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FORESHORE PROTECTION REVIEW -
PENRITH LAKES WILDLIFE LAKE

by

M J Blacka and A M Badenhop

Technical Report 2009/09
September 2009

THE UNIVERSITY OF NEW SOUTH WALES
SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING
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1. INTRODUCTION

The Water Research Laboratory (WRL) of the University of New South Wales was commissioned by Penrith Lakes Development Corporation (PLDC) to undertake a review of the foreshore protection for the Wildlife Lake, which is a part of the Penrith Lakes scheme. This review follows a previous analysis of the foreshore protection undertaken for the Wildlife Lake (and other lakes) by Anderson *et al.* (2006). The current layout of the Wildlife Lake as analysed in this study is shown in Figure 1.1. Figure 1.2 shows both the current and previously analysed Wildlife Lake plan layouts overlaid for comparison. This report draws closely on information previously provided by WRL to PLDC for foreshore protection assessments, and it is recommended that the previous reports be considered when utilising the recommendations in this report.

The revision of the foreshore protection for the Wildlife Lake documented in this report assesses the six cross sections as presented in the briefing document labelled Sections A to G and shown in Figures 3 to 9. While a standard 1V:6H sloping foreshore has been considered in this analysis (similar to the foreshore design analysed in Anderson *et al*, 2006), the other foreshore profiles are generally flatter and targeted at achieving a more natural foreshore appearance. A range of foreshore protection options were initially required to be considered in this assessment for each section, including:

- No wave protection
- Emergent macrophytes
- Sandstone boulders
- Loose "gabion" rock
- Compacted raw feed (0.5 m thick).

During this study the foreshore protection options to be considered evolved from the above list, such that loose gabion rock was not considered in the analysis, and raw feed was considered in varying layer thicknesses as a loosely spread material. These protection options and the various cross sections have been considered over the entire foreshore of the Wildlife Lake, including the islands within the lake. Empirical desktop methods have been used in this assessment, with some techniques based on previous physical modelling experience for the Penrith Lakes project while others were based on available literature. The designs recommended are conservative and conceptual only and are based on simple coastal engineering analysis. These designs are suitable for use without further study, however, could be refined through more detailed numerical and physical modelling.

2. LITERATURE REVIEW

This section details a review and summary of available literature, both specific literature regarding foreshore protection for the Penrith Lakes scheme, as well as generally published literature that may be of assistance in assessing the various foreshore protection options.

2.1 Emergent Macrophytes

2.1.1 Overview of Emergent Macrophytes

Emergent macrophytes have been suggested as a possible form of foreshore protection for the Wildlife Lake. While some experimental work has been completed regarding the foreshore protection benefits of emergent macrophytes, there are no proven universal empirical equations that can be used to define the protection ability of emergent macrophytes. Recent research suggests, however, that "wave heights are typically reduced by 50%" by wetland vegetation and "the peak spectral periods also drops as the spectrum becomes more broad banded with higher frequency components" (Coastal Engineering Research Center, 2008). It should also be noted that the majority of literature addresses the use of macrophytes for riverbank protection rather than lake foreshore protection.

The use of vegetation for erosion control was discussed in a previous foreshore protection review (Anderson *et al.* 2006). Several cases were cited where vegetation had proven to be effective for foreshore protection with harsher wave climates than that expected at the Wildlife Lake, and with very mild slopes. Further review focussed on guidelines for establishing a vegetated shoreline; including plant species, shore slopes and vegetation extent and planting techniques.

There are several different factors that influence the efficacy of using vegetation for foreshore protection:

- The type of vegetation
- The slope of the bank
- The location of the vegetation relative to wave attack
- The density of vegetation
- The width of the vegetation or plant bed
- Plant maturity.

Experimental work has shown that different types of vegetation are more resistant to wave attack than others. Coops *et al.* (1996) demonstrated that while *Phragmites australis* (common reed) was able to resist 23 cm waves, *Scirpus lacustris* (common club rush) was not. Frankenburg and Tilleard (1991) claimed that under regulated flow regimes, *Phragmites australis* is the only Australian native species that can effectively stabilise river banks. Experimental work by Cox *et al.* (2000) found that transplanted clumps of *Phragmites australis* could resist attack by 0.3 m waves even on a steep slope of 1:3.

Soil loosening processes were able to be prevented by just 50% grass cover on unstable banks. Brooks (1998) found that bank cohesion was more influenced by vegetation than silt and clay content and that different vegetation types may have more influence on stability than vegetation density, with ground and mid-storey species perhaps more important than tree species. Similarly, Brisbane City Council (2003) noted that grasses and sedges are able to withstand higher shear stresses than trees.

The sustainable slope of the bank is affected by the presence of vegetation. Bare slopes were found to be 2-3 times more likely to fail than vegetated slopes. On unplanted slopes, considerable slope adjustment was seen even under 10 cm waves, and the slope was likely to be gentler than the vegetated slope (Coops *et al.* 1996).

Vegetation at the average low water level is particularly important in preventing undercutting of the root zone (Thorne, 1990 in Raine and Gardiner, 1995). On high steep banks, stability is greatest when reeds grow from below the waterline all the way over the top of the bank (Frankenburg *et al.* 1996). Vegetation zonation from the water's edge to the top of the bank plays an important role in bank stabilisation. Bank stability against wave erosion is best provided by a combination of reeds, shrubs and trees (Frankenburg *et al.* 1996). Species with a "dense network of fibrous roots" are generally more effective at stabilising banks, however, trees with woody roots may enhance drainage and overall stability (Thorne, 1990 in Raine and Gardiner, 1995). The density of the vegetation is likewise important, as the presence of one tree may simply promote turbulence and increased bank attack, whereas erosion will be reduced if other trees are within the wake zone of that tree.

2.1.2 Tschirky et al. (2000)

One of the few extensive comparable field and laboratory studies was completed on Lake Ontario over a three year period by Tschirky *et al.* (2000). It was found that wave transmission varied inversely to plant bed length (width of planting across the profile), and increased plant density, and slightly inversely to incident wave height; and the wave transmission was directly proportional to water depth. The study was completed under the conditions found in Table 2.1.

Table 2.1
Study Parameter Ranges (Tschirky *et al.* 2000)

Parameter	Field Conditions	Laboratory Conditions
Significant wave height (m)	0.02 – 0.40	0.05 – 0.21
Peak wave period (s)	1 - 5	1.25 – 2.5
Average plant density (plants/m^2)	21 - 80	25 - 150
Plant bed length (m)	30 - 120	2.5 - 10
Water depth (m)	0.4 – 1.75	0.5 – 0.95

The dominant plant species in the field site were bulrushes (*Scirpus validus*[1], *Scirpus americanus*) and cattails (*Typha angustifolia, Typha latifolia*), while the laboratory experiment was completed on a 10 m long bed of bulrushes (*Scirpus validus*). These species are not native to Australia.

While trends observed in both field and laboratory studies were in general agreement, two separate wave transmission equations were developed for the laboratory and field data due to the differences in plant bed lengths.

Table 2.2
Wave Transmission Prediction Equations (Tschirky *et al.* 2000)

Equation	R^2	Range of Conditions
1. Laboratory $K_t = \dfrac{1}{1+e^{\left(-1.6-2.86d+0.0033P_p+0.21B\right)}}$	0.93	See Table 2.1 Laboratory Conditions
2. Field $K_t = \dfrac{1}{1+e^{\left(0.75-1.93d+0.019P_p+0.02B\right)}}$	0.65	See Table 2.1 Field Conditions

Note: d= average water depth, B = plant bed length, P_ρ = average plant density (no. plants per m^2) , K_t = wave transmission coefficient ($H_{transmitted}/H_{incident}$)

[1] It may be that *Scirpus validus* is used synonymously with *Scirpus lacustris* (see earlier Coops *et al.* 1996), in which case it may be inferred that these equations would be conservative for *Phragmites australis*, used more commonly in Australia.

2.2 Raw Feed

2.2.1 Overview of the use of Raw Feed and Previous Design Methodologies for Penrith Lakes

Raw feed available for use in the foreshore protection has been considered by WRL in numerous previous studies, including both physical model studies to assess the erodeability of the raw feed, as well as desktop studies for several of the Penrith Lakes to assess foreshore protection options. The characteristics of the raw feed considered in these various analyses has been either a widely graded mix of sand and gravel (primary raw feed), or a modified raw feed having a minimum grain size cut off.

Previous physical model testing of the raw feed was completed at WRL by Cox and Foster (1984), Peirson *et al.* (1990) and Bettington and Cox (1991). Bettington *et al.* (1996) and Anderson *et al.* (2006) used the results of the physical model testing to provide indicative rates of erosion under certain wave conditions. The previous foreshore protection designs have considered foreshore erosion as comprising two separate processes, firstly the short term impacts of storm cut and secondly the longer term effects of littoral transport. During storm events it has been considered that steep foreshore profiles armoured with raw feed would be reshaped to a flatter more dissipative 'S' profile, where material is eroded from the original profile (storm cut). Storm cut is generally considered as a rapid process (occurring over a duration of hours). Under long term exposure to angled wave attack, the smaller grainsize portions of the raw feed material has been determined to be susceptible to longshore transport within the active wave zone (littoral drift). Littoral drift is considered as a slow process (occurring over durations of years and decades), and will result in zones of erosion and deposition of foreshore material around the lake foreshore.

To assess the suitability of raw feed as a foreshore protection option, previous WRL investigations have first identified the volume of raw feed material available to be eroded from the foreshore profile before the underlying compacted earth is exposed. This available volume has been based on a 0.5 m layer thickness of raw feed. Subsequent to this, the storm demand or the volume of storm cut erosion expected during a design storm wave event (typically 50 year Average Recurrence Interval (ARI) event) was determined. The remaining volume of raw feed material still protecting the foreshore slope following a 50 year ARI storm event was considered as the maximum volume of material that could be removed during the design period as a result of littoral transport, without compromising the entire layer thickness of protective raw feed material. Calculations were then undertaken to predict the approximate volume of littoral transport during a 50 year period, and so long as the predicted littoral transport volume was less than the maximum tolerable volume, the raw feed protection option was considered suitable.

2.2.2 WRL TR84/03 (Cox and Foster, 1984)

A range of physical model tests were undertaken by Cox and Foster (1984) at prototype scale in the 3 m flume at WRL, investigating the erosion of raw feed and compacted overburden under wave attack. Tests were undertaken for profile slopes of 1V:6H and 1V:3H with perpendicular wave attack. The raw feed material tested had approximately 15% sand, but was intended to replicate raw feed with 25% - 30% sand. Grading curves for typical raw feed extracted from the Penrith Lakes at the time of the study, as well as the raw feed tested in this flume study, are shown in Figure 2.1.

Equilibrium profiles are presented in Cox and Foster (1984) from the flume testing for raw feed on both 1V:6H and 1V:3H slopes after 3 hours of wave attack, for wave heights ranging from 0.1 – 0.5 m. Threshold wave heights initiating sediment movement were also determined for the raw feed. For an initial slope of 1V:6H, the maximum erosion depth for an equilibrium profile was found to be 0.22 m (for wave heights up to 0.5 m).

Compacted overburden was found from the flume tests to be unsuitable for foreshore protection, as it suffered ongoing and uncontrolled erosion.

2.2.3 WRL TR90/03 (Peirson et al. 1990)

Three different gradings (5 mm minus removed, 20 mm minus removed, 50 mm minus removed) of raw feed were tested by Peirson *et al.* (1990) at a length scale of 1:5. Figure 2.2 shows the grading of the three different materials tested by Peirson *et al.* (1990). The different materials were tested under perpendicular wave attack in the 3 m flume for embankment slopes of 1V:4H and 1V:6H. Subsequently, the raw feed with 5 mm minus material removed was deemed the most efficient for foreshore protection works, and further oblique wave tests were undertaken in the wave basin for a slope of 1V:6H and for wave angles of 30°, 45° and 60° (where 0° would be waves travelling parallel to the shoreline and 90° would be perpendicular wave attack).

Equilibrium profiles for the different raw feed gradings were established for different wave conditions under perpendicular wave attack (from the flume testing). Threshold wave conditions initiating movement for each of the three raw feed grades were also identified for the perpendicular wave attack and are presented in Table 2.3 below.

Table 2.3
Threshold Wave Conditions for Initiation of Sediment Transport (Peirson *et al.* 1990)

Revetment Slope	Revetment Material Grade	Wave Conditions Initiating Movement
1V:4H	5 – 100 mm	H=0.3 m, T=1.3 s
	20 – 100 mm	H=0.4 m, T=1.5 s
	50 – 100 mm	H=0.4 m, T=1.8 s
1V:6H	5 – 100 mm	H=0.3 m, T=1.5s
	20 – 100 mm	H=0.5 m, T=1.8 s
	50 – 100 mm	H=0.6 m, T=2.0 s

The initial wave basin tests for the 5 mm – 100 mm material and 1V:6H slope indicated that the lowest wave height threshold for sediment movement occurred for a 45° wave attack. As such, most tests and detailed analysis was undertaken for this wave angle. Sediment discharge rates and thresholds of sediment movement were presented for a range of wave conditions for the 5 mm – 100 mm material under 45° oblique wave attack and are reproduced in Tables 2.4 and 2.5 below.

Table 2.4
Threshold Wave Height for Sediment Transport under Oblique Wave Attack (Raw Feed with 5 mm Minimum Cut off)

Wave Attack Angle[1] (°)	Slope 1V:4H	Slope 1V:6H
30	-	0.32
45	-	0.22
60	-	0.20
90	0.25	0.28/0.43

(1) Defined as the angle between the wave crest and the embankment face

Table 2.5
Sediment Discharge Rates (m^3/hr/m) under Oblique Wave Attack (Raw Feed with 5 mm Minimum Cut off)

H	Sediment Discharge Rate (m^3/hr/m) as a Function of Wave Angle and Slope					
	30°		45°		60°	
	Slope 1V:4H	Slope 1V:6H	Slope 1V:4H	Slope 1V:6H	Slope 1V:4H	Slope 1V:6H
0.2	0	-	0	0	0	-
0.3	0	-	0	0	0	-
0.4	0.011	-	0.011	0	0.022	-
0.5	0.056	-	0.267	0.022	0.244	-
0.6	-	-	0.333	0.055	-	-
0.7	-	-	0.411	0.088	-	-

2.2.4 WRL TR91/04 (Bettington and Cox, 1991)

A range of physical model tests were undertaken by Bettington and Cox (1991) at prototype scale in the 3 m flume at WRL, investigating erosion of raw feed material under oblique wave attack. Tests were undertaken for profile slopes of 1V:6H and 1V:10H with oblique wave attack at an angle of 45°. These tests were undertaken for unmodified primary raw feed, where the tested material is expected to have a grading similar to the material shown in Figure 2.1.

Rates of erosion (m^3/hr/m) determined from the oblique wave flume testing of primary raw feed are presented for wave heights up to 0.2 m, on slopes of 1V:6H and 1V:10H. Threshold wave heights initiating sediment movement were also determined for the raw feed. These results are reproduced in Tables 2.6 and 2.7 below.

Table 2.6
Summary of Sediment Transport Results for 1V:6H Slope and 45° Oblique Wave Attack (Bettington and Cox, 1991)

Wave Height (m)	Wave Period (s)	Duration (hrs)	Approx. Sediment Transport Rates (m^3/hr/m)
0.04	0.65	0.25	0
0.06	0.75	1.00	0.5×10^{-3}
0.08	0.84	1.00	1.5×10^{-3}
0.12	1.02	0.25	3.8×10^{-3}
0.16	1.15	0.25	5.2×10^{-3}
0.20	1.25	0.25	9.4×10^{-3}

Table 2.7
Summary of Sediment Transport Results for 1V:10H Slope and 45° Oblique Wave Attack (Bettington and Cox, 1991)

Wave Height (m)	Wave Period (s)	Duration (hrs)	Approx. Sediment Transport Rates (m^3/hr/m)
0.03	0.59	0.13	0
0.07	0.55	0.25	0
0.08	0.79	1.00	0
0.12	1.00	1.25	0.5×10^{-3}
0.15	1.11	1.25	2.6×10^{-3}
0.20	1.27	0.5	5.2×10^{-3}

Based on the prototype testing, the required layer thickness was reduced from a previously recommended 0.75 m thickness to a 0.5 m thickness. This reduction was possible, as it was identified that after some of the fines were removed from the raw feed layer, the remaining larger stones form an armour layer to protect the swash zone from further erosion.

A grain size analysis was presented for the material that had been transported during the testing, for both the 1V:6H slope and the 1V:10H slope. This analysis indicated that for waves up to 0.2 m height, the material was reasonably evenly distributed from 0 mm to 20 mm grain size for a 1V:6H slope, while for a shallower 1V:10H slope, the majority of the material transported had a grain size of 0.2 mm – 1.5 mm. Less than 10% of the transported material had a grain size greater than 10 mm. That is, for the 1V:10H slope, only the finer fraction of material was transported.

2.2.5 WRL TR96/13 (Bettington et al. 1996)

Bettington *et al.* (1996) examined the use of raw feed for foreshore protection for Recreation Lakes A and B, which was based on the information obtained in the previous physical modelling studies undertaken at WRL. With respect to the effect of raw feed grading on erodability, Section 5.1 of Bettington *et al.* (1996) stated:

"For uniform materials the voids comprise approximately 40% of the total volume, while in materials with a wide grade the voids between the rocks tend to be filled by the fines. In previous works the raw feed available for use in bank protection was approximately 40% sand (fines) and 60% gravel. With embankments constructed of this material as the fines are removed, the revetment 'armours up', the depth of the profile would remain largely unchanged as the fines are washed from the larger voids.

PLDC has indicated that the raw feed which will be available for bank protection within the recreational lakes may consist of up to 60% sand and 40% gravel. It is anticipated that under wave attack selective sorting of the finer material will occur such that fines removed from the embankment could locally reduce the material by as much as a third. As a result, to compensate for this, the overall embankment thickness will need to be increased from 0.5 m (40% sand) to 0.65 m (60% sand) for future works comprising sandy raw feed."

