# THE IMPORTANCE OF DETAILED FLOOD IMFORMATION FOR LEVEE DESIGN AND UPGRADE

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## Abstract

The use of substantial levees to protect major urban centres from inundation is widespread across western NSW. A number of these existing levees were initially built in the mid-century and were generally based on the extent and height of the flood of record.

More recently, a number of these levees have been subject to significant remediation and upgrade programs, involving works to increase the assurance of a level of protection and improve structural integrity. Commencing a levee upgrade program is a major economic commitment for Government; it is essential that the correct tools and information are available to the upgrade design. Key to that information is the availability of the correct post levee flood gradient which can be derived from flood modelling.

The levee at Deniliquin was initially constructed in 1955 and over the last 15 years Council has engaged in a significant levee upgrade program which was completed in 2012. As part of the Deniliquin Flood Study a two dimensional hydraulic model was established which considered the performance of the finished levee design height against current design modelling.

This paper will explore the issues that can arise when the right tools or information are not available at the time of the levee upgrade program, specifically by considering a case study at Deniliquin.

## Background

Levees are an important flood mitigation measure, often protecting large urban or rural areas from significant flooding. They are typically built along a boundary between an urban area and a river or creek, and act to confine the floodwaters from spreading over the wider floodplain. Levees are an attractive floodplain management option for their ability to keep an area completely flood-free, up until the levee's design height is overtopped by a large enough flood. Disadvantages include their high cost relative to other measures, their visual impact on the area from the community's perspective, and their risk of exacerbating flood behaviour when they are overtopped, by causing sudden and uncontrolled inundation of an area, often with high hazard flows. This is often misunderstood and the presence of a levee can lead to a false sense of security against flooding.

The maximum flood height which a levee will protect against is both intrinsic to every levee, and an unknown with respect to what Annual Exceedance Probability (AEP) the overtopping flood will have. That is, while it may be known the height at which a levee is overtopped (the lowest height along the levee after accounting for flood gradient), the AEP which this height corresponds to is not possible to quantify with complete certainty, due to inherent unknowns in the estimation of design flood levels. For example, an area may have a defined 1% AEP flood level of 50 mAHD at the town gauge. Because this level is only an estimate, it is not possible to say that a levee in the area with an elevation of 50 mAHD will protect against a 1% AEP flood, as the 1% AEP level may actually be up to 51 mAHD, or even 49 mAHD.

This unknown quantity is accounted for by adding a freeboard value to the design flood level for the levee, and constructing the levee to this height. The freeboard is an estimate of effects which are known to occur, but cannot easily be estimated or are not consistent between flood events. Components of freeboard include wave action, localised hydraulic effects, uncertainty with flood profiles, local maintenance issues and post-construction settlement. The value of freeboard varies with local factors which determine the magnitude of each of the aforementioned components; however, a freeboard of 500 mm is considered typical in New South Wales (FDM 2005). While 500 mm is typical, in reality, the freeboard can vary from as little as 0.1 m to over 1 m, in the context of the available information.

This paper will consider how the choice of levee freeboard in Deniliquin has evolved over the 30 years since the first formal design for a levee was proposed in 1984. Discussion will be given as to how two different freeboards were adopted in the town (100 mm and 500 mm) and the consequences that choice has had for the current level of protection.

## Levees in Deniliquin

### *Introduction*

The town of Deniliquin is located on either side of the Edward River and is protected on both sides of the river by an extensive levee structure. The town, which in 2011 had a population of 6 441, is located in the Riverina region of NSW, 234 km southwest of Griffith and 205 km downstream of Albury (the Edward River is an anabranch of the Murray River). From a flood risk perspective, the town has three separate areas:

1. *North Deniliquin*, located on the north side of the Edward River and Brick Kiln Creek,
2. *Davidson Street*, a developed area of land bounded by the river and Brick Kiln Creek, and,
3. *South Deniliquin*, the main part of the town, located on the south side of the Edward River.

Each area has experienced significant inundation during past floods, and each has a separate levee structure. There is one crossing of the river in the town, where the National Bridge connects Davidson Street to South Deniliquin. There are no tributaries or anabranches to the river in the immediate vicinity of the town, save for a number of small creeks (including Brick Kiln, Aljoes and Tarangle) which split away from the main channel and re-join it during high flow on the river. The three areas are shown in Figure 1.

