wall)

Freeboard Item	Allowance (m)	Probability **(1)**	Joint Probability Component **(2)**
Wave action			
• Run-up (incl. wave height)	0.46	0.5	0.23
• Set-up	0.07	0.5	0.035
Local water surge	0.1	1	0.1
Uncertainties in Flood Levels	0.30	1	0.30
Levee Settlement	0.0	0.5	0.0
Defects in Levee	0.0	0.5	0
Climate Change	0.15	1	0.15
Total			0.815
Freeboard Allowance			**0.80**

(1) Probability of the typical height occurring at location during flood.
(2) Probability weighted positive variation for this component

4.4 North Wagga Wagga Levee Freeboard Allowance

The required North Wagga Wagga freeboard allowance has been summarised in Table 4.5 and Table 4.6. The calculations have assumed that the levee consists of well grassed earthfill embankment levees and retaining wall levees respectively.

Table 4.5 North Wagga Wagga Levee – Freeboard Allowance (Earthfill Embankment)

Freeboard Item	Allowance (m)	Probability (1)	Joint Probability Component (2)
Wave action • Run-up (incl. wave height) • Set-up	 0.31 0.04	 0.5 0.5	 0.16 0.02
Local water surge	0.1	1	0.1
Uncertainties in Flood Levels	0.25	1	0.25
Levee Settlement	0.025	0.5	0.012
Defects in Levee	0.10	0.5	0.05
Climate Change	0.15	1	0.15
Total			0.742
Freeboard Allowance			**0.75**

(1) Probability of the typical height occurring at location during flood.
(2) Probability weighted positive variation for this component

Table 4.6 North Wagga Wagga Levee – Freeboard Allowance (Retaining Wall)

Freeboard Item	Allowance (m)	Probability (1)	Joint Probability Component (2)
Wave action • Run-up (incl. wave height) • Set-up	 0.30 0.04	 0.5 0.5	 0.15 0.02
Local water surge	0.1	1	0.1
Uncertainties in Flood Levels	0.25	1	0.25
Levee Settlement	0.0	0.5	0.0
Defects in Levee	0.0	0.5	0
Climate Change	0.15	1	0.15
Total			0.67
Freeboard Allowance			**0.70**

(1) Probability of the typical height occurring at location during flood.
(2) Probability weighted positive variation for this component

4.5 Application of Freeboard Allowance

The freeboard values calculated for the Wagga Wagga levees will be used to determine a general freeboard allowance rather than a variable freeboard to suit specific locations. For example, it could be argued that a section of levee which is protected by heavily timbered river banks could be provided with a reduced freeboard as a result of protection offered against wave action. Conversely, it could be argued that if these same trees are lost during a major flood, an inadequate freeboard would result at a critical time during the flood.

It is also important to note that the freeboard calculations are based on a continuation of the current maintenance regime at Wagga Wagga. Should maintenance be reduced and/or defects be not promptly repaired, an increased freeboard would be warranted.

Based on the freeboard assessment, it is therefore proposed that the levees be designed with freeboards as follows :-

- Main Levee 0.9 metres
- North Levee 0.75 metres

Although retaining wall type levees could have a lower freeboard, it is considered that for the short lengths of retaining walls present at Wagga Wagga, a variable freeboard would be inappropriate.

5. Conclusions

Conclusions arising from this freeboard study for the Wagga Wagga Levee system are:-

1. The levees at Wagga Wagga are to be designed to accommodate the following design floods :-
   - Main Levee – 100 yr ARI flood event
   - North Wagga Wagga Levee – 20 yr ARI flood event
2. Additional to these design flood levels, an appropriate freeboard allowance is to be added to provide the levee design crest levels. This freeboard will provide a reasonable certainty that the risk exposure associated with a particular design flood is actually provided.
3. Freeboard is calculated from a number of specific components, which include :-
   - Wave action
   - Local water surge
   - Uncertainties in design flood levels
   - Post construction settlement a defects in the levee
   - Climate change
4. There are no formal freeboard standards in Australia, and estimates of acceptable freeboard for the Wagga Wagga levees are made based on a Joint Probability Analysis basis.
5. Joint probability analysis is applied to the freeboard component values to address the chance of two or more conditions occurring at the same time.
6. Freeboard allowance for the Wagga Wagga main levee is calculated as :-
   - Embankment type levee – 0.90 metres
   - Retaining wall type levee – 0.80 metres
7. Freeboard allowance for the North Wagga Wagga Levee is calculated as :-
   - Embankment type levee – 0.75 metres
   - Retaining wall type levee – 0.70 metres
8. A consistent freeboard allowance is considered appropriate for the Wagga Wagga levees. The freeboard allowance is :-
   - Wagga Wagga Main Levee – 0.9 metres
   - North Wagga Wagga Levee – 0.75 metres.
9. Freeboard calculations are based on a continuation of the current levee maintenance regime at Wagga Wagga.

6. Recommendations

Recommendations arising from this freeboard study for the Wagga Wagga Levee system are:-

1. The design freeboard allowance for the Wagga Wagga levee system be :-
   - Wagga Wagga Main Levee – 0.9 metres
   - North Wagga Wagga Levee (including Bank Two) - 0.75 metres
2. That sound levee maintenance practices be continued, to ensure that the recommended levee freeboard remains appropriate for the levee..

7. References

1. Australian Commonwealth Scientific and Research Organization (CSIRO), *Hydrological Consequences of Climate Change*, 2007.
2. California Institute of Technology, "The Effect of Waves on Rubble-Mound Structures" W.M.Keck Laboratory of Hydraulics and Water Resources.
3. Chris Stanton, Stanton Associates, *Flood Levee Design Based on Progressive Failure Probability*.
4. Cooperative Research Centre for Catchment Hydrology, *Joint Probability Approaches to Design Flood Estimation: A Review*, 1998.
5. Duncan McLuckie et al, *Adapting for Climate Change Impacts on Flooding*, 2007.
6. NSW Department of Environment, climate Change and Water, Draft Flood Risk Management Guide, 2009.
7. NSW Department of Natural Resources, Floodplain Development Manual, 2005.
8. NSW Department of Natural Resources, Floodplain Risk Management Guideline No.15 Freeboard for Urban Levees.
9. Robin Fell, Geotechnical engineering of embankment dams. 2004.
10. SAVILLE Jr., T. *Wave run-up on shore structures*. Journal of the Waterways Division, 82, 925-1–925-14. 1956.
11. Sinclair Knight Merz, Deniliquin Flood Protection Levee Study, 1997.
12. Standards Australia, Australia/ New Zealand standard 1170.2:2002, Structural design action, Part 2 Wind Actions. 2002
13. USBR, *Dam Safety Risk Analysis Methodology, Version 3.3, Technical Service Centre*, September 1999).
14. U.S Department of the Interior, Freeboard criteria and Guidelines for Computing Freeboard Allowances for Storage Dam, 1981.
15. Webb, McKeown & Associates Pty, Ltd, *Murrumbidgee River Wagga Wagga Flood Study,* 2004
16. WMAWater, *Wagga Wagga Floodplain Risk Management Plan*, 2009.
17. WMAWater, *Wagga Wagga Floodplain Risk Management Study*, 2009.
18. Climate Change in New South Wales. Part 2. Projected Changes in Climate Extremes. CSIRO. 2004.