The methodology adopted for this assessment is based on the assumption that the raw feed layers will be placed as 0.5 m thickness (60% gravel) or 0.65 m thickness (40% gravel). Based on these layer thicknesses, the steepest permissible slope was determined for the foreshore of the lakes. This analysis took into consideration both the storm cut and the littoral sediment transport. No clear indication was made as to the technique on which the sediment transport calculations were based. In discussion of the storm cut process, reference was made to the measured storm cut from Peirson *et al.* (1990). In discussion of the littoral transport processes, indication was given that the rates of littoral transport were calculated based on both Bettington and Cox (1991) (physical modelling of oblique wave attack on un-modified raw feed) and Peirson *et al.* (1990) (physical modelling of perpendicular and oblique wave attack on raw feed with 5 mm minimum cut off). It should be noted that these two studies investigated different variations of raw feed, and identified different erosion rates and storm cut depths. The foreshore protection analysis undertaken in this study was for raw feed having a range of grading curves as shown in Figure 2.3, which can be seen to have a 5 mm minimum grain size cut off.

2.2.6 WRL TR2005/12 (Anderson et al. 2006)

This report detailed the design of foreshore protection for Recreation Lakes A and B as well as the Wildlife Lake. Section 2 states that "*Armouring is to be undertaken with raw feed sand and gravel with 5 mm cutoff……. Design advice and review presented within this study requires the same rawfeed material be used for armouring of the embankments*".

Section 2.1 goes on to describe material selection and states "*Figure 3* (Grading Curve – same as reproduced in Figure 2.3 of this report) *indicates that a range of grain size distributions for the 5 mm- cutoff rawfeed gravel are acceptable. Bettington et. al. (1996), however, makes it clear that the ratio of gravel to sand within the mixture is a crucial design parameter. This work indicated that while the minimum design thickness for a 60% gravel and 40% sand rawfeed armour layer is 0.5 m, it is 0.65 m for a mixture of 40% gravel and 60% sand*". It should be noted though, that raw feed with a 5 mm cut off will have 0% sand.

For analysis of littoral raw feed erosion rates, Anderson *et al.* (2006) adopted the transport rates of Peirson *et al.* (1990) for slopes of 1V:4H and 1V:6H (erosion rates for raw feed with a 5 mm minimum grain size). Based on the results of Bettington and Cox (1991), it was estimated that the raw feed would erode half as quickly on a 1V:10H slope, compared with a 1V:6H slope. This was used to extrapolate the erosion rates from Peirson *et al.* for the flatter slope of 1V:10H and higher wave climates. The sediment transport rates used in the Anderson *et al.* (2006) analysis considered only the rates for the raw feed material coarser than 5 mm.

Predictions made by WRL in Anderson *et al.* (2006) using raw feed erosion rates determined from Peirson *et. al*. (1990), are summarised in Tables 2.8 and 2.9 below. These results indicated for the Wildlife Lake that during a 50 year ARI event (significant wave height up to 0.7 m), the maximum volume of storm cut from a 1V:4H slope armoured with raw feed was greater than 2.5 m^3/m (erosion depth of full 0.5 m thick layer, indicating failure of the revetment). For a slightly flatter 1V:6H slope the predicted storm cut was 3.9 m^3/m (erosion depth of 0.4 m or 80% of the available raw feed layer). For flatter slopes of

1V:8H and 1V:10H the extrapolated erosion rates predicted no storm cut for significant wave height up to 0.45 m.

Table 2.8
Storm Cut (Volume of Erosion) to Revetment (m^3/m) following Several Hours of Wave Attack (Anderson *et. al.* 2006)

Significant Wave Height (m)	**Volume of Material Removed (m^3/m)**			
	1V:4H	1V:6H	1V:8H	1V:10H
0.40	0.04	0.00	0.00#	0.00#
0.45	0.72	1.38	0.00#	0.00#
0.50	1.46	1.74	-	-
0.60	2.47*	2.56	-	-
0.75	>> 2.47*	3.88	-	-
0.90	>> 2.47*	5.47*	-	-

* Indicates failure of the 0.5m thick revetment (or 0.65m for 60% sand)
# Indicates assumed values
- Indicates test data is not available

Table 2.9 presents the results from Table 2.8 in terms of the depth of raw feed material removed from the profile. These results assume that material is uniformly removed from ± H_s (significant wave height) either side of the still water level.

Table 2.9
Storm Cut (Average Depth of Erosion) to Revetment (m) following Several Hours of Wave Attack (Anderson *et. al.* 2006)

Significant Wave Height (m)	**Depth of Material Lost from Profile (m)**			
	1V:4H	1V:6H	1V:8H	1V:10H
0.40	0.01	0.00	0.00#	0.00#
0.45	0.19	0.25	0.00#	0.00#
0.50	0.35	0.29	-	-
0.60	0.50*	0.35	-	-
0.75	>> 0.50*	0.43	-	-
0.90	>> 0.50*	0.50*	-	-

* Indicates failure of the 0.5m thick revetment (or 0.65m for 60% sand)
# Indicates assumed values
- Indicates test data is not available

Results presented in Anderson *et al.* (2006) for littoral transport over a 50 year period found that for a raw feed armoured slope of 1V:4H, most of the foreshore would experience less than 0.1 m^3/m of littoral raw feed erosion, with localised high rates predicted of up to 1.1 m^3/m on the eastern foreshore. For flatter slopes of 1V:6H and 1V:8H, littoral transport rates were determined to be less than 0.1 m^3/m around the entire foreshore of the Wildlife Lake.

2.2.7 Implications for Current Wildlife Lake Assessment

The primary raw feed considered in this report for the current Wildlife Lake foreshore protection has no minimum grain size cut off. The analysis previously completed by Anderson *et al.* (2006) and the associated raw feed foreshore protection design, was only applicable for raw feed having a 5 mm minimum grain size cut off. It is expected that the additional sandy portion of the raw feed will result in higher erosion rates, and consequently, thicker layers of raw feed are required for foreshore protection in high wave climate areas.

In terms of storm cut erosion, an assessment has been made to compare the storm cut results obtained by Cox and Foster (1984) for primary raw feed without removal of fine material, with the results obtained by Peirson *et al.* (1990) for raw feed with 5 mm minus material removed, and raw feed with 50 mm minus removed. This analysis compared the maximum erosion cut for perpendicular wave attack (based on the presented equilibrium profiles from each modelling report) for a slope of 1V:6H, with wave conditions having wave height of 0.2 – 0.3 m and 0.5 – 0.6 m (using comparable wave height ranges for each study). The results of the analysis are shown in Table 2.10 below.

Table 2.10
Maximum Storm Cut Depth for Different Raw Feed Gradings
(Perpendicular Wave Attack)

Approx Wave Height (m)	**Maximum Storm Cut Depth (m)**		
	Raw Feed No Min. Cut Off	**Raw Feed 5 mm Min. Cut Off**	**Raw Feed 50 mm Min. Cut Off**
0.2 – 0.3	0.10	0.03	Below Threshold
0.5 – 0.6	0.22	0.08	0.05

While this analysis is somewhat crude, it indicates that the expected storm cut for unmodified raw feed is approximately 140 mm deeper, than for the raw feed with 5 mm minus material removed, under wave conditions with wave height approximately 0.5 – 0.6 m. For smaller wave conditions with wave heights of 0.2 – 0.3 m, the difference in storm cut is approximately 70 mm.

In terms of longshore or littoral erosion of the raw feed foreshore protection, the analysis completed in Anderson *et al.* (2006) assumed that there was no littoral transport of material below a threshold significant wave height of 0.4 m. This was based on the transport rates from the physical modelling study in Peirson *et al.* (1990), and was therefore only applicable for raw feed with a 5 mm minimum grain size cut off. Bettington and Cox (1991) noted that for raw feed with no minimum cut off, the finer portion of the sediment (less than approximately 2 mm grain size) will be transported at wave heights greater than approximately 0.06 m. However, the finer material is only removed from within the pore space of the coarser gravel matrix, which is not transported until the wave height is at least approximately 0.3 – 0.4 m. This indicates that the littoral sediment transport volumes for the revised raw feed with no minimum cut off are likely to be initially higher than predicted in Peirson *et al.* (1990) and Anderson *et al.* (2006), until the layer becomes armoured (through winnowing of fines). Once the layer becomes armoured, it is expected that sediment transport rates would once again be more in line with the rates determined by Peirson *et al.* (1990) for raw feed with a 5 mm minimum cutoff.

Vegetation to be grown around the foreshore will benefit from the increased finer sand component in the raw feed layer. The vegetation is also likely to result in reduced removal of the sand component of the raw feed layer (compared to the predicted rates from the physical model studies), as the sand will be further trapped within the root matrix.

2.3 Sandstone Boulders

The use of sandstone boulders as foreshore protection is considered a more robust and engineered solution, that is typically suited to more extreme wave conditions and/or steeper slopes than can be tolerated by the other sand/gravel protection options considered.

Two design equations are commonly used by coastal engineers for sizing of rubble armouring, these being the Hudson Equation and the van der Meer Equation. The Hudson Equation (CERC, 2008) is the more traditional and basic empirical design equation, and is known to predict required armour sizes conservatively. The van der Meer Equation (CIRIA, 2006) considers a larger range of design parameters for sizing of rubble armouring, and typically provides reasonable but slightly less conservative armour size predictions.

$$M_{50} = \frac{\rho_r g H^3}{K_D \Delta^3 \cot\alpha} \quad \text{(Hudson equation)}$$

$$\frac{H_s}{\Delta D_{n50}} = c_{pl} P^{0.18} \left(\frac{S_d}{\sqrt{n}} \right)^{0.2} \xi_m^{-0.5} \quad \text{(van der Meer equation for plunging waves)}$$

Where:

M_{50} = Median armour stone mass (kg)
D_{n50} = median armour stone equivalent cube side length (m)

ρ_r = Armour stone density (kg/m^3)
ξ_m = Surf similarity parameter
α = slope angle (º)
K_D = Hudson stability coefficient
Δ = Relative buoyant density
H_s = Significant wave height
C_{pl} = Constant (6.2 for plunging waves)
P = Notional permeability of the structure
S_d = Damage parameter
n = Number of waves.

WRL has identified the seaward slope and crest of foreshore section E (Figure 1.7) of the considered foreshore profiles, to be more of a submerged armoured structure than a typical emergent revetment (for normal lake water levels). It is generally considered that when wave energy is able to pass over the crest of a submerged structure, less energy impacts on the armouring, and therefore smaller armouring should generally be required. There are some design equations for submerged breakwater armouring, however, during periods of low lake water level the outer mound will behave as a standard emergent overtopped revetment. It is therefore appropriate to adopt the design equations of Hudson and van der Meer for this location, due to the possibility of low water levels.

3. WAVE CLIMATE REVIEW

3.1 Requirements for Wave Climate Review

As shown in Figure 1.2, the current Wildlife Lake design resembles the layout previously analysed by Anderson *et al.* (2006), however, in terms of wave climate and foreshore protection, a range of changes have been made, including:

- Increasing the northern extent of the lake by approximately 100 m to 200 m
- Reducing the northern extent of the southern peninsula by approximately 200 m
- Reconfiguring the layout of the islands within the lake.

As there is the potential for changes in the wave climate at various locations around the lake foreshore, the wave climate during extreme 50 year ARI conditions has been reassessed. A sensitivity analysis has also been undertaken to investigate the wave climate during 20 year ARI and 100 year ARI wind conditions. In terms of wave climate under typical or more frequently occurring conditions, it is expected that the changes to the layout of the Wildlife Lake would have had relatively little effect.

3.2 Design Wind Climate

Early foreshore protection assessments undertaken by WRL for various lakes in the Penrith Lakes scheme adopted the AS1170 design wind speeds for assessment of the wave climate, as there was no extensive recorded wind data available. Since 1990 wind measurements have been made at Penrith Lakes. Recorded wind data up to 2003 was considered in the assessment undertaken by Anderson *et al.* (2006), where the data was used to develop a modified AS1170 design wind climate. In summary, design extreme wind speeds were extrapolated from the 13.5 years of recorded data, and it was recognised that the AS1170 design wind speeds were overly conservative. The recommended Terrain Category using the AS1170 method for Penrith is Category 1, however, it was identified from the extrapolation of the recorded wind data that Terrain Category 2 design wind speeds were more realistic. As well as this, the recommended directional wind speed reduction factors were modified slightly to more closely reflect the recorded wind data.

While it is recognised that there is now 19 years of wind speed data at the Penrith Lakes site, to expedite this project, the same extreme wind climate that was considered for use in Anderson *et al.* (2006) has been adopted. As this wind climate did consider 13.5 years of the recorded data, it is unlikely that the wind climate during extreme events would have altered substantially as a result of the additional six years of data. It is recognised that PLDC may in the future wish to re analyse the entire length of available wind data, and consider the effects that this may have on the wave climate and foreshore protection design.

The wind climate used in this investigation, as developed in Anderson *et al.* (2006), is shown in Table 3.1.

Table 3.1
10 Minute Design Wind Speeds for Penrith Lakes
(Based on Measured Data and AS1170)

ARI	U_{10min} Directional Wind Speed (ms^{-1})							
	N	NE	E	SE	S	SW	W	NW
1	13.0	10.5	11.0	11.0	11.0	12.5	17.2	16.8
2	14.4	11.6	12.1	12.1	12.1	13.8	19.0	18.6
5	16.1	12.9	13.6	13.6	13.6	15.5	21.2	20.8
10	17.3	13.9	14.5	14.5	14.5	16.6	22.7	22.3
20	18.4	14.7	15.5	15.5	15.5	17.6	24.2	23.7
50	19.7	15.8	16.6	16.6	16.6	18.9	25.9	25.4
100	20.6	16.6	17.4	17.4	17.4	19.8	27.1	26.6

3.3 Design Wave Climate and Nearshore Wave Dissipation

3.3.1 50 Year ARI Wind Wave Climate

Wind wave heights were estimated using the principles of SPM (1984), the US Army Coastal Engineering Manual (EM 1110-2-1100, 2002) and the software ACES within CEDAS (version 4.0.3) as described below. To assess the effects of different fetch for different locations around the Wildlife Lake foreshore, the wind wave analysis was undertaken at a range of discretised representative locations (44 locations in total) around the foreshore, selected to give reasonable interpretation of the wave climate.

Due to the convoluted shape of the Wildlife Lake and the internal islands, the available fetch in all directions (discretised into 5º directional increments) was determined for each of discretised foreshore locations, and used in the Restricted Fetch technique (as described in the SPM, 1984, p 3-51), for wave prediction. Using the design wind data presented in Table 3.1 and the wave hindcasting techniques discussed, extreme local wind wave conditions were estimated for the Wildlife Lake foreshore. Predicted significant wave heights were found to vary from less than 0.2 m up to 0.6 m for the 50 year ARI wind events. The wave climate determined for the Wildlife Lake layout considered in Anderson *et al.* (2006) had significant wave heights up to 0.7 m for a localised stretch of the eastern foreshore, which is 0.1 m higher than the revised calculations. This indicates that in general, the wave climate is reasonably similar for both the current lake layout, and that previously considered.

The range of calculated wave climates was discretised into five separate categories (each category covering a 0.1 m range in significant wave height). Table 3.2 below shows the discretised wave climate bins. Figure 3.1 shows the predicted 50 year ARI wave climate map for the entire foreshore of the Wildlife Lake.

Table 3.2
Discretised 50 Year ARI Wave Climate Bins for the Wildlife Lake

Wave Category	Significant Wave Height, H_s (m)	Spectral Peak Wave Period, T_p (s)
A	<0.2	1.6
B	0.20 – 0.29	1.6 – 1.8
C	0.30 – 0.39	1.8 – 2.1
D	0.40 – 0.49	2.1 – 2.3
E	0.50 – 0.60	2.3 – 2.5

3.3.2 Sensitivity Analysis

As requested in the project brief, an analysis has been undertaken to consider the sensitivity of the wave climate to variations in the wind speed. In particular, the sensitivity analysis was to consider the 20 year and 100 year ARI storm conditions. Considering the design 10 minute sustained wind speeds shown in Table 3.1, the wind speed is 1.3 to 1.7 m/s less during a 20 year ARI event compared with the 50 year ARI event, and the wind speed is 0.8 to 1.2 m/s higher for a 100 year ARI event compared with the 50 year ARI event. These differences in wind speed translate to a reduction in significant wave height of 0.01 to 0.03 m between the 50 and 20 year ARI events, and an increase of 0.01 to 0.03 m in the significant wave height for a 100 year ARI event. Clearly such small changes in the wave climate indicate that the wave climate is relatively insensitive to ARI of the storm event. This also indicates that any foreshore protection designed to adequately meet a 20 year ARI event, should in theory suffer little more damage as a result of wave attack in a 100 year ARI storm event.

3.3.3 Nearshore Wave Breaking and Dissipation

Waves are expected to shoal, break, and dissipate as they pass over the foreshore slope. For the flatter slopes, there is expected to be a reasonable difference in wave heights at various distances seaward from the shoreline due to this breaking and dissipation process. To understand this process better, calculations have been made using the surf-zone model by Dally, Dean and Dalrymple (1984) within the numerical model of SBEACH (version 4.03). This analysis has considered each of the analysed foreshore sections (Sections A to G as shown in Figures 1.3 to 1.9), as well as a range of wave conditions as shown in Table 3.1.

Results of this analysis for each of the sections and wave climate categories are included in Appendix A.