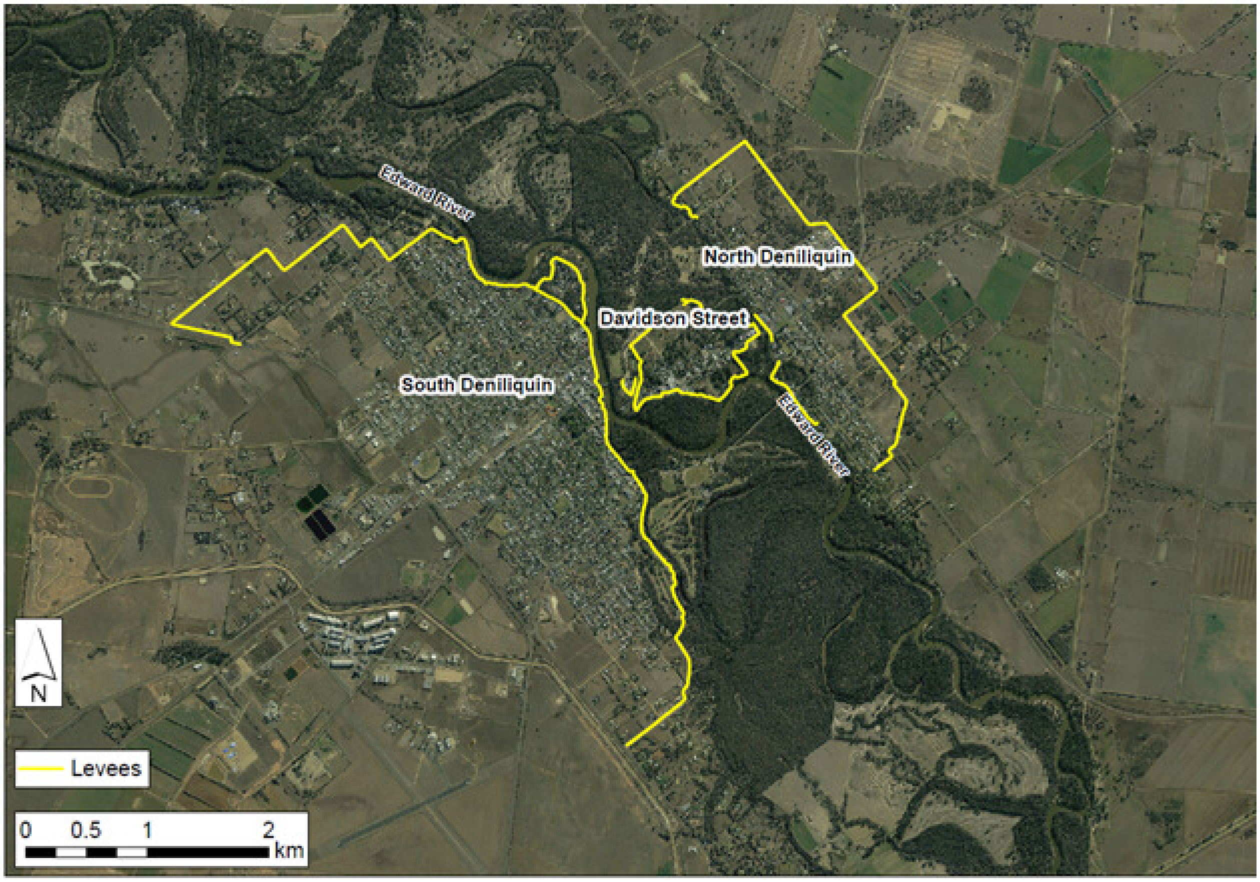

**Figure 1 Overview of Deniliquin**

***Flood Behaviour***

Deniliquin has a long history of flooding, with major floods in 1870, 1917, 1955, 1956 and 1975 all shaping the development of the town and the community's perception of flooding. Flooding is caused by high rainfall or snowmelt on the catchment, which extends upstream of Albury into the headwaters of the Murray River. The large catchment area and the long history of flooding mean there is a well developed warning system in place, with a warning time of around 7 - 10 days. Although the general lead up to a peak flood level can last months, the peak itself is experienced over a few days.