3.4 Modified Wave Climate with Additional South-Western Island

Following the initial wave climate analysis documented in Section 3.3, the effects of an additional island in the south-western corner of the Wildlife Lake on the wave climate were considered (as requested during the course of this study by PLDC). This island provides significant wave reduction around the southern foreshore of the lake, to the west of the southern peninsula. The wave climate analysis adopted the same assessment technique as discussed in Section 3.3. Results of the wave climate analysis with the inclusion of the south-western island are shown in Figure 3.2. It should be noted that the island geometry and location considered in this analysis was developed by WRL to provide a maximum level of protection for the southern foreshore, while still being located in the approximate area requested by PLDC. If the size or location of the island is changed significantly, the protection offered by the island may alter.

4. FORESHORE PROTECTION DESIGN METHODOLOGY

4.1 Overview

Four alternative foreshore protection options have been considered in this investigation. Varying degrees of information are available (as summarised in the literature review) for assessing each of the options, and as such, the reliability of each assessment has to be taken into consideration when recommending suitable foreshore protection strategies. For example, considerable amounts of physical modelling and foreshore protection design has previously been undertaken for the raw feed material, however, there is little available quantitative information regarding the protection offered by planting of the foreshore.

Based on the analysis presented in Sections 4.2 – 4.7, a range of design guideline figures have been produced for each of the foreshore cross sections (see Figures 4.1 – 4.19). These designs take into consideration the full range of expected wave climates around the Wildlife Lake foreshore, as well as each of the cross section geometries, and the different foreshore protection options. The designs are based on the requirement of minimal maintenance as a result of typical and storm conditions up to a 50 year ARI event. For some foreshore protection alternatives there is only limited information available on which to base the foreshore designs (such as the erosion of raw feed on flatter 1V:20H slopes). For these cases, the available information has been extrapolated to provide conservative preliminary design solutions.

4.2 No Foreshore Protection

For this investigation WRL have assumed that the land surrounding the Wildlife Lake will comprise compacted overburden material, as has been the case for previous foreshore protection assessments undertaken for the Penrith Lakes scheme. If no foreshore protection was provided it is expected that the foreshore slopes would also comprise compacted overburden material.

While it is recognised that several of the cross section profiles being considered have moderately flat slopes (1V:20H, see Figures 1.3 to 1.9), if no foreshore protection is provided, there is little control over long term changes in foreshore alignment as a result of ongoing low energy wave conditions. Cox and Foster (1984) recommended from their physical model testing, that compacted overburden material was not a suitable foreshore material, as it suffered uncontrollable and ongoing erosion when subjected to wave attack.

Realignment of the foreshore would occur in places of higher wave energy, and it would be expected that erosion scarps would develop around the foreshore during storm events.

Considering the wave climate analysis undertaken in Section 3, it can be seen that there are very few stretches of the Wildlife Lake foreshore that could be expected to suffer minimal erosion when a storm occurs, if no foreshore protection is provided. It is therefore recommended that if a low maintenance solution is required, the option of no foreshore protection not be considered.

4.3 Emergent Macrophytes

4.3.1 Design Considerations

When considering the effectiveness of protection offered by planting around the shoreline, a range of factors have to be considered, including:

- Tolerable wave conditions
- Wave reduction
- Additional bank stability.

It has been identified in Section 2.1, that the ability of plants to withstand wave exposure is limited to waves less than approximately 0.2 – 0.3 m in height, depending on the species of plant (the length of time the plant has been established is also expected to affect this). Under more severe wave conditions establishing plants would be difficult and require considerable maintenance. The plants would also be at risk of suffering damage during storm events, which could in turn lead to additional erosion around the foreshore, especially in areas where the plants are relied upon to stabilise the foreshore.

Based on this criteria, WRL have identified areas where the wave climate is expected to be suitable for plants to become established, and to not suffer damage from wave attack during moderate to extreme wave events. These areas comprise zones of foreshore where the wave climate is expected to have a significant wave height of no more than approximately 0.2 m. The small stretches of foreshore that are exposed to a wave climate category A (see Table 3.2 and Figure 3.1) are identified as suitable planting areas, for all of the proposed foreshore cross sections. Based on the analysis of the nearshore wave dissipation (results presented in Appendix A), it can also be seen that for cross sections A, B, C and D, the region extending 4 – 5m from the shoreline into the lake also has tolerable wave exposure for wave climate categories B and C.

For the flatter 1V:20H slopes of cross sections A, B, C and D, plants may be able to be successfully grown further from the shoreline than this outer 4 – 5 m band, as the higher wave climate is only associated with short duration and infrequent events. Some localised damage to the plants may occur during larger storm events, and as such, a minimum level of loose raw feed protection is also recommended for these slopes. It is expected that the plants would naturally recover over time.

For the design guideline figures presented (Figures 4.1 to 4.19), areas suitable for planting where no damage to the plants is expected, have been identified. Planting over the remainder of the 1V:20H is strongly recommended, and will reduce any erosion that may occur and also reduce the extent of wave runup above the lake water level. These areas have also been identified on the figures as areas where planting is recommended, but possible damage during storm conditions should be expected.

4.3.2 Other Considerations

As discussed in Anderson *et al.* (2006) the following guidelines are given for the establishment of a vegetated shoreline.

1. Plant Species. Detailed botanical advice would be required for selection of appropriate plant species at the Wildlife Lake, and should take into account (but not be limited to) the following: the plant structure and planting density (to offer dissipation of waves and reinforcement of embankment comparative to the species listed in the literature review); biodiversity; effects on water quality; seasonal growth patterns, and; resilience to flooding or water level changes.
2. Vegetation Extent. Wider vegetation regions offer more effective protection and the *minimum* recommended width is 6 metres. As the selected species may thrive only within a range of water depths / distance from the shore, the maximum width becomes a function of the slope i.e. the more gradual the shore slope, the broader the possible planting width.
3. Planting and Growth. The specifics of planting techniques used at Penrith will be subject to the species selected, and should take into consideration the susceptibility of plants to currents, inundation and attacks from fauna or other plant species. If project constraints allow, establishment of a healthy vegetated foreshore region could be performed *prior* to filling of the lake. This could be performed by using seedlings or sprigs, with adequate irrigation and protection until the vegetation is well established. Once established, filling of the lakes could be performed. This method has the advantage of allowing better access during the establishment phase. The use of sprigs,

seedlings or tubestock is not recommended if planting occurs while the lakes are filled. While some cases studies have reported a degree of success using temporary artificial wave dissipation barriers to protect the plants in the planting and growth phases, studies by WRL (including physical model studies) have shown that transplanting of 'rhizome clumps', preferably from nearby sources, provides the most satisfactory survival rates.

4.4 Loosely Spread Raw Feed

4.4.1 Overview

Previous assessments of raw feed foreshore protection have identified the steepest slope at which a 0.5 m thick raw feed layer was not compromised during a 50 year design period (as a result of combined storm cut and littoral losses). Based on discussions with previous WRL investigators, it is assumed that the previous use of a 0.5 m thick raw feed layer was due to practical restrictions on placement of the material. As such, the option of optimising the foreshore protection by placing thinner layers of raw feed in low energy wave climate zones has not been previously investigated.

For the current construction methodology, PLDC have advised WRL that a minimum layer thickness of raw feed that can be placed with suitable tolerance is 0.1 m. For design considerations, it was requested by PLDC that minimum raw feed layer thicknesses be specified, for each different foreshore profile (Figures 1.3 – 1.9), when subjected to each wave climate category (Table 3.2).

4.4.2 Storm Cut Assessment

Storm cut erosion volumes were presented by Anderson *et al.* (2006) for slopes as shallow as 1V:6H, based on previous physical modelling (see Table 2.8 for reproduction of these volumes). These erosion volumes were for raw feed having a 5 mm minimum grain size cut off. Furthermore, during this study, comparisons between equilibrium profiles measured during previous wave flume tests have identified (for a slope of 1V:6H) that raw feed with no minimum cut off will experience a maximum storm cut depth approximately 140 mm deeper for wave heights of 0.5 – 0.6 m, and 70 mm deeper for wave heights of 0.2 – 0.3 m, than raw feed with a 5 mm minimum cut off. No assessment of raw feed erosion volumes for slopes as flat as 1V:20H has previously been undertaken.

Based on the storm cut volumes from Anderson *et al.* (2006), predictions have been made for storm cut depths on 1V:6H and 1V:20H slopes, including an allowance for additional storm cut due to the difference in raw feed grading. These predictions are shown in Tables 4.1 and 4.2 below. The storm cut depths have been determined by assuming that the erosion volume occurs uniformly over an area of +/- H_s about the still water level.

Table 4.1
Raw Feed Storm Cut Volumes and Depths for a 1V:6H Slope

Wave Category	Wave Height, H_s (m)	Storm Cut Volume (1) (m^3/m)	Storm Cut Depth (2) (m)	Additional Cut Depth Due to Fine Material (3) (m)	Total Storm Cut Depth (m)
A	< 0.20	0.0	0.00	0.00	0.00
B	0.20– 0.29	0.0	0.00	0.07	0.07
C	0.30 – 0.39	0.0	0.00	0.10	0.10
D	0.40 – 0.49	1.7	0.29	0.14	0.43
E	0.50 – 0.60	2.6	0.35	0.18	0.53

(1) Approximate storm cut volume for raw feed with 5 mm minimum grain size cut off
(2) Approximate storm cut depth for raw feed with 5 mm minimum cut off
(3) Additional allowance for storm cut due to raw feed having no minimum grain size cut off

Table 4.2
Raw Feed Storm Cut Volumes and Depths for a 1V:20H Slope

Wave Category	Wave Height, H_s (m)	Storm Cut Volume (1) (m^3/m)	Storm Cut Depth (2) (m)	Additional Cut Depth Due to Fine Material (3) (m)	Total Storm Cut Depth (m)
A	< 0.20	0.0	0.00	0.00	0.00
B	0.20– 0.29	0.0	0.00	0.07	0.07
C	0.30 – 0.39	0.0	0.00	0.10	0.10
D	0.40 – 0.49	1.7	0.09	0.14	0.23
E	0.50 – 0.60	2.6	0.13	0.18	0.31

(1) Approximate storm cut volume for raw feed with 5 mm minimum grain size cut off
(2) Approximate storm cut depth for raw feed with 5 mm minimum cut off
(3) Additional allowance for storm cut due to raw feed having no minimum grain size cut off

4.4.3 Littoral Drift Assessment

Results presented in Anderson *et al.* (2006) for littoral transport over a 50 year timeframe found that for a raw feed (with 5 mm minimum grain size cut off) armoured slope of 1V:4H, most of the foreshore would experience less than 0.1 m^3/m of littoral erosion, with localised rates predicted up to 1.1 m^3/m on the eastern foreshore. For flatter slopes of 1V:6H and 1V:8H, littoral transport rates were determined to be less than 0.1 m^3/m around the entire foreshore of the Wildlife Lake. This translates to an erosion depth of approximately 0.03 m over a 50 year period, which is considerably less than the erosion that will result from storm cut. These littoral drift calculations were based on the erosion rates determined from Peirson *et al.* (1990), and had no sediment transport below a threshold wave height of 0.4 m. The wave climate driving littoral transport for the Wildlife Lake is expected to have changed very little for the current Wildlife Lake layout, compared to that considered in Anderson *et al.* (2006). However, the raw feed material proposed for use has no minimum grain size cut off, and therefore littoral erosion rates are expected to be slightly higher, at least initially.

The only physical modelling previously undertaken which assessed littoral drift of primary raw feed with no minimum grain size cut off, was by Bettington and Cox (1991). Wave heights up to only 0.2 m and slopes of 1V:6H and 1V:10H were considered in this study, with the resulting littoral drift erosion rates as shown in Tables 2.6 and 2.7. Clearly for raw feed with no minimum grain size cut off, the threshold wave height for initiation of littoral sediment transport is significantly lower than 0.4 m, as was adopted in the previous study of Anderson *et al.* (2006) for the coarser raw feed grading. The littoral drift erosion rates presented by Bettington and Cox (1991) for waves up to 0.2 m height, were approximately an order of magnitude less than the erosion rates presented in Peirson *et al.* (1990) for wave heights up to 0.7 m.

Based on the observations of Bettington and Cox (1991), it can be assumed that the majority of the littoral erosion experienced for smaller wave heights (less than 0.4 m) is associated with winnowing of the fines from within the upper portions of raw feed layer (as confirmed by the grading analysis undertaken in Bettington and Cox (1991) of the eroded material). However, the gravel component of the raw feed layer is expected to remain intact, and as such, this winnowing will produce very little reduction in the actual thickness of the raw feed layer.

Once the raw feed slope is exposed to wave heights above approximately 0.4 m, erosion of the gravel component of the raw feed will begin to occur. A conservative approximation is to assume that the littoral drift erosion volumes will be approximately double those identified by Anderson *et al.* (2006), as the raw feed currently proposed for use has approximately 40% of material smaller than 5 mm. For this study, a simple but conservative allowance for littoral erosion is therefore been to adopt a littoral drift erosion volume of approximately double that identified by Anderson *et al.* (2006), which equates to 0.2 m^3/m.

4.4.4 Recommended Raw Feed Layer Thickness

As with previous foreshore protection designs, the minimum required raw feed layer thickness is the sum of the 50 year ARI storm cut, and the littoral losses expected over a 50 year design period. Given that the majority of the erosion will result from storm cut, and that the wave climate during more frequent storm events such as the 20 year ARI is very similar to the design 50 year ARI wave climate, WRL has made an allowance of approximately 0.1 m additional layer thickness to that required for predicted storm cut and littoral losses. This will provide further protection should multiple extreme events occur within the 50 year design life, as often occurs.

Based on the expected storm cut and littoral drift erosion rates discussed in Sections 4.4.2 and 4.4.3, recommended minimum raw feed layer thicknesses have been produced, for slopes of 1V:6H and 1V:20H, for each wave climate category. These recommended minimum layer thicknesses are shown in Table 4.3.

Table 4.3
Recommended Minimum Raw Feed Layer Thicknesses

Slope	Wave Category	Wave Height, H_s (m)	Recommended Minimum Raw Feed Layer Thickness (m)
1V:6H	A	< 0.20	0.2
1V:6H	B	0.20– 0.29	0.3
1V:6H	C	0.30 – 0.39	0.3
1V:6H	D	0.40 – 0.49	0.6
1V:6H	E	0.50 – 0.60	0.7
1V:20H	A	< 0.20	0.2
1V:20H	B	0.20– 0.29	0.2
1V:20H	C	0.30 – 0.39	0.3
1V:20H	D	0.40 – 0.49	0.4
1V:20H	E	0.50 – 0.60	0.5

4.4.5 Other Considerations

While the raw feed is suitable on continuous slopes as steep as 1V:6H for all wave climates around the Wildlife Lake, it is advised that more traditional rock rubble (sandstone boulders) be used for protection on the crest of the seaward part of foreshore section E (bird sanctuary) for wave climate categories D and E (50 year ARI significant wave heights greater than 0.4 m). The use of sandstone boulders would also provide a more conservative solution for the lower wave climate categories, however, a thick compacted layer of raw feed would also be adequate. It is expected that if raw feed is adopted to protect this region for wave climate categories A, B and C, erosion would transport material landward off the crest of the outer mound during storm events. It is recommended that these regions be monitored, and if required increased protection be applied. More discussion and recommended sizes for sandstone boulder armouring are presented in Section 4.5.

Having considered all of the previous physical modelling studies and foreshore protection designs, it is apparent that there is not good definition of littoral erosion rates for primary raw feed under wave attack, for waves greater than 0.2 m height and for slopes flatter than 1V:6H. Further physical modelling could be undertaken to more accurately identify the likely erosion rates of loose raw feed for expected wave conditions.

4.5 Sandstone Boulders

4.5.1 Design Considerations

The analysis undertaken for the foreshore protection options of emergent macrophytes and raw feed suggests that generally there is no requirement for more traditional and rigid armouring such as sandstone boulders (except for some parts of foreshore section E, see Figure 1.7). However, to allow this foreshore protection to be considered for application for visual or environmental diversity, some analysis has been undertaken of the likely armour sizes to be stable under the predicted wave loading. This analysis has used the desktop assessment techniques of the Hudson Equation (CERC, 2008) and the van der Meer Equation (CIRIA, 2007) for identifying suitable armour sizes (as presented in Section 2.4). It should be noted that these equations are typically only considered for application on revetment slopes no flatter than 1V:6H. It is not typical to place rubble armouring on slopes milder than this for wave protection. Data has, however, been provided for a slope of 1V:20H to provide an initial estimate, which could be refined at a later date with more detailed modelling.

Predicted sandstone boulder armouring sizes required for slopes of 1V:6H and 1V:20H are shown in Table 4.4, and are based on an average prediction from the Hudson and van der Meer Equations.

Table 4.4
Recommended Sandstone Boulder Armour Size

Wave Climate Category	Significant Wave Height, H_s (m)	Slope	Armour Stone Size (D_{n50}, mm)	Layer Thickness (mm)
A	<0.2	1V:6H	75	150
B	0.20 – 0.29	1V:6H	110	220
C	0.30 – 0.39	1V:6H	140	220
D	0.40 – 0.49	1V:6H	175	350
E	0.50 – 0.60	1V:6H	200	400
A	<0.2	1V:20H*	45	90
B	0.20 – 0.29	1V:20H*	65	130
C	0.30 – 0.39	1V:20H*	85	170
D	0.40 – 0.49	1V:20H*	110	220
E	0.50 – 0.60	1V:20H*	125	250

* Denotes slope that is flatter than standard application of prediction equations

Guidelines for armour stone grading from CIRIA (2007) are as follows:

- Narrow or single-sized gradation:
  - D_{85} / D_{15} less than 1.5
- Wide gradation:
  - $D_{85} / D_{15} = 1.5$ to 2.5
- Very wide or quarry run gradation:
  - $D_{85} / D_{15} = 2.5$ to 5.

In most cases armour stone is narrow graded, however, in some river bank applications wide graded riprap is used. This could be determined during detailed armour design.

The only foreshore section where sandstone boulder armouring is recommended to prevent unacceptable erosion, is the seaward part of section E (bird refuge section) for wave climate categories D and E. When the lake water level is at RL 10 m (normal lake water level, NWL), this seaward region may be subject to breaking waves during storm events. If a storm occurs during a period when the lake water level is low, the crest will be subject to more severe breaking waves and overtopping. While a thick layer of compacted raw feed may be adequate protection for wave categories A, B and C, a double layer of sandstone boulders would provide a more conservative and lower maintenance design solution for these regions. Referring to Table 4.4 above, it is recommended that the outer bund (both seaward and leeward slopes) of foreshore cross section E, be armoured with a double layer of 150 mm D_{n50} sandstone boulders in regions with a wave climate category of A, B and C, and a double layer of 200 mm D_{n50} sandstone boulders for regions with a wave climate category of D or E.

4.5.2 Other Considerations in the Application of Sandstone Boulder Protection

Sandstone rubble could be susceptible to fretting under wetting / drying conditions and tests should be undertaken at the detailed design stage to determine weathering characteristics of the proposed sandstone and/or set criteria for suitable performance of the stone. Sandstone units of these sizes could also be susceptible to pilfering.

4.6 Vertical Extent of Foreshore Protection

4.6.1 Lake Water Level Fluctuations and Lake Filling

Lake levels are to be maintained using catchment runoff supplemented by pumping from the Nepean River. Operating rules require that drawdowns in the Wildlife Lake only exceed 0.5 m for 5% of the time. Modelling of drawdowns in the Wildlife Lake over a 95 year historical period (Badenhop *et al.* 2006) indicated that without supplementary pumping, drawdown would exceed 0.9 m for 5% of the time. With the maximum pumping possible, drawdown would exceed 0.6 m for 5% of the time. All other considered scenarios of pumping result in expected drawdown between 0.6 - 0.9 m occurring 5% of the time. To adequately protect foreshore slopes during periods of low water level, it is recommended that armouring be carried down the slope to level of RL 8.5 m (1.5 m below NWL).

It should be noted that foreshore slopes may be susceptible to erosion during initial filling of the Wildlife Lake. If no maintenance is to be undertaken during the filling period, extension of the foreshore protection below RL 8.5 m may be required to reduce the risk of erosion. However, it may be more efficient to simply monitor the foreshore during the filling period and provide maintenance to the required areas.

4.6.2 Wave Runup Levels

Wave runup levels for each foreshore profile were derived for each wave climate category using the runup formulation presented in Section 5.1 of the ACES Technical Manual, as published by the US Army Corps of Engineers (CERC, 1992). The runup coefficients after Mase (1989) were used in the application of the runup formulation. These equations are for gentle planar beach slopes. The technique was applied to assess runup levels on slopes of

1V:6H, 1V:10H and 1V:20H, with the results shown in Table 4.5. From these results, the maximum runup level has been interpolated by WRL for each of the assessed foreshore profiles and each 50 year ARI wave climate category. These maximum runup levels are presented in Table 4.6.

Table 4.5
Wave Runup Calculation on Uniform Slopes

Slope	Wave Category A		Wave Category B		Wave Category C		Wave Category D		Wave Category E	
	$R_{2\%}$ (m)	R_{max} (m)	$R_{2\%}$ (m)	R_{max} (m)	$R_{2\%}$ (m)	R_{max} (m)	$R_{2\%}$ (m)	R_{max} (m)	$R_{2\%}$ (m)	R_{max} (m)
1V:6H	0.3	0.4	0.4	0.5	0.6	0.7	0.7	0.9	0.9	1.0
1V:10H	0.2	0.2	0.3	0.4	0.4	0.5	0.5	0.6	0.6	0.7
1V:20H	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.3	0.4	0.4

Table 4.6
Wave Runup Levels for Design Foreshore Profiles, Without Expected Wave Reduction from Plant Beds (with normal water level at RL10 m)

Foreshore Section	Wave Category A	Wave Category B	Wave Category C	Wave Category D	Wave Category E
	R_{max} (m RL)	R_{max} (m RL)	R_{max} (m RL)	R_{max} (m RL)	R_{max} (m RL)
Section A	10.3	10.4	10.5	10.6	10.7
Section B	10.1	10.2	10.3	10.3	10.4
Section C	10.2	10.3	10.4	10.5	10.6
Section D	10.1	10.2	10.3	10.3	10.4
Section E	10.1	10.2	10.2	10.3	10.4
Section F	10.4	10.5	10.7	10.9	11.0
Section G	10.2	10.4	10.5	10.6	10.7

In cases where planting of the foreshore is undertaken, the maximum runup levels are expected to be reduced below those predicted in Table 4.6 above. A sensitivity analysis was undertaken using the formulations of Tschirky *et al.* (2000) as presented in Section 2.1.2 for determining wave transmission through plant beds. This analysis considered a range of plant bed lengths, water depths, and plant densities, and found that transmission coefficients were most sensitive to plant bed length (width of planting across the foreshore profile). For a typical water depth of 0.5 m, wave transmission coefficients were predicted to range from 0.3 – 0.6, for plant bed lengths of 10 m – 20 m. For shallower water depths, transmission coefficients drop even lower. These predictions are similar to the observations noted in CERC (2008).

For a typical wave reduction of 50% (transmission coefficient of 0.5) as waves pass through the plant beds, wave runup is also predicted to drop by approximately 50%. This results in a reduction in the upper level that wave protection is required, where planted 1V:20H foreshore slopes are adopted.

4.6.3 Section E Inner Water Level

To assist in preventing erosion to the landward slope of the outer bund on regions with foreshore profile E (Figure 1.7), it is recommended that the water level of the inner pond be maintained at the same level (or higher if possible) as the main lake water level. This will reduce erosion caused by overtopping waves during periods of lower lake water level.

5. CONCLUSIONS

5.1 Overview of Study

WRL have undertaken a review of the foreshore protection design for the Wildlife Lake at Penrith Lakes, with this report presenting the findings of the review. A previous analysis of the Wildlife Lake foreshore protection was undertaken by Anderson *et al.* (2006), and since this analysis, the layout and foreshore design has changed. While the plan layout of the lake has only undergone minimal changes (in terms of wave climate and required foreshore protection), the range of foreshore profiles has changed significantly. In particular, the foreshore profiles are generally flatter and targeted at achieving a more natural foreshore appearance.

As requested in the project brief, seven different foreshore cross section profiles have been considered (as shown in Figures 1.3 to 1.9), with four different foreshore protection options, including:

- No wave protection
- Emergent macrophytes
- Sandstone boulders
- Loosely spread raw feed.

5.2 Literature Review

A literature review was undertaken which considered both the specific literature available for the Penrith lakes scheme, as well as general literature that has been published and was useful in undertaking the analysis. Of particular importance in this literature review was the previous physical modelling analysis that had been undertaken by WRL in several investigations to assess the erodeability of the raw feed material. This included the clarification of the particular grading of raw feed considered in each of the previous studies and the effect of the grading on erodability. The results of these previous investigations provided the foundation on which erosion of proposed foreshore protection material was determined.

Other important findings from the literature review included the suitable wave climate and environmental conditions for planting emergent macrophytes and the wave reduction capabilities of such plant beds.

5.3 Wave Climate Review

A review was undertaken of the 50 year ARI wave climate for the Wildlife Lake. This review was based on the wind climate presented in Anderson *et al.* (2006), which considered measured wind speed data as well as design wind speeds from AS1170. Wind wave heights were estimated using the principles of SPM (1984), the US Army Coastal Engineering Manual (EM 1110-2-1100, 2002) and the software ACES within CEDAS (version 4.0.3). The 50 year ARI storm wave climate was found to vary around the foreshore of the lake, with some areas exposed to waves with a significant wave height of less than 0.2 m, while other areas have a significant wave height of up to 0.6 m. The wave climate was discretised into five categories:

- Wave climate category A: $H_s < 0.20$ m $T_p < 1.6$ s
- Wave climate category B: $H_s = 0.20 – 0.29$ m $T_p = 1.6 – 1.8$ s
- Wave climate category C: $H_s = 0.30 – 0.39$ m $T_p = 1.8 – 2.1$ s
- Wave climate category D: $H_s = 0.40 – 0.49$ m $T_p = 2.1 – 2.3$ s
- Wave climate category E: $H_s = 0.50 – 0.60$ m $T_p = 2.3 – 2.5$ s.

5.4 Foreshore Protection Design

An analysis was undertaken to assess the suitability of the four different foreshore protection options on the seven different foreshore cross section profiles. Based on the analysis, a range of design guideline figures have been produced for each of the foreshore cross sections (see Figures 4.1 – 4.19). These designs take into consideration the full range of expected wave climates around the Wildlife Lake foreshore, as well as each of the cross section geometries, and the different foreshore protection options. The designs are based on the requirement of minimal maintenance as a result of typical and storm conditions up to a 50 year ARI event. For some foreshore protection alternatives there is only limited information available on which to base the foreshore designs (such as the erosion of raw feed on flatter 1V:20 slopes). For these cases, the available information has been extrapolated to provide conservative design solutions.

In general, the results of the analysis can be summarised into a series of recommendations:

- No foreshore protection is not a suitable option, as there is little control over realignment of the foreshore through decades of wave exposure.
- Emergent macrophytes should be able to be grown without experiencing damage during storm events, in areas where the 50 year ARI wave climate is less than 0.2 – 0.3 m.

These areas are defined as across the entire profile for wave climate category A (see Figure 3.1), and within a band approximately 4 m wide around the shoreline for wave categories B and C (on a 1V:20H slope). Planting outside of these zones is strongly recommended, for both the environmental advantages, as well as for the additional erosion resistance, however, some localised damage to the plants during storm events should be expected. As a result, profiles will require additional protection using loosely spread raw feed.

- Minimum layer thicknesses of primary raw feed have been determined for each foreshore profile and wave climate category, with the recommended layer thicknesses varying between 0.2 m and 0.5 m for a 1V:20H slope and 0.2 and 0.7 m for a 1V:6H slope. These layer thicknesses take into consideration the effects of both storm erosion as well as long term littoral drift.
- Sandstone boulders are generally not required for armouring the foreshore, however, the required size of the boulders has been determined for each wave climate category and slope, and ranges from 75 mm to 200 mm (see Table 4.4).
- Sandstone boulders are recommended to armour the outer bund of foreshore cross section E (bird sanctuary) for wave climate categories D and E, to provide adequate protection from breaking and overtopping waves during times of low water level.

Foreshore protection is recommended to be extended down to a level of RL 8.5 m (1.5 m below NWL), to provide adequate protection during periods of severe lake drawdown. This protection may need to be extended to provide protection during lake filling, if the foreshore is not to be maintained.

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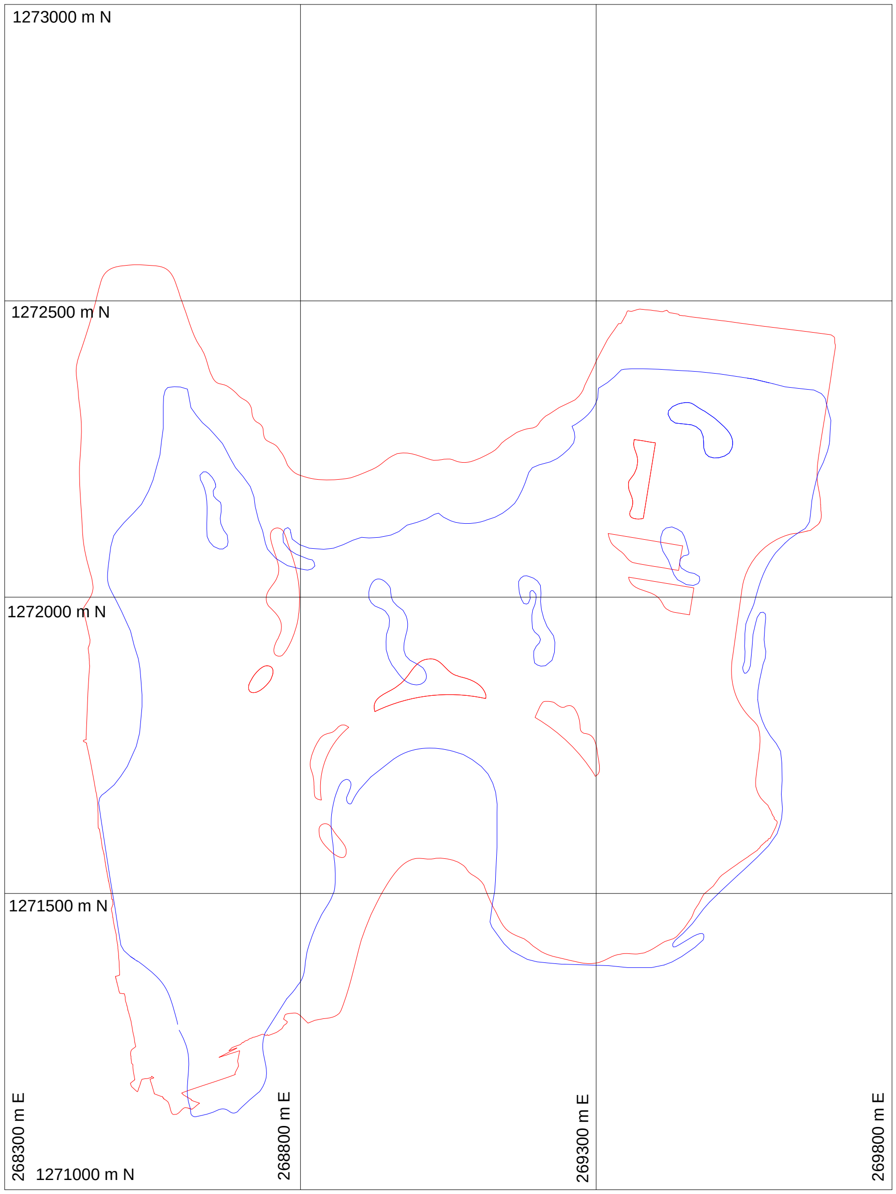
WILDLIFE LAKE LAYOUT

Figure 1.1



Current Lake Layout

Previous Lake Layout

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OVERLAY OF CURRENT WILDLIFE LAKE LAYOUT AND THAT CONSIDERED IN ANDERSON ET AL. (2006)

Figure 1.2

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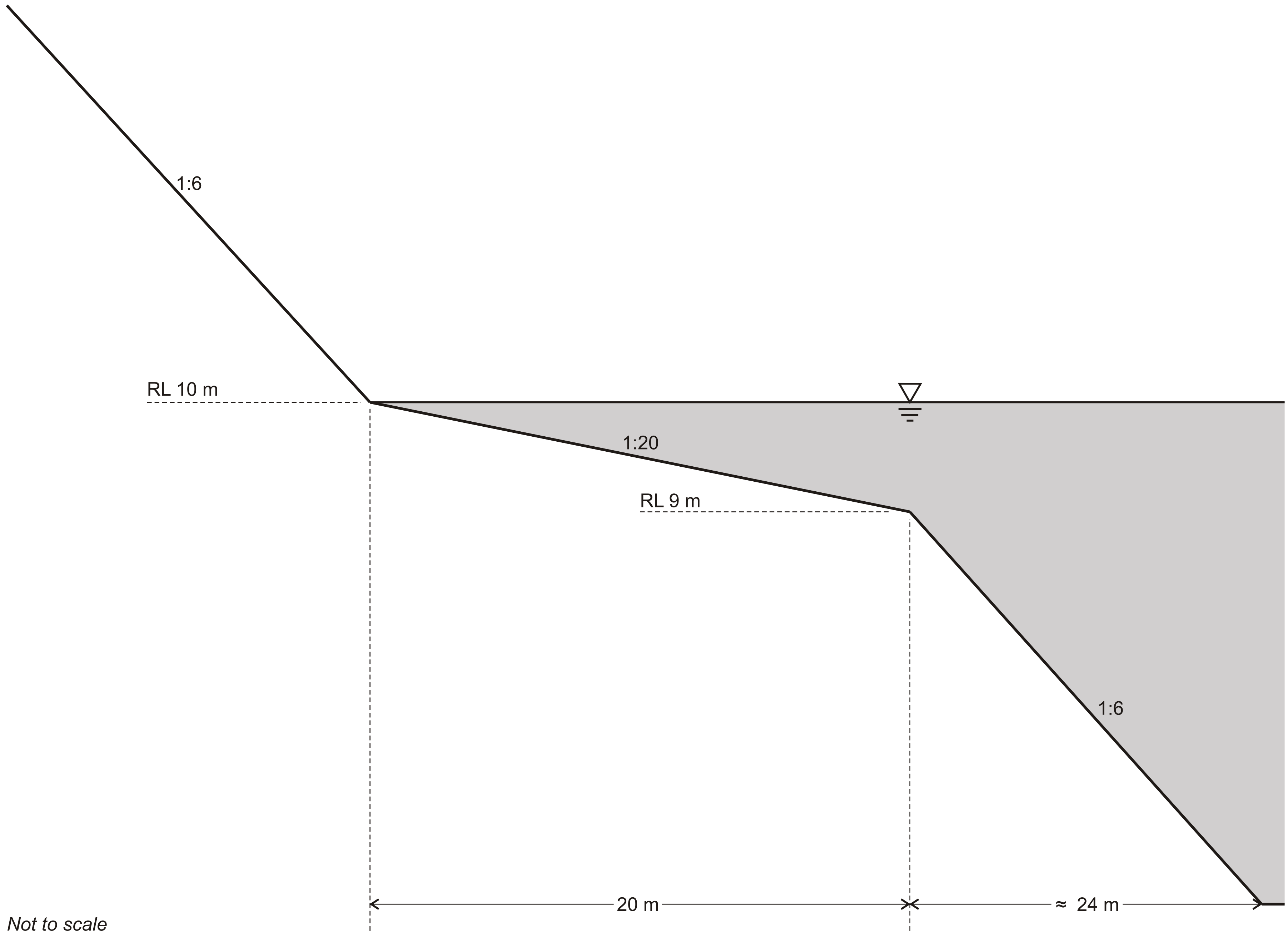
FORESHORE CROSS SECTION A