A large flood in Deniliquin entails the river rising to a depth of several metres, inundating the riparian zone before the river breaks its banks, spreading out over the wider floodplain. There are no well defined flowpaths outside of the riparian zone, and so flows spread over a large area, often guided by roads, irrigation canals or similar manmade embankments. Downstream of the township, the floodplain is less confined and floodwaters have a flow width of several kilometres in rare events.

The three levees (surrounding the aforementioned three areas of the town) act to confine the floodwaters to the riparian zone between North and South Deniliquin. In addition, the Davidson Street levee acts to keep flows in Brick Kiln Creek and the main channel, until it is overtopped and water flows over Davidson Street. Some development exists between the levee system and the river, for example Mclean Beach Caravan Park and Memorial Park, and these areas experience more frequent inundation.

### *Early Development of a Levee System*

The development of a levee for Deniliquin began in August 1955, when 'three to four miles of major levee banks' ('Flood Peak', 1955) were built in response to an imminent flood. As would be expected of a major levee built in less than a week, the result was a haphazard structure that was primarily aimed at withstanding a single flood. Nevertheless, the general success of the levee in protecting the town meant it was kept in place and then added to over the next 40 years. Reports indicate that additions were made in 1956, 1975 and 1993, in each instance in response to an impending flood event. Amendments entailed both improvements to the structural integrity and impermeability of the existing levee, as well as increasing its height in different areas. All three levees in the town followed this pattern of development.

## Deniliquin Flood Plain Management Study - 1984

The Deniliquin Floodplain Management Study was published in 1984 and constitutes the most recent (prior to the current study) estimation of both design flood discharges and design flood levels for the town. In addition, the study made an assessment of the floodplain management options available to the town, and recommended an upgrade of the levee system protecting North and South Deniliquin. The main findings of the report were as follows:

- The 100 year ARI discharge of the Edward River at Deniliquin was found to be 2500 $m^3/s$, and this corresponded to a flood level of 92.33 mAHD at the National Bridge. This level and other levels up and downstream were determined using a 1D model (HEC-2) combined with estimation of rating curves at several cross-sections.
- The existing levee (in 1984) was built on and using a range of materials, some of which had a risk of piping failure during a flood event.
- The levees around North and South Deniliquin should be raised to the height of the 100 year ARI flood plus a 1 metre freeboard. A 1 metre freeboard was considered to give an adequate level of protection and necessary to obtain funding from state and federal governments. This upgrade would involve raising the (then) existing levees by around 1 m, and up to 2.2 m in some sections.
- The recommended levees should contain spillways, where the levee height is 0.5 m lower, in the vicinities of Wyatt Street in South Deniliquin and Smart Street in North Deniliquin. At Wyatt Street the spillway would allow flow to spill in to the lagoon through the town, making it the preferred location.
- The Davidson Street levee should be removed. The study found that in the 100 year ARI flood, the levee obstructs flow over a significant section of the floodway, adversely impacting the flood level at North and South Deniliquin.

While the recommendation of a 1 m freeboard is above the 0.5 m generally used in current practice, it was accepted at the time of the study. Similarly, the study's use of a 1D model results in design flood levels needing to be interpolated and extrapolated to locations across the floodplain. That is, a 100 year ARI flood level of 92.33 mAHD is estimated to occur at both the National Bridge and the bridge over Brick Kiln Creek (shown on Figure 4) connecting Davidson St to North Deniliquin. These modelling assumptions have evolved since the use of 2D hydraulic models became widespread, but that is not to say it was not best practice at the time of the study.

## Deniliquin Flood Protection Levee Study - 1997

A study assessing the flood protection of the proposed levee, including its cost, freeboard, alignment and structure type, was completed in 1997. The study followed an economic appraisal of the levee system (Dept. of Water Resources, 1991) and an Environmental Impact Statement for the proposed levee design (Kinhill, 1996) and was largely aimed at considering various aspects of the design in light of the general dissatisfaction in the community with the proposed levee. Following a proposal to upgrade the levee based on designs proposed in the 1984 study, the community felt that the levee would have significant environmental, aesthetic and economic impacts. Generally speaking, it was felt that the proposed levee, which included a 1 m freeboard, was too high and would have a detrimental effect both on individual property owners through whose properties the levee would be raised, and the town as a whole, via the reduced amenity of the Edward River.

In response to these objections, the study made a detailed assessment of what freeboard should be used, by considering the different components of freeboard and their probabilities, as well as other factors specific to each of the three areas. Using a joint probability approach, an estimation of the preferred freeboard allowance was made, reproduced here in Table 1.