Figure 1.3

09030.1.3.cdr



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FORESHORE CROSS SECTION B

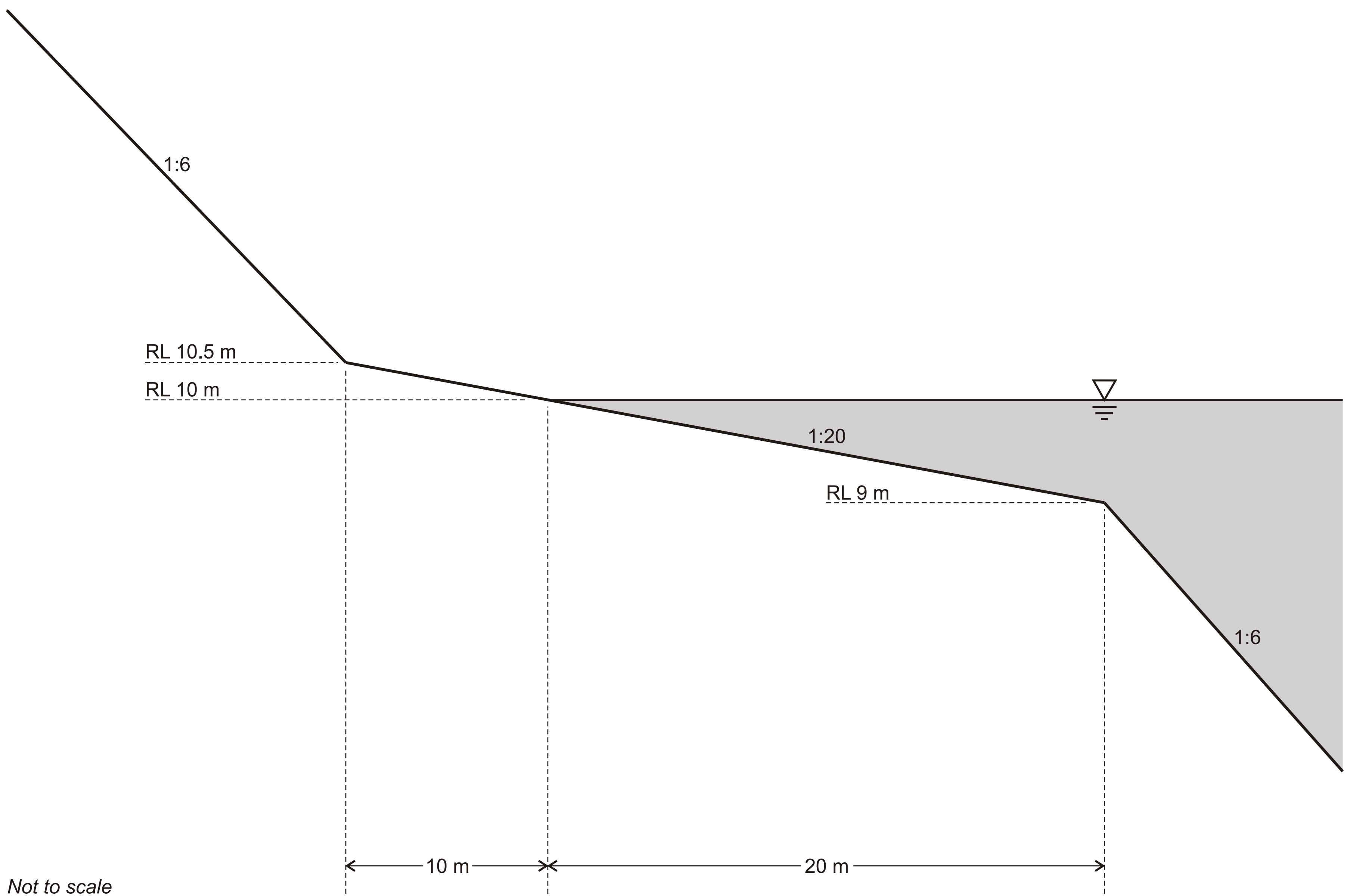

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Figure 1.4

09030.1.4.cdr

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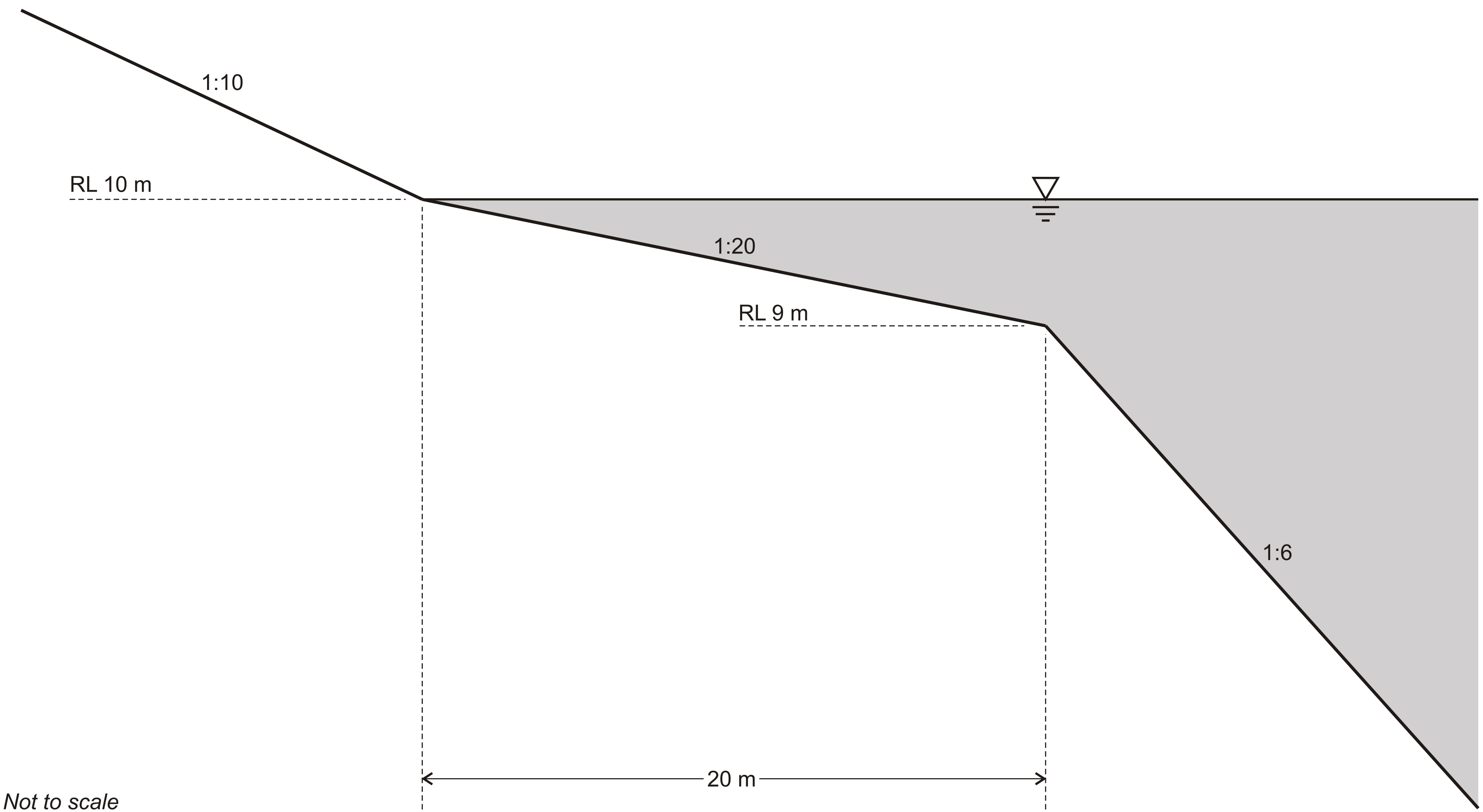
FORESHORE CROSS SECTION C

Figure 1.5

09030.1.5.cdr



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FORESHORE CROSS SECTION D

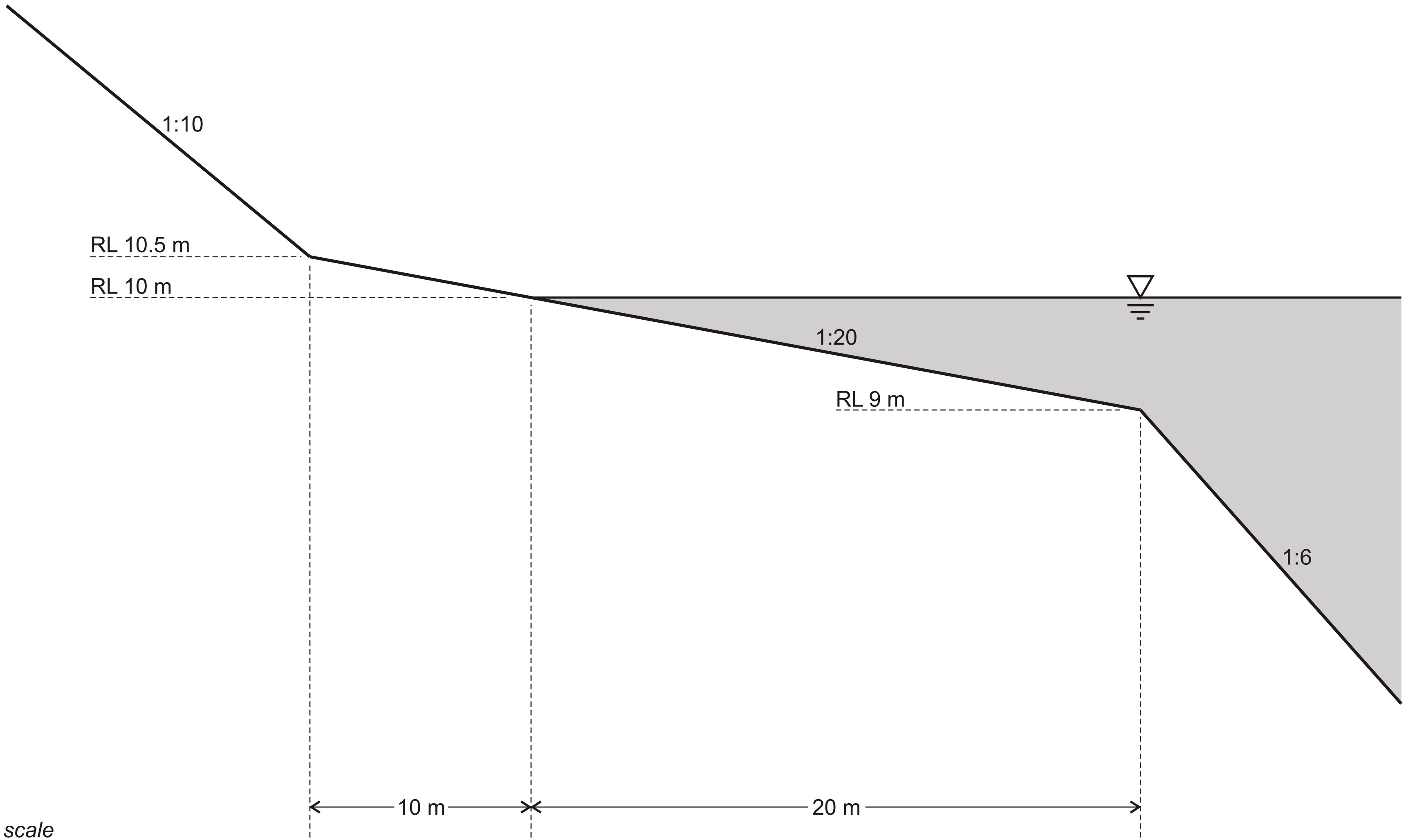

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Figure 1.6

09030.1.6.cdr

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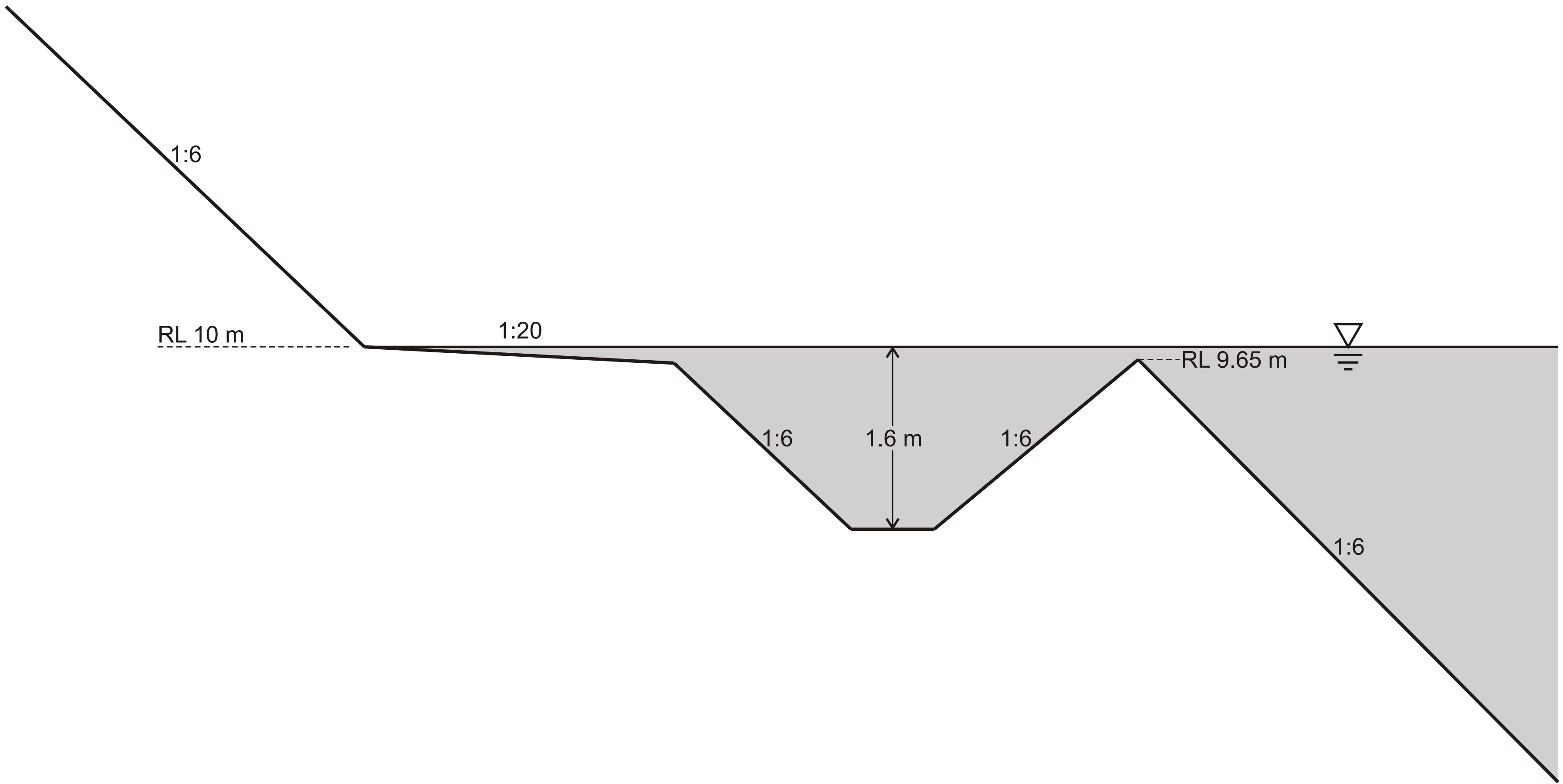
FORESHORE CROSS SECTION E



Not to scale

Figure
1.7

09030.1.7.cdr

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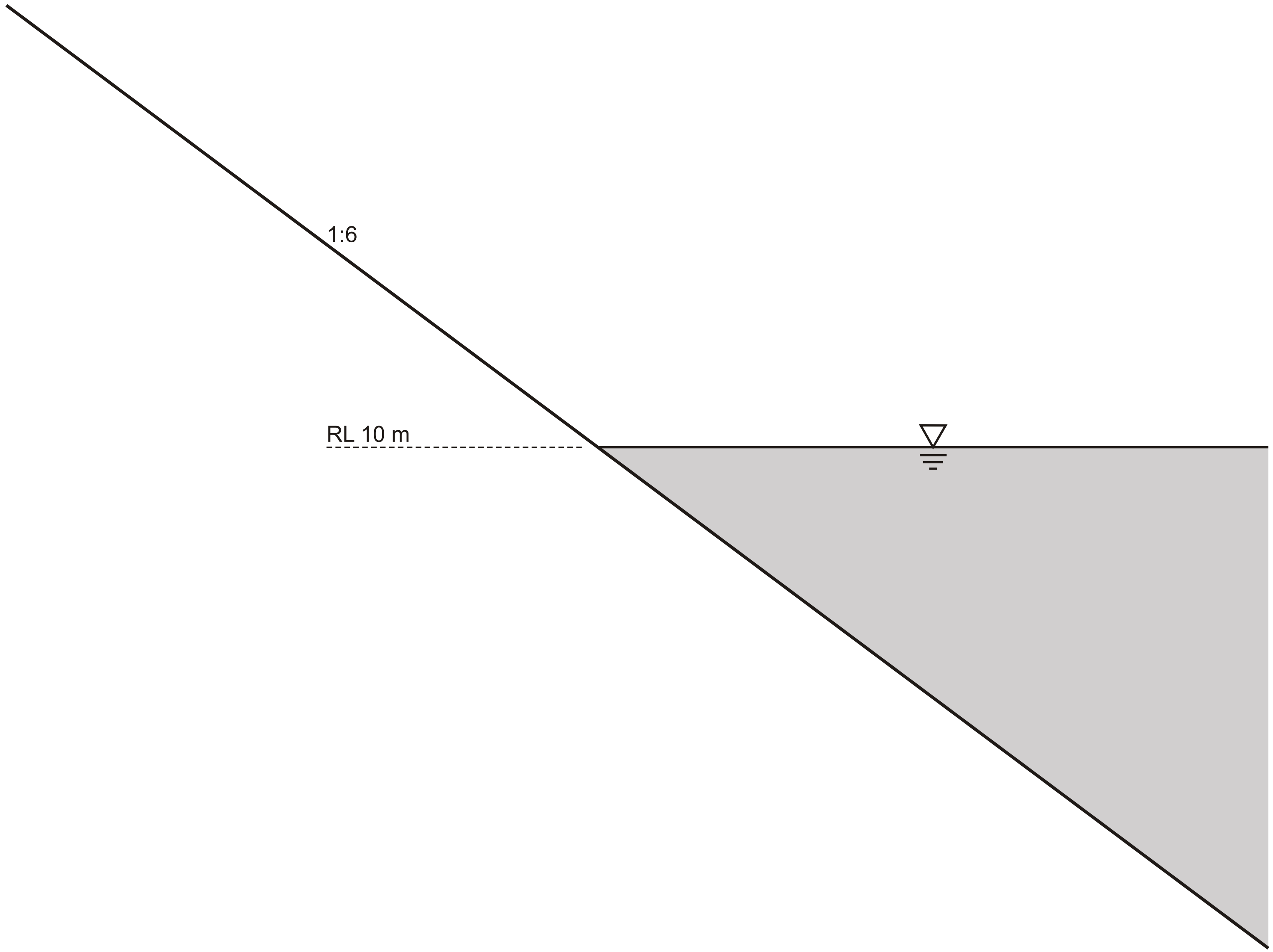
FORESHORE CROSS SECTION F



Not to scale

Figure 1.8

09030.1.8.cdr

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FORESHORE CROSS SECTION G

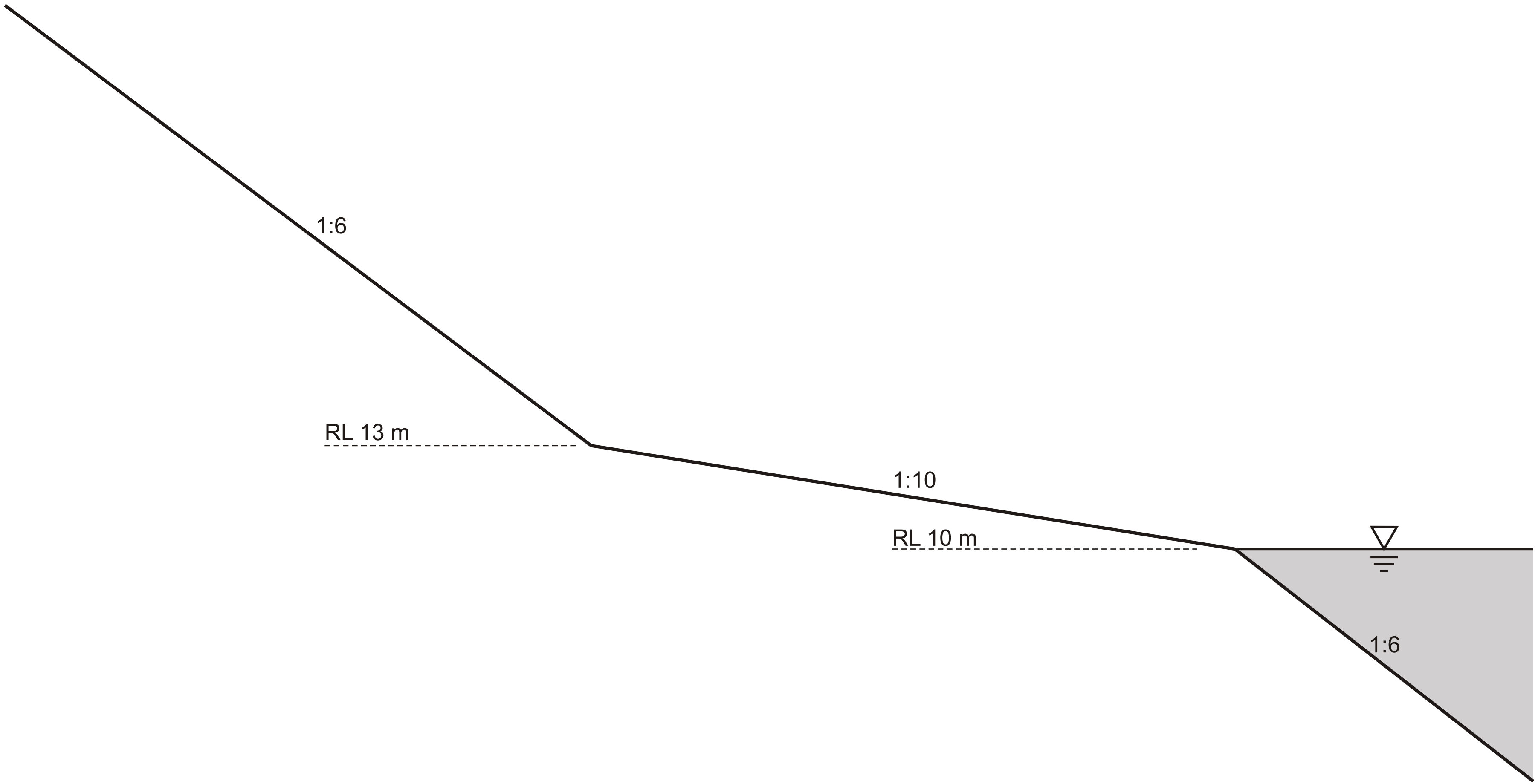

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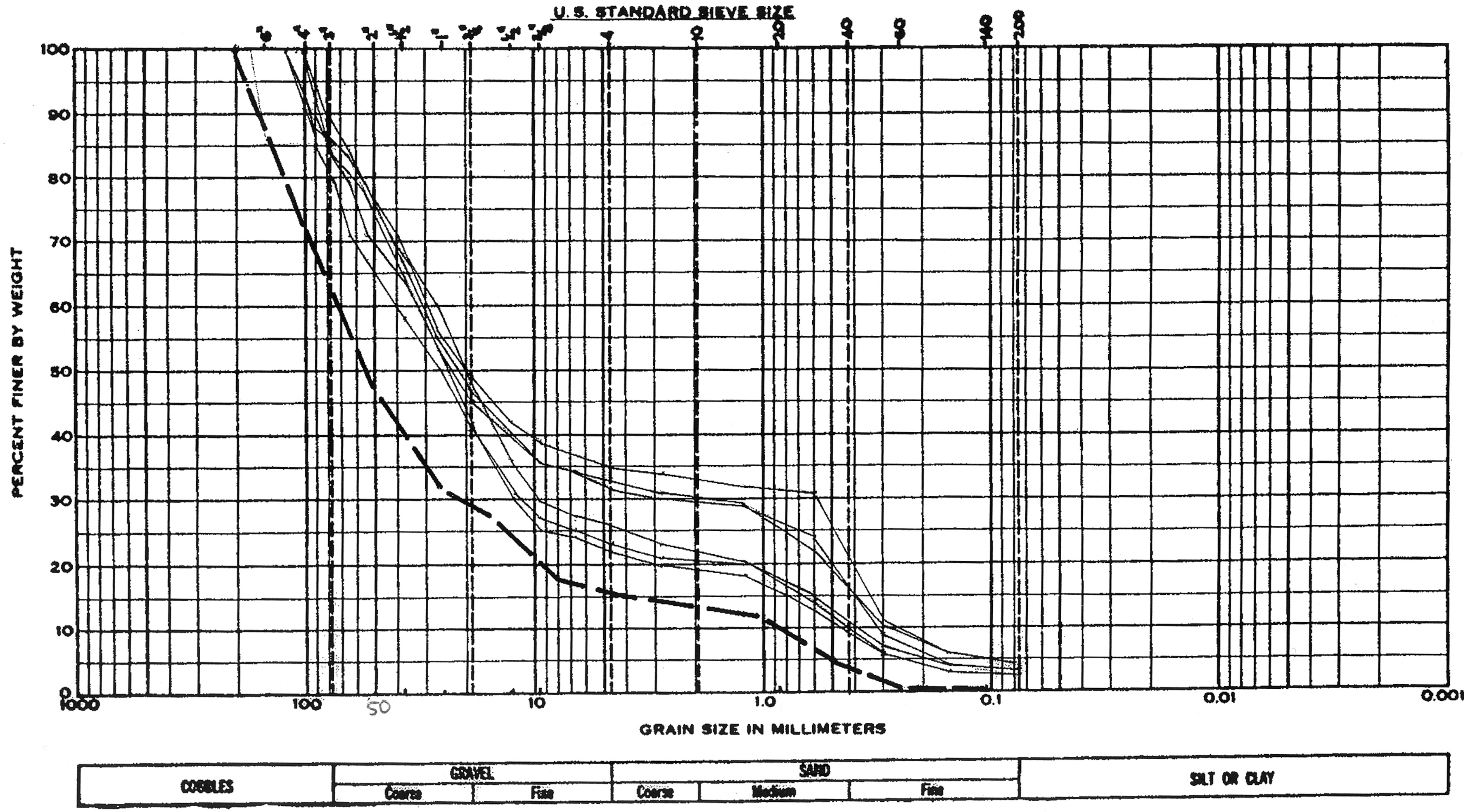
Figure 1.9

09030.1.9.cdr



SIEVE ANALYSES OF RAW FEED MATERIALS

Typical samples of Table 3
Tested raw feed beach material

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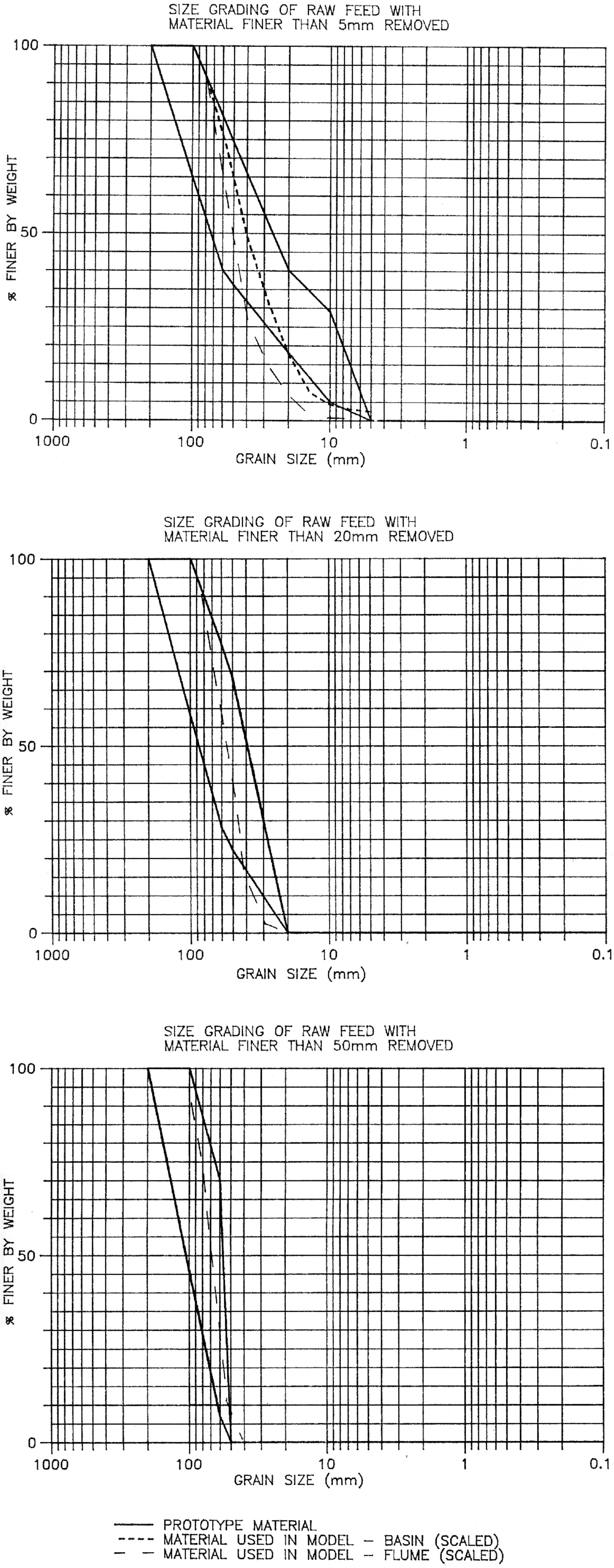
RAW FEED GRADING CURVES
AS TESTED IN COX AND FOSTER (1984)

Figure 2.1

09030.2.1.cdr



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MODIFIED RAW FEED GRADING CURVES AS TESTED BY PEIRSON et. al. (1990)

Figure 2.2

09030.2.2.cdr

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RAW FEED GRADING RANGES FOR DESIGNS IN BETTINGTON et. al. (1996)

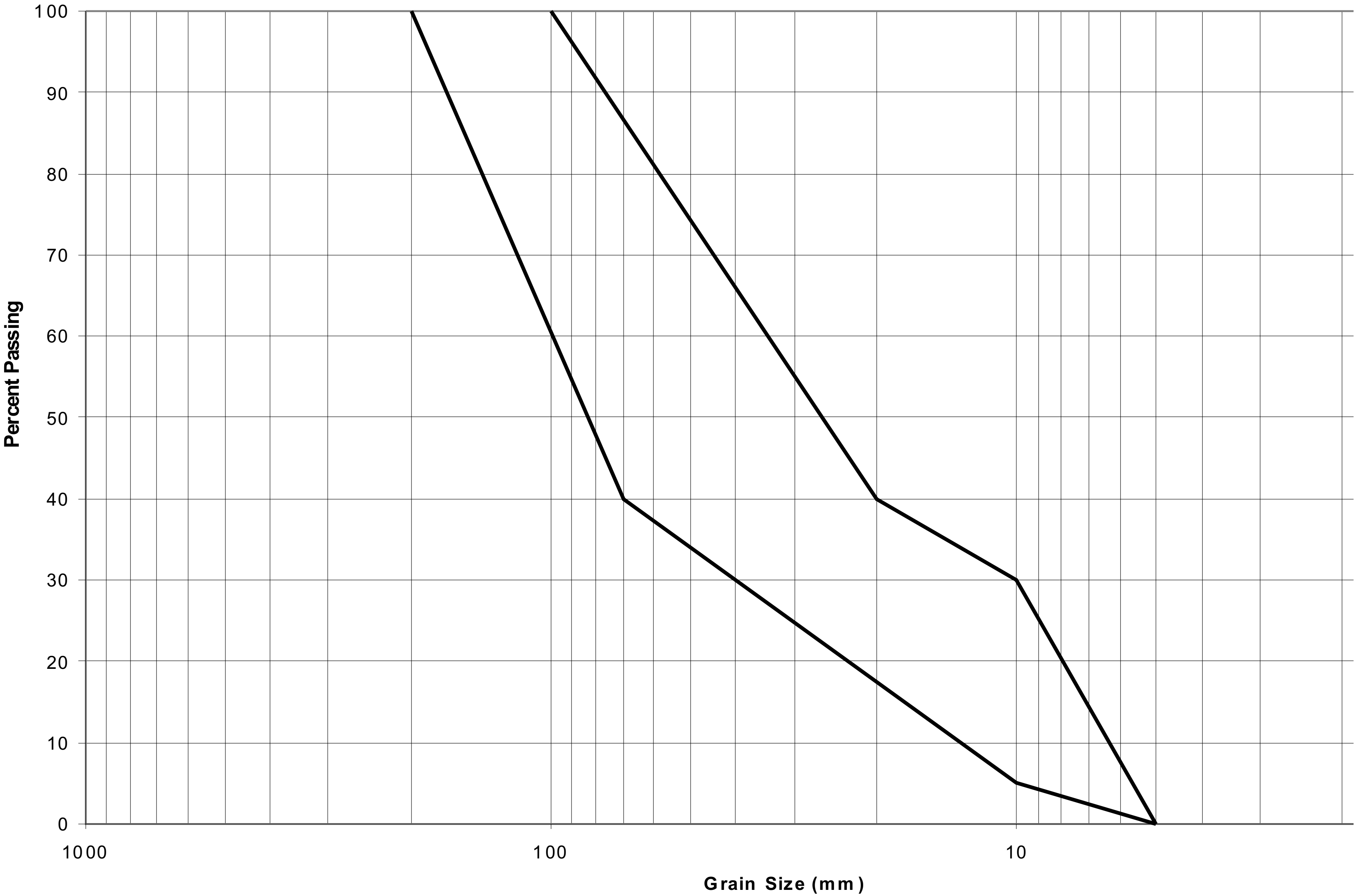
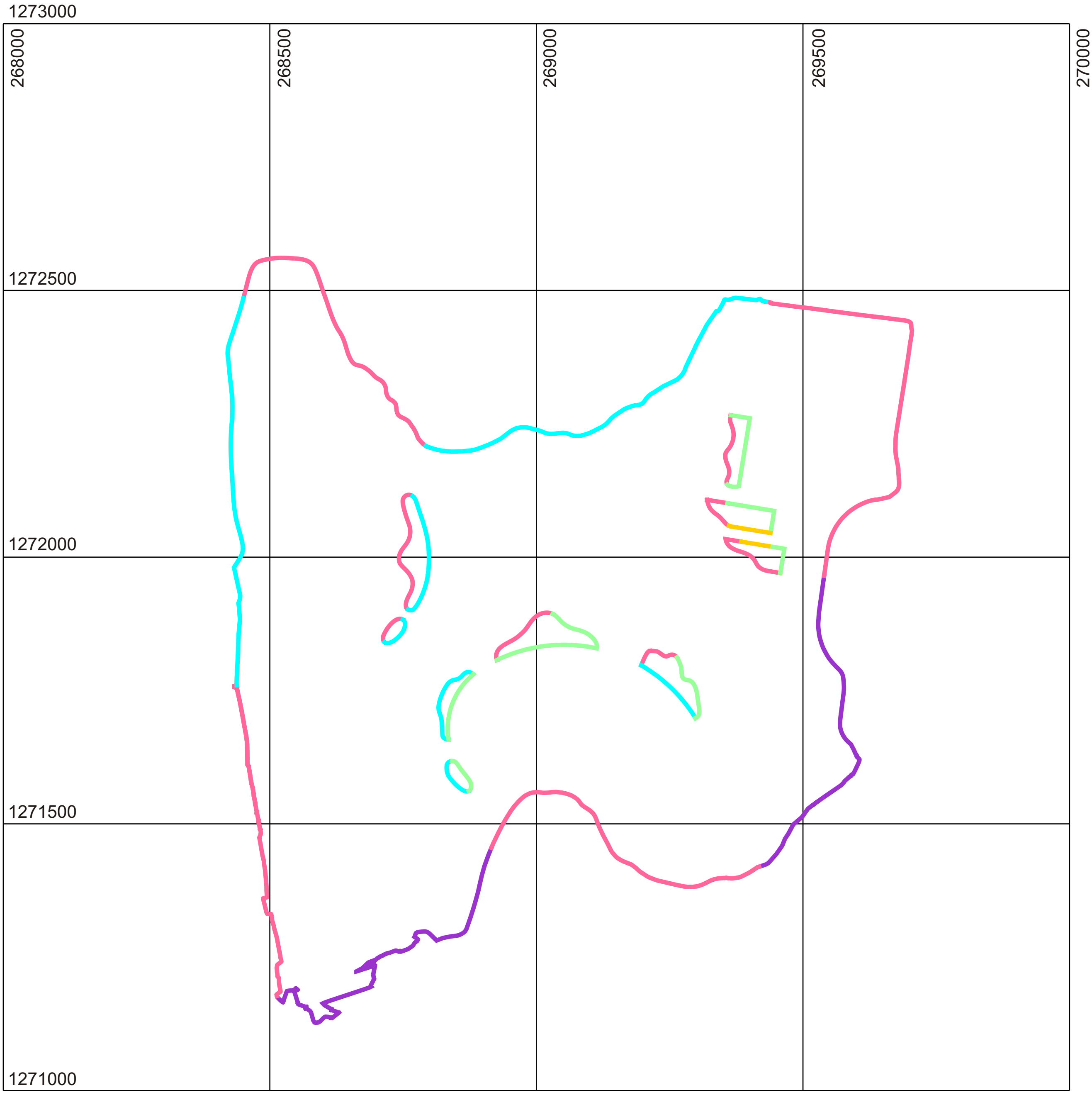