**Table 1 Typical Maximum Freeboard Factors with Joint Probability (Sinclair Knight Merz, 1997)**

| Freeboard Factor | Typical Height (mm) | Probability | Component (mm) |
|---|---|---|---|
| **Wave Action** | 400 | 0.5 | 200 |
| **Wave Run-up** | 200 | 0.5 | 100 |
| **Flood Profile Calculation** | 100 | 1.0 | 100 |
| **Levee Settlement, Cracks, Holes etc** | 150 | 0.5 | 75 |
| **Total** | | | 475 |
| **Freeboard Allowance** | | | 500 |

The results of this approach were adopted for the South Deniliquin levee, which was recommended to have a freeboard of 500 mm. In contrast, the North Deniliquin levee was recommended to have a freeboard of 100 mm, as it was felt that the 500 mm estimate should be balanced against several factors specific to North Deniliquin. These included:

- the environmental and social characteristics of the northern bank of the Edward River and development there requiring access to a low wide river bank,
- substantially lower damage costs associated with the area, and
- the geotechnical features of the area (sand banks) making seepage a concern, which may result in a higher levee not offering the protection that its height suggests.

Furthermore, a lower freeboard was recommended with the caveat that elements of North Deniliquin would be evacuated prior to the Davidson St area being breached, and cutting of water and sewerage infrastructure at a similar time.

In addition to many other changes to the proposed levee, mainly relating to the type of structure and its alignment through individual properties, the study recommended a spillway on Wyatt Street, between Poictiers and Harfleur Streets, as well as a spillway on Blackett Street. The spillway was recommended to be 200 mm above the 100 year ARI level, which was 91.86 mAHD on Wyatt Street and 91.8 to 91.5 mAHD on Blackett Street. There was no recommendation for a spillway in North Deniliquin.

### ***Current Height and Alignment***

The levee as it currently exists was completed in 2012, following a series of smaller studies after the 1997 study, which looked at individual sections of the levee. Generally, the current levee is the elevation recommended in the 1997 study, which itself was based on the 1984 study and applying different freeboards. For example, the levee is 92.83 mAHD at the National Bridge, which represents a 500 mm freeboard on top of the 100 year ARI flood level from the 1984 study. Similarly, the level in North Deniliquin at the Brick Kiln Creek Bridge is 92.43 mAHD, which is 100 mm on top of the same flood level (92.33 mAHD). Some sections of the levee have a higher freeboard of up to 1 m, for example at the southern end of the South Deniliquin levee and one section of the non-river side of the North Deniliquin levee.

The current levee system has a single spillway, beginning at Poictiers Street and extending over 3 km to the end of the South Deniliquin levee, well beyond the two sections recommended in the levee protection study. The spillway is designed to provide a controlled overtopping of the levee and has a design freeboard of 200 mm. Its elevation is 91.86 mAHD to 91.8 mAHD over the first 300 m, and then a constant height of 91.8 mAHD. The section of the levee that the spillway is located on was the subject of further assessment following the levee protection study (1997), which included the Deniliquin Levee Bank Steering Committee coming up with 7 possible alignments, one of which was chosen and currently exists. The point in time at which the 91.8 mAHD level was determined to function as a spillway over the entire length was not able to be determined at present.

### ***Findings of Current Study***

The most recent flood study of the area (‘Edward River Deniliquin Flood Study’) was completed in 2013 by WMAwater. The study provided the first assessment of flood behaviour for the entire Deniliquin LGA since the floodplain management study in 1984. The study included a revised flood frequency analysis using the longer period of record, and used a 2D hydraulic model to simulate design flood behaviour in the LGA. With respect to the hydrological and hydraulic methods involved, the primary differences to the 1984 study were as follows:

- A revised 1% AEP flow of 2204 $m^3/s$ (down from 2500). The lower estimate was a result of the longer length of record, inclusion of the previously omitted 1917 flood event, use of more sophisticated estimation techniques and revision of the stage-discharge relationship based on re-assessment of gauged flows from 1931.
- Better resolution of the area's topography, using LiDAR data collected in 2012.
- A more sophisticated hydraulic model. As the previous model estimated design flood behaviour by extrapolating rating curves for different cross-sections, the study's use of a 2D hydraulic model (based on the TUFLOW software) represents a significant improvement in the spatial reliability of the design flood levels produced by the model.