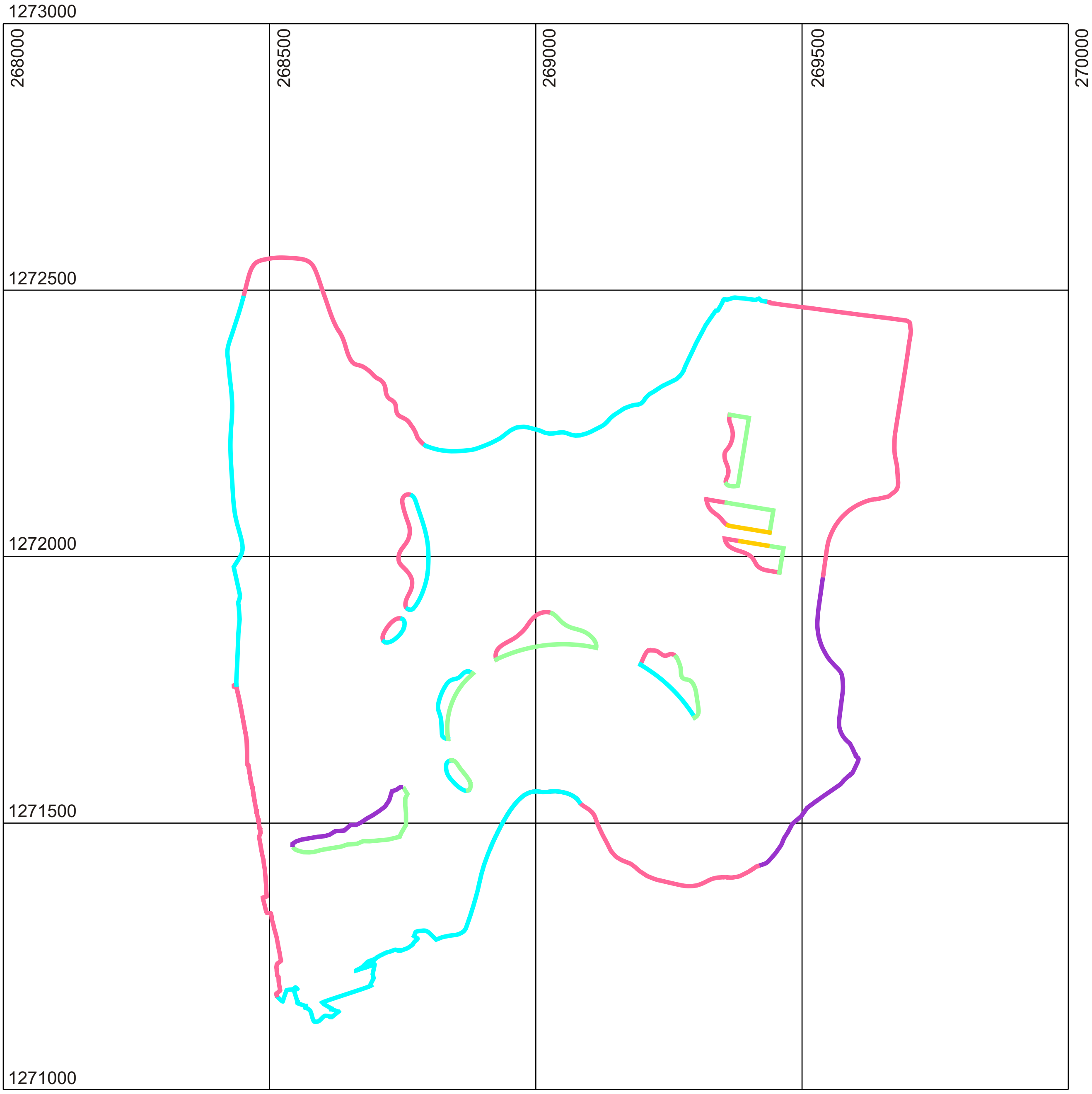
Figure 2.3

09030.2.3.cdr



- Wave Category A: H_s < 0.20 m
- Wave Category B: H_s = 0.20 - 0.29 m
- Wave Category C: H_s = 0.30 - 0.39 m
- Wave Category D: H_s = 0.40 - 0.49 m
- Wave Category E: H_s = 0.50 - 0.60 m

WRL Report No. 2009/09	50 YEAR ARI WAVE CLIMATE	Figure 3.1 09030.3.1.cdr



Wave Category A: H_s < 0.20 m

Wave Category B: H_s = 0.20 - 0.29 m

Wave Category C: H_s = 0.30 - 0.39 m

Wave Category D: H_s = 0.40 - 0.49 m

Wave Category E: H_s = 0.50 - 0.60 m

WRL Report No. 2009/09	50 YEAR ARI WAVE CLIMATE WITH SOUTH WESTERN ISLAND	Figure 3.2 09030.3.2.cdr

WRL

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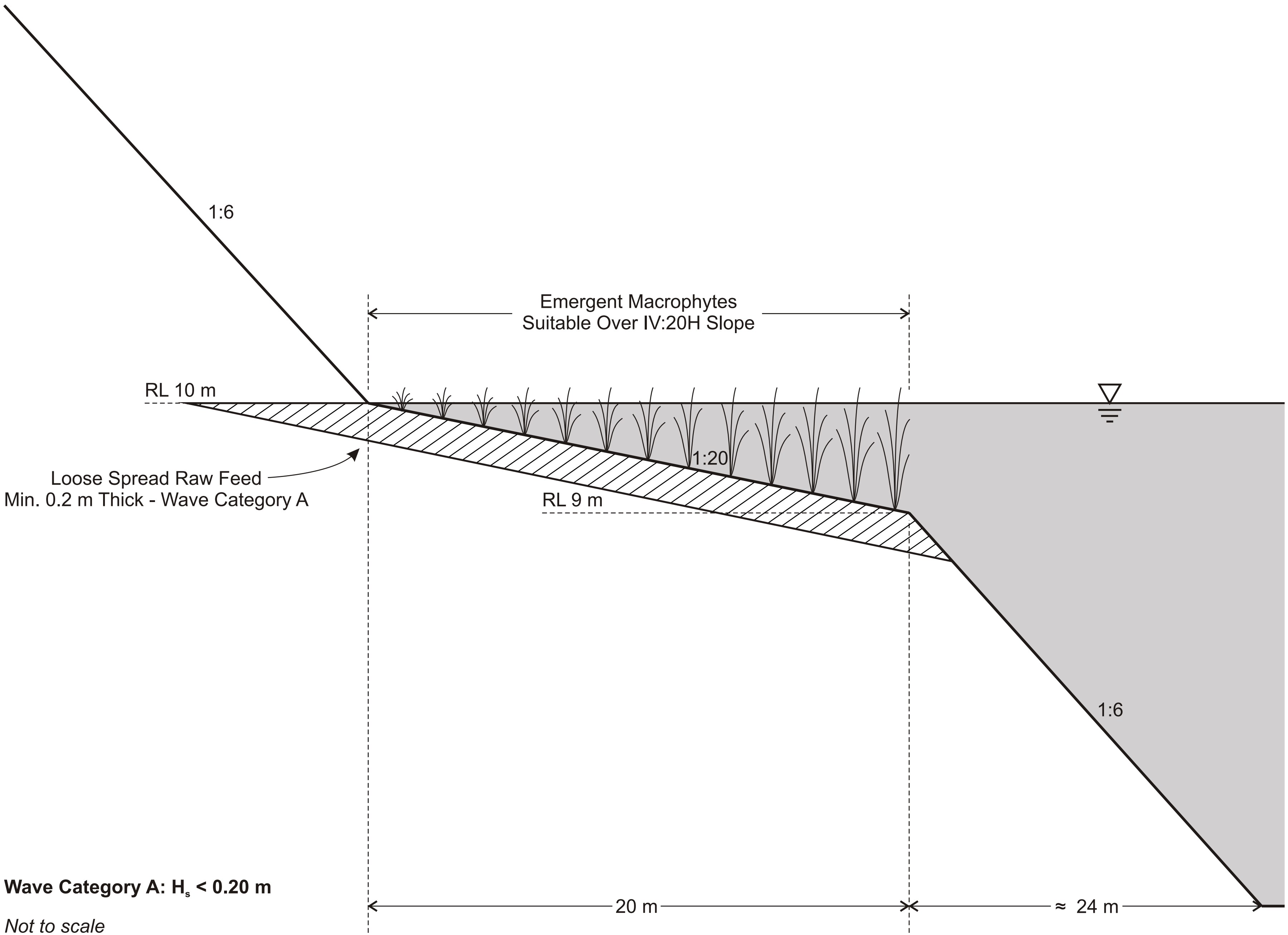
SECTION A
WAVE CATEGORY A



Wave Category A: H_s < 0.20 m

Not to scale

Figure
4.1

09030-4.1.cdr

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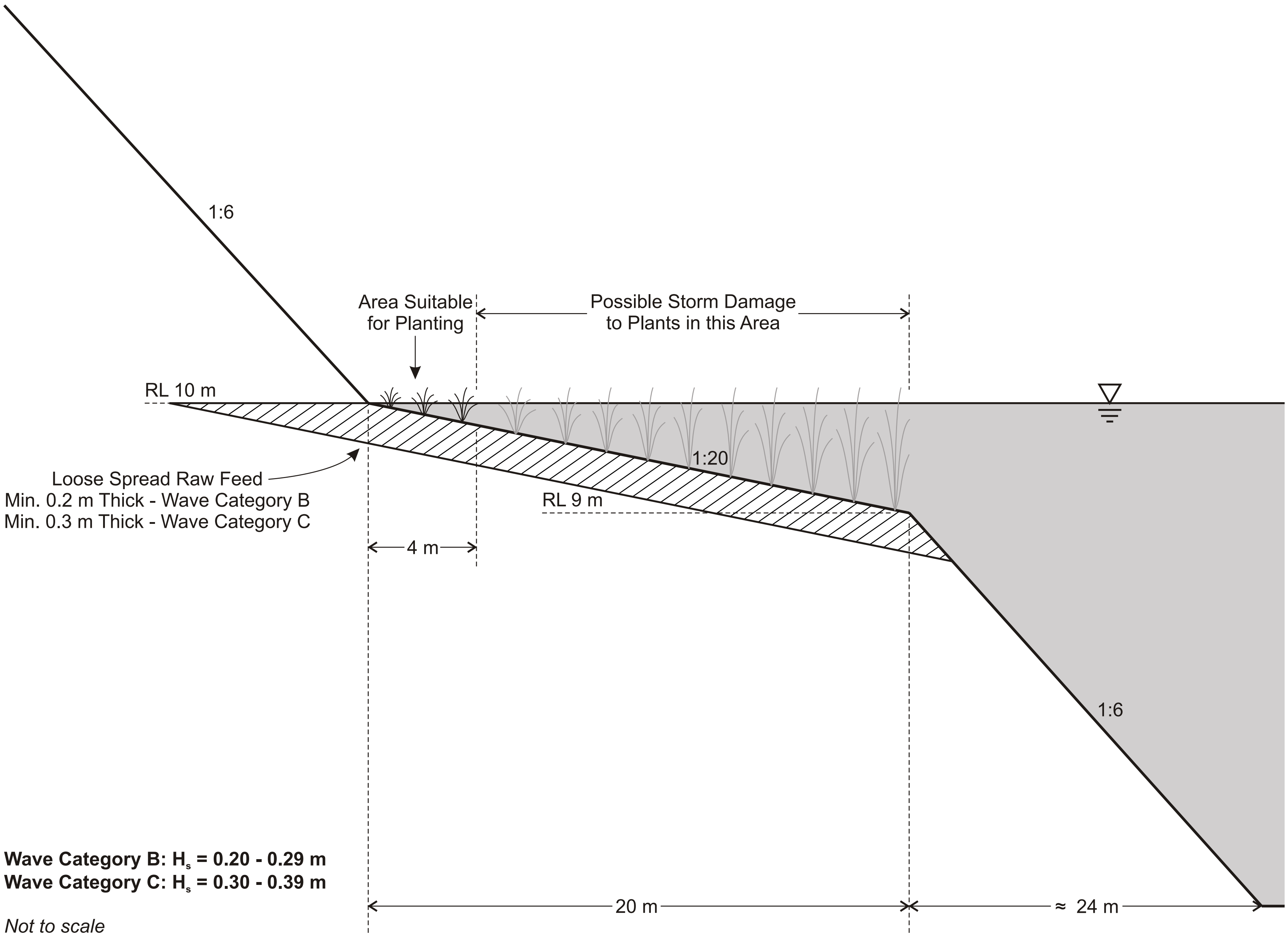
SECTION A
WAVE CATEGORIES B AND C



Wave Category B: H_s = 0.20 - 0.29 m
Wave Category C: H_s = 0.30 - 0.39 m

Not to scale

Figure
4.2

09030-4.2.cdr

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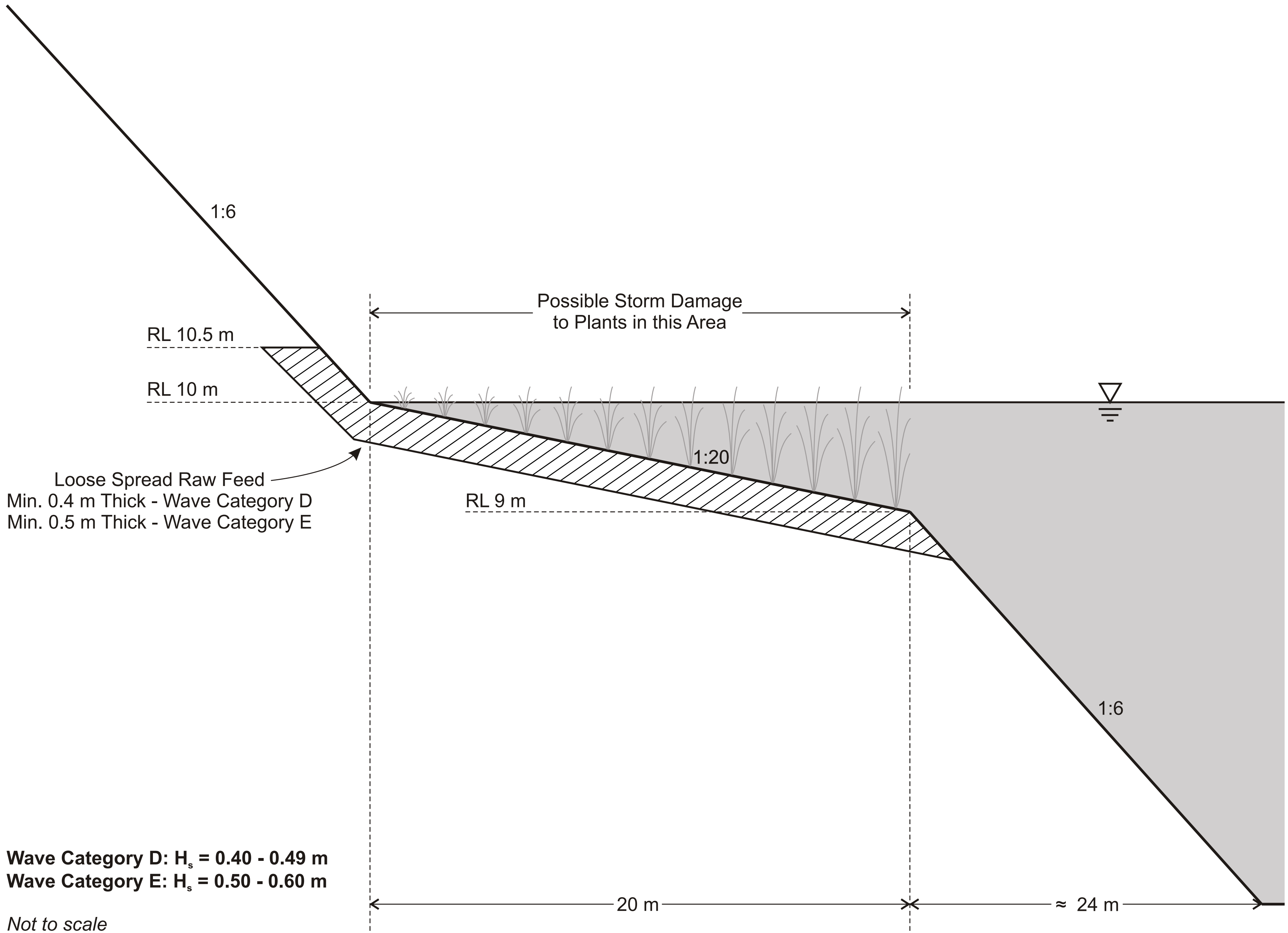
SECTION A
WAVE CATEGORIES D AND E