***Levee Gradient***

The study found that the flood gradient established by the 1984 floodplain management study and used by the 1997 levee protection study was based on assumptions that have since evolved, most notably in North Deniliquin. The difference in the two gradients is shown in Figure 2, which shows the flood level gradients produced by the two studies. The largest difference is in the vicinity of the Davidson Street crossing, where they differ by around 300 mm.

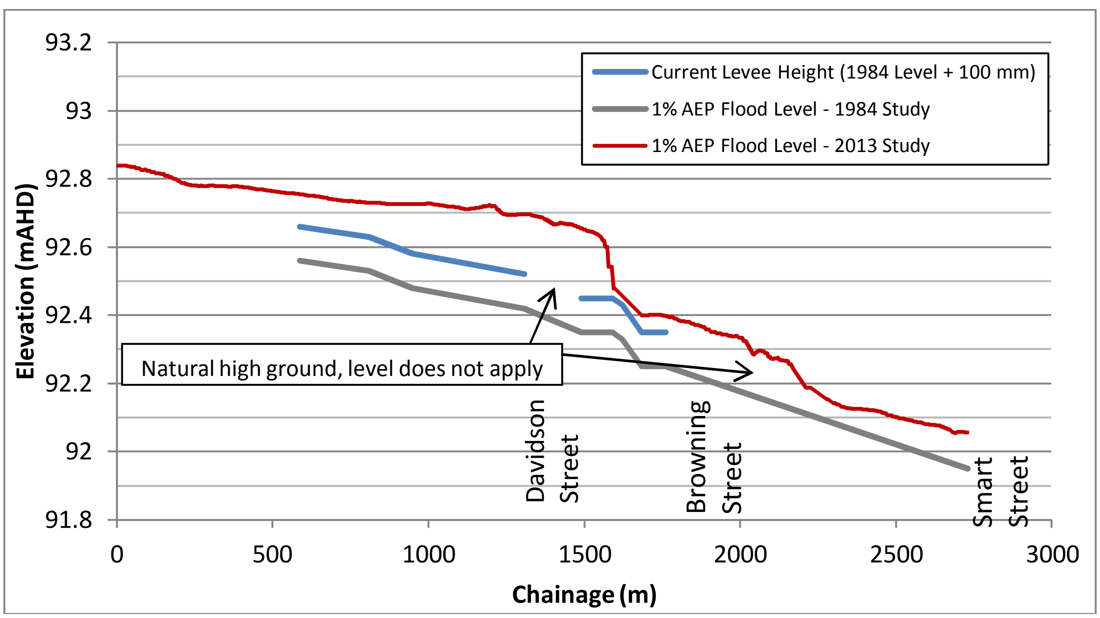


**Figure 2 Change in Design Flood Gradient in North Deniliquin**

The gradient in the 1984 study, which was used to set the height of the levee, was based on the assumption that at the peak flood level, the flood level would be equal along the model cross-sections, which lie perpendicular to the general direction of flow. This assumption is not specific to that study, but is rather an inherent assumption in any model that represents a floodplain with a series of generally parallel cross-sections.

The results of the current study show that at the point where Brick Kiln Creek begins, the water splits away from the main channel and travels approximately 400 m to the bridge over Brick Kiln Creek, dropping by around 0.1 m. In contrast, the main channel winds around to the National Bridge over a distance of 1700 m, with the water level dropping by around 0.4 m. The inaccuracy in the prior flood level arises from its assumption that the water level will be equal at Brick Kiln Creek Bridge and National Bridge, despite the described difference in flow behaviour. The area of interest is shown in Figure 4.

The revised flood levels along the 'wet' side of the North Deniliquin levee cause the levee to be overtopped by up to 200 mm, at three different locations. This 200 mm represents the increase in design flood level (up to 300 mm along the levee) minus the 100 mm freeboard on the North Deniliquin levee. Once overtopped, parts of the North Deniliquin area becomes inundated as the floodwaters spread laterally from Brick Kiln Creek.

### *Spillway Function*

A review of the suite of reports regarding the levee design does not clearly define how the extent or level of the south Deniliquin Levee spillway were determined. The current study found that the spillway was generally too high to function as a spillway, and in large flood events would act to retain water inside the levee. The spillway, which is located on the northern end of the South Deniliquin levee, is 3.24 km long and raised to a height of 91.8 mAHD (except for the first 300 m, which rises to 91.86 mAHD). Figure 3 shows the height of the spillway as compared to the 1% AEP event. Under the current results, the spillway has a freeboard of between 0.4 and 0.9 m, with the majority above 0.5 m.

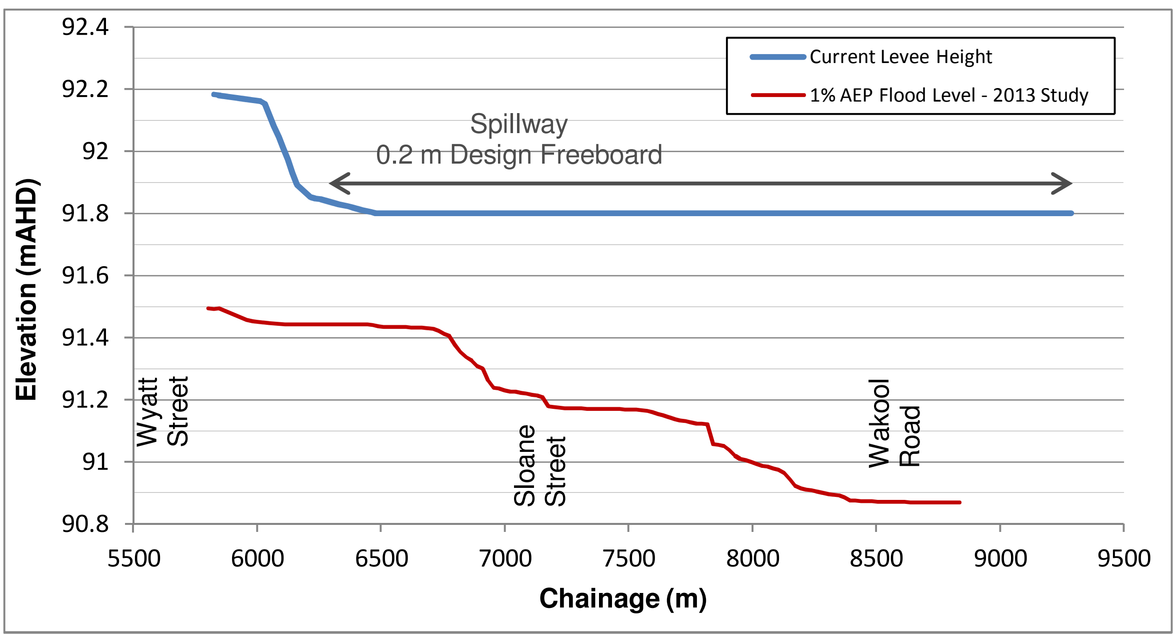


**Figure 3 Spillway Height vs. Current Design Flood Level**

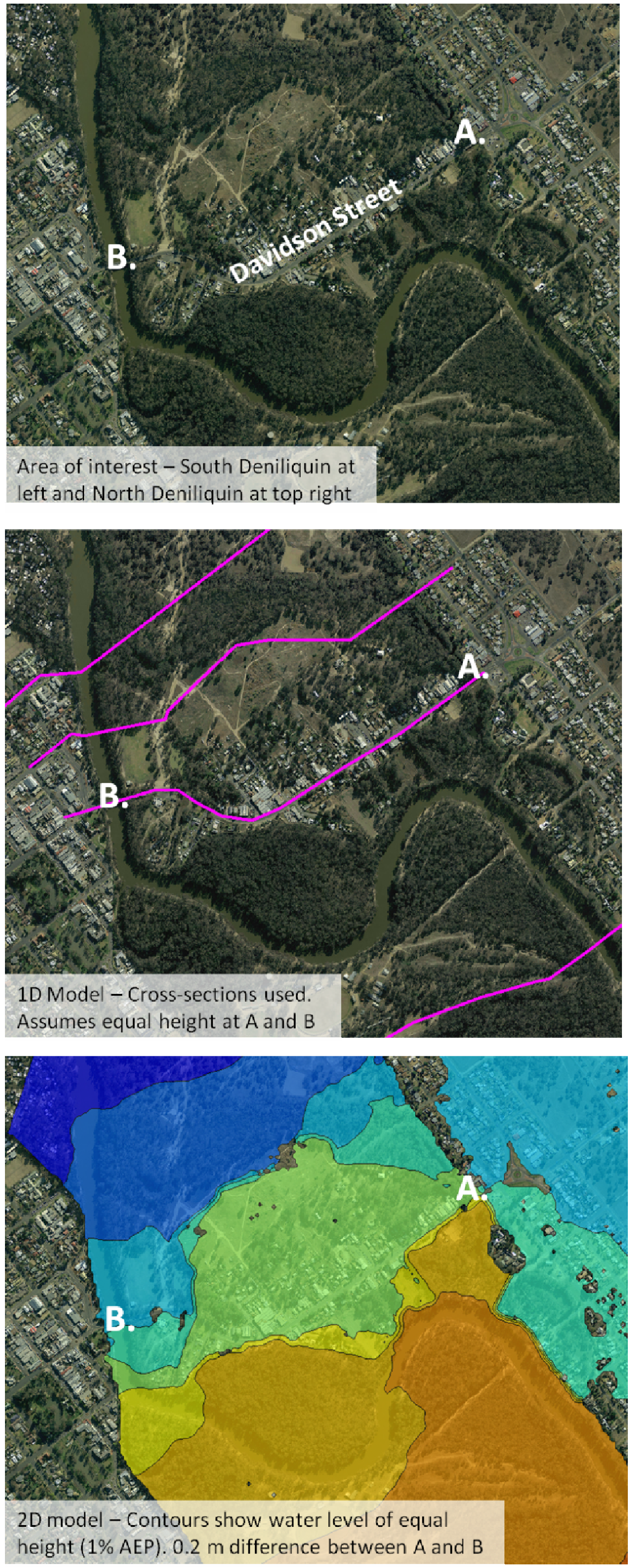


**Figure 4 Change in Model Schematisation**

## Discussion

The evolving understanding of flood behaviour in Deniliquin raises significant questions about best practice with regards to the choice of freeboard levee height and the floodplain management process in general. The current study has found that sections of the levee do not function as intended, and that their malfunction is a result of an inaccurate flood gradient being applied. This section will focus on three main questions in relation to the levee design in Deniliquin:

1. To what extent should freeboard represent model inaccuracies, and how best to communicate this function?
2. When is it appropriate (if at all) for local factors to effectively override the recommended freeboard for an area?
3. At what point in the floodplain risk management process was a reassessment of the flood gradient warranted (for both North Deniliquin and the spillway in South Deniliquin), given that such a reassessment would have avoided the current predicament.

### *Function of Freeboard*

Freeboard is a height added to a design flood level or design height of a levee that aims to account for factors not captured in the design estimate, such as wave action, wave setup and inaccuracies in the hydrologic or hydraulic analysis. Each of these components may have different values, and will occur with particular probability. For Deniliquin, the 1997 levee protection study estimated a 100% likelihood that the flood profile was incorrect by 100 mm, and at the most, it could be off by 300 mm. Given the uncertainties of the modelling process (and the benefit of hindsight), this is considered to be a fair assumption. Whether 100 mm, 300 mm or another value is chosen depends in the perceived uncertainties in the area of interest.

As is made clear by the extensive detail to which it is covered in the 1997 levee protection study, levee freeboard is both difficult to estimate and easily contended by local stakeholders. Each of the components of freeboard (wave action, wave setup, settlement and profile inaccuracies are the main components identified in the 1997 study) are difficult to quantify in both their magnitude and likelihood.

The effect of this is not only that the ‘true’ design flood level is an unknown quantity, but that the concept of freeboard can appear to be a rough estimate. Exacerbating this is the separation of the levee height into a design level and a freeboard value. This separation encourages the interpretation that the design level is a known, well-understood value, while the freeboard represents the unknowns, and hence when a freeboard is unfavourable, it is more easily treated as being a negotiable value, a perceived 'weak point' in the flood estimate. In fact, the design flood level only represents a best estimate, and a discharge with the same probability as the design flood may result in any number of peak flood levels, above or below the estimated flood level of that probability.

If a freeboard is to be used in a potentially unfavoured (to the community) levee design, expounding its function to the community is paramount in gaining their understanding of the management process. The freeboard is not 'free' space where the levee will be dry in its design event, nor is it an arbitrarily chosen value intended as a quick fix where the modeller is unsure of his or her analysis.

### *Balancing Freeboard against Local Needs*

The majority of the current levee in North Deniliquin has a freeboard of 100 mm, 400 mm lower than the freeboard adopted for most of South Deniliquin. This estimate of freeboard was determined in the 1997 study, which found that 100 mm would provide 'a significant level of increased protection while recognising a balanced approach to issues that are specific to North Deniliquin'. It is apparent from that report that the originally proposed levee, with a freeboard of 1 m, was very unpopular with residents. It is not clear whether the reduced level of protection associated with a 100 mm freeboard was communicated to the residents, but it can be assumed there was an understanding that they faced a greater flood risk than South Deniliquin, as there was a 'recognized need' to evacuate elements of North Deniliquin prior to Davidson St being inundated.

The outstanding issue in regards to the existing North Deniliquin levee is that it has a design height of a 1% AEP event, yet its crest height is 400 mm below the South Deniliquin levee, which is also based on the 1% AEP event. Without an informed understanding of the function of freeboard, it may be concluded that the two levees offer an equal level of protection. The rare nature of floods means the community's understanding of flood risk in an area naturally deteriorates in the absence of significant flooding (or controversial mitigation works). While the increased flood risk may have been well understood in 1997 (at the time of the levee protection study) it is most likely lesser so now, especially with new residents.

A possible alternative approach to the levee design height in North Deniliquin is to reduce the design event associated with the levee while increasing its freeboard to a more widely accepted value. Except for small differences in its gradient, the North Deniliquin levee profile is not dissimilar to a 2% AEP event with a 300 mm freeboard. While the use of any standard less than the 1% AEP flood has significant associated issues, it is also apparent that a levee set to the 1% AEP level with 500 mm freeboard is in some ways not feasible in North Deniliquin.

### *Review of Flood Gradient in the Floodplain Management Process*

The change in flood gradient between the 1997 levee protection study and the current flood study, and the associated implications for the North Deniliquin levee and the South Deniliquin levee spillway, clearly illustrate the need for regular review of flood modelling assumptions. While any study that defines design flood behaviour will do so authoritatively (i.e. it will present *the* flood behaviour), any design flood behaviour will have uncertainties arising from assumptions in its analysis, as well as the possibility that the flood behaviour will change due to the floodplain or hydrology.

In hindsight, the 1997 levee protection study presented an opportunity to review the flood levels and assumptions established more than 10 years earlier. The study was commissioned in the context of a community that had strong objections to the proposed levee, and a need to make a re-assessment of the financial costs of the proposal. Despite these varying objectives, additional attention may have been given to the assumed flood height, especially in North Deniliquin where there were no historical flood gradients to compare against, and in the spillway section of South Deniliquin where the levee moved away from the main channel, and hence the historical flood levels were less applicable.

## Conclusions

Flood risk in Deniliquin is significantly mitigated by the town's levee system. The levee, which was first established in 1955 and recently upgraded, has a crest level based on the 1% AEP level with a varying freeboard. The 1% AEP level was determined in 1984, while the freeboard, which ranges from 100 mm to 1 m, was largely defined in the 1997 study. Recent re-assessment of the design flood behaviour has shown that previously established modelling assumptions regarding the flood gradient in Deniliquin are not valid. Consequently, the 1% AEP design flood profile overtops parts of the current levee crest (which includes the 1% AEP flood level plus freeboard) in North Deniliquin. Furthermore, a low freeboard of 100 mm was adopted for most of North Deniliquin, causing the levee to be vulnerable to slight changes in the estimate of the design flood level. The model result resolution from 1984 was also not sufficient to appropriately define the height for the spillway located at the north-west end of the south Deniliquin levee.

Revelation of flawed modelling assumptions and revision of design flood levels are not uncommon in design flood estimation, and their occurrence, in itself, is not cause for alarm. However, given that some 30 years have elapsed since design flood levels were determined for the town, it seems imprudent that the modelling assumptions in question were not reviewed earlier. In hindsight, the 1997 levee protection study was an opportune time to review or re-assess the design flood behaviour. Similarly, the choice of freeboard in North Deniliquin is, in hindsight, too low to allow the structure to fulfil its design purpose. These revisions to the estimation of flood level and freeboard represent advances in understanding flood risk in the area, and provide valuable lessons for floodplain management in general.

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