Wave Category D: H_s = 0.40 - 0.49 m
Wave Category E: H_s = 0.50 - 0.60 m

Not to scale

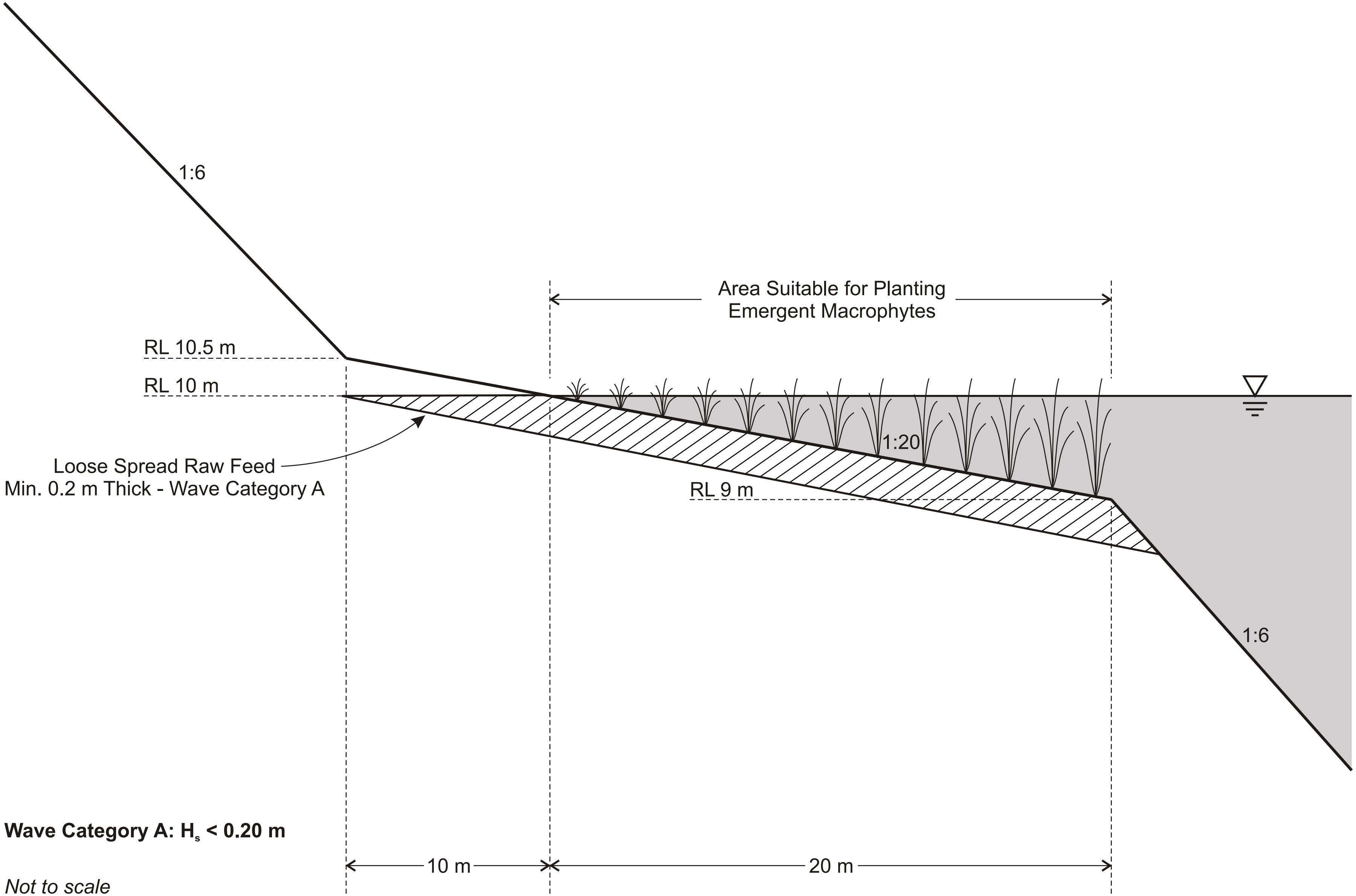
Figure 4.3

09030-4.3.cdr

WRL

Report No. 2009/09

SECTION B
WAVE CATEGORY A

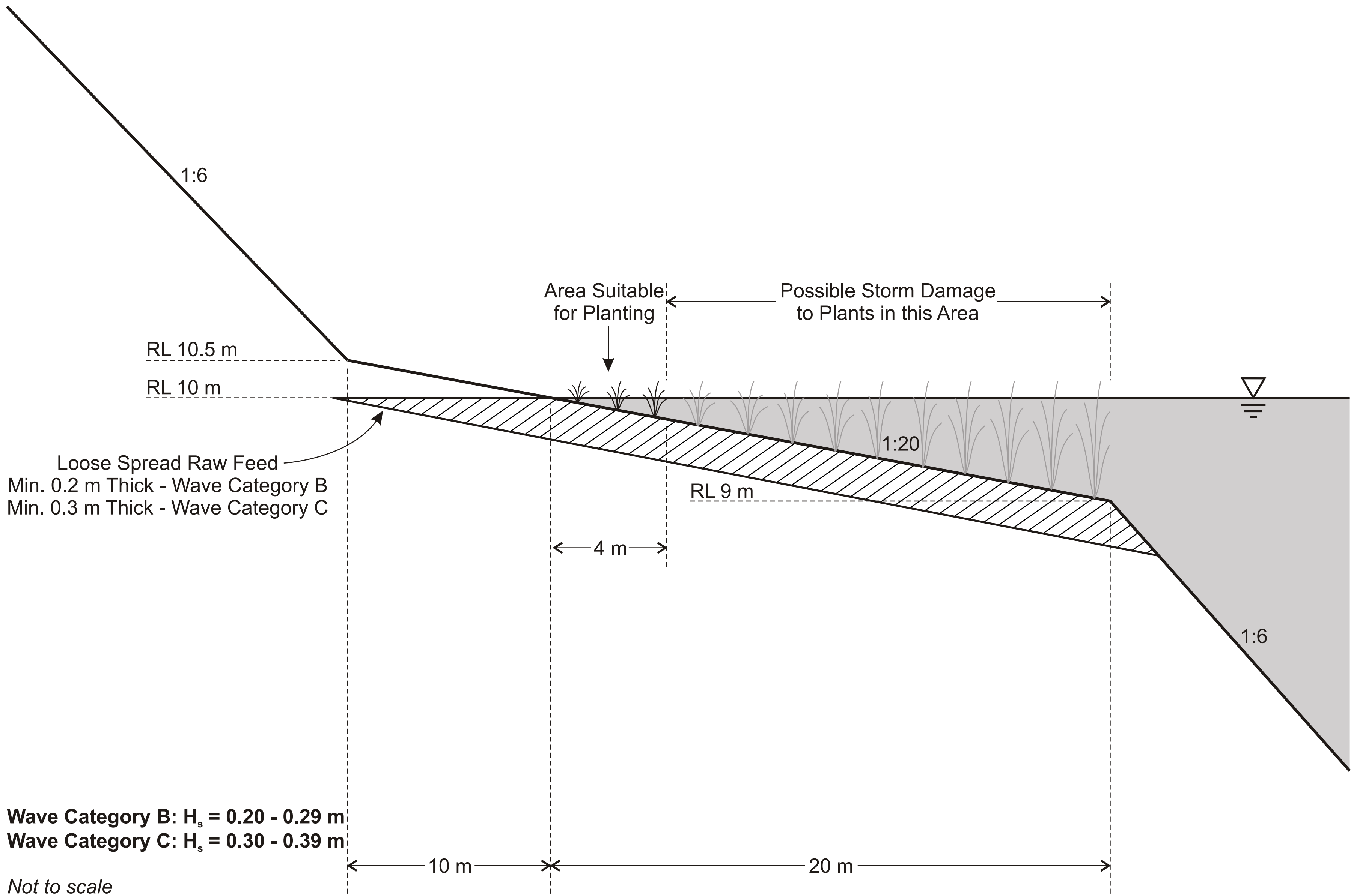


Wave Category A: H_s < 0.20 m

Not to scale

Figure
4.4

09030.4.4.cdr



Wave Category B: H_s = 0.20 - 0.29 m
Wave Category C: H_s = 0.30 - 0.39 m

Not to scale

WRL
Report No. 2009/09

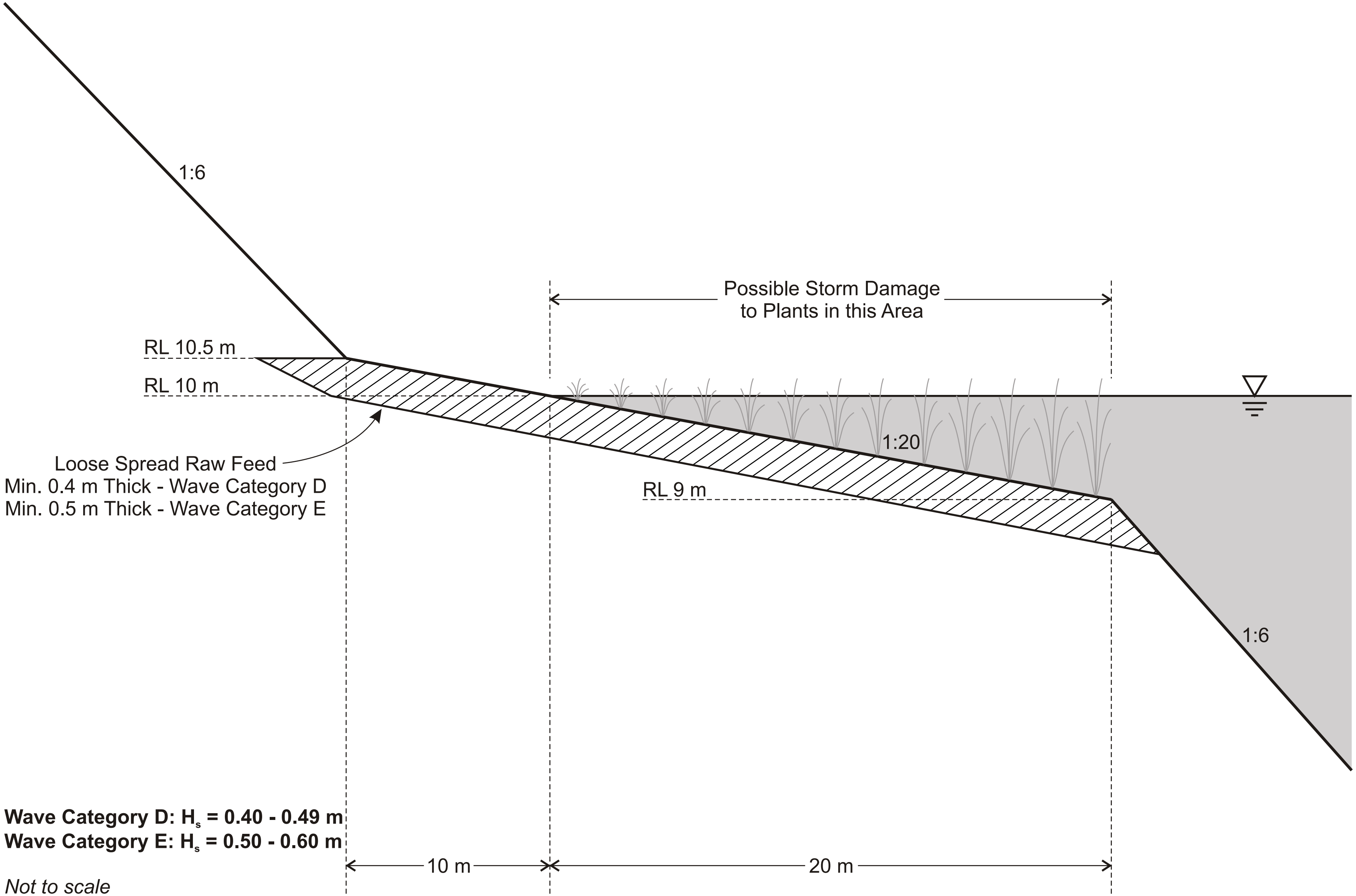
SECTION B
WAVE CATEGORIES B AND C

Figure
4.5

09030-4.5.cdr

WRL
Report No. 2009/09

SECTION B
WAVE CATEGORIES D AND E



Wave Category D: H_s = 0.40 - 0.49 m
Wave Category E: H_s = 0.50 - 0.60 m

Not to scale

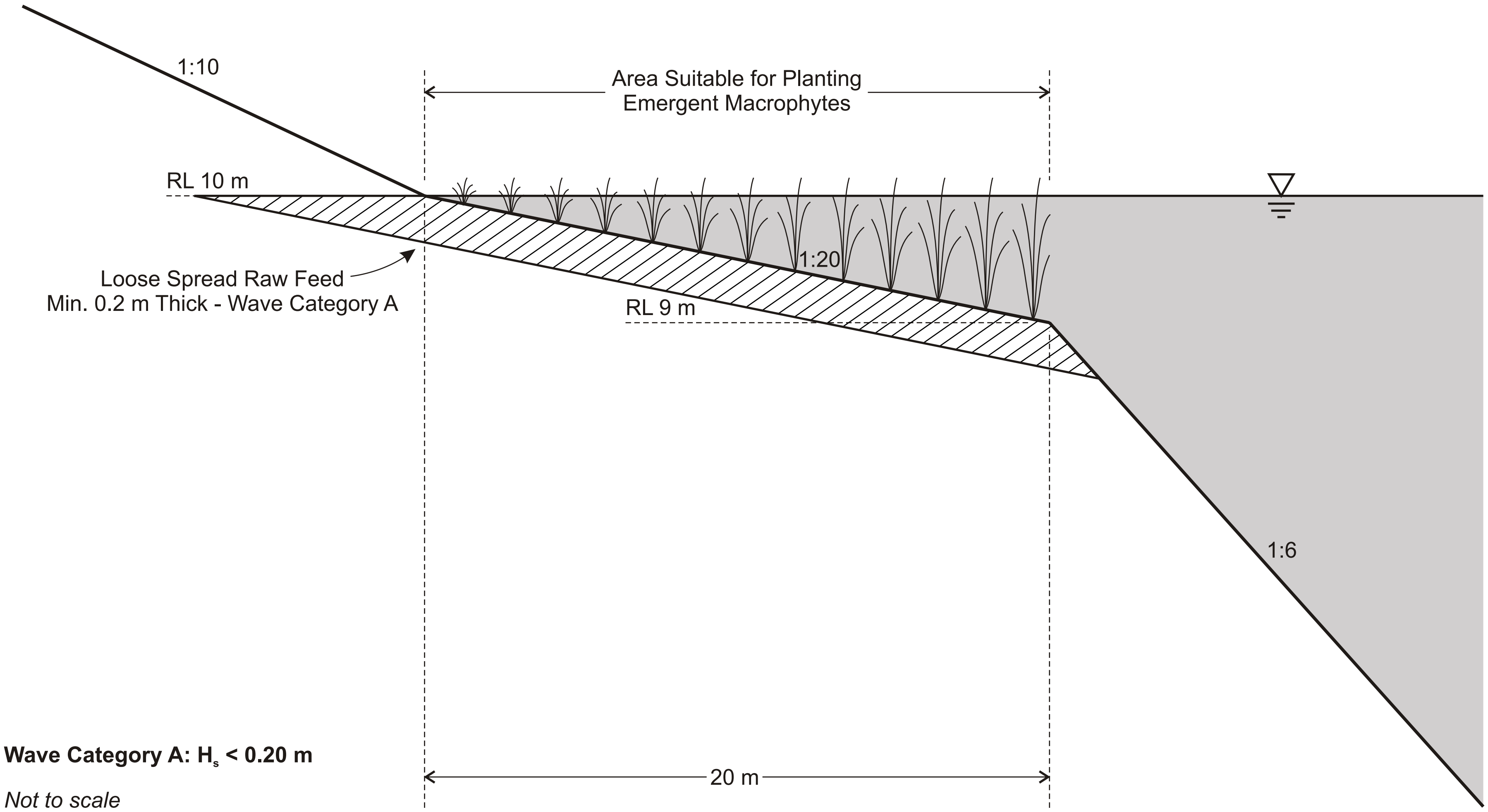
Figure
4.6

09030.4.6.cdr

WRL

Report No. 2009/09

SECTION C
WAVE CATEGORY A



Wave Category A: H_s < 0.20 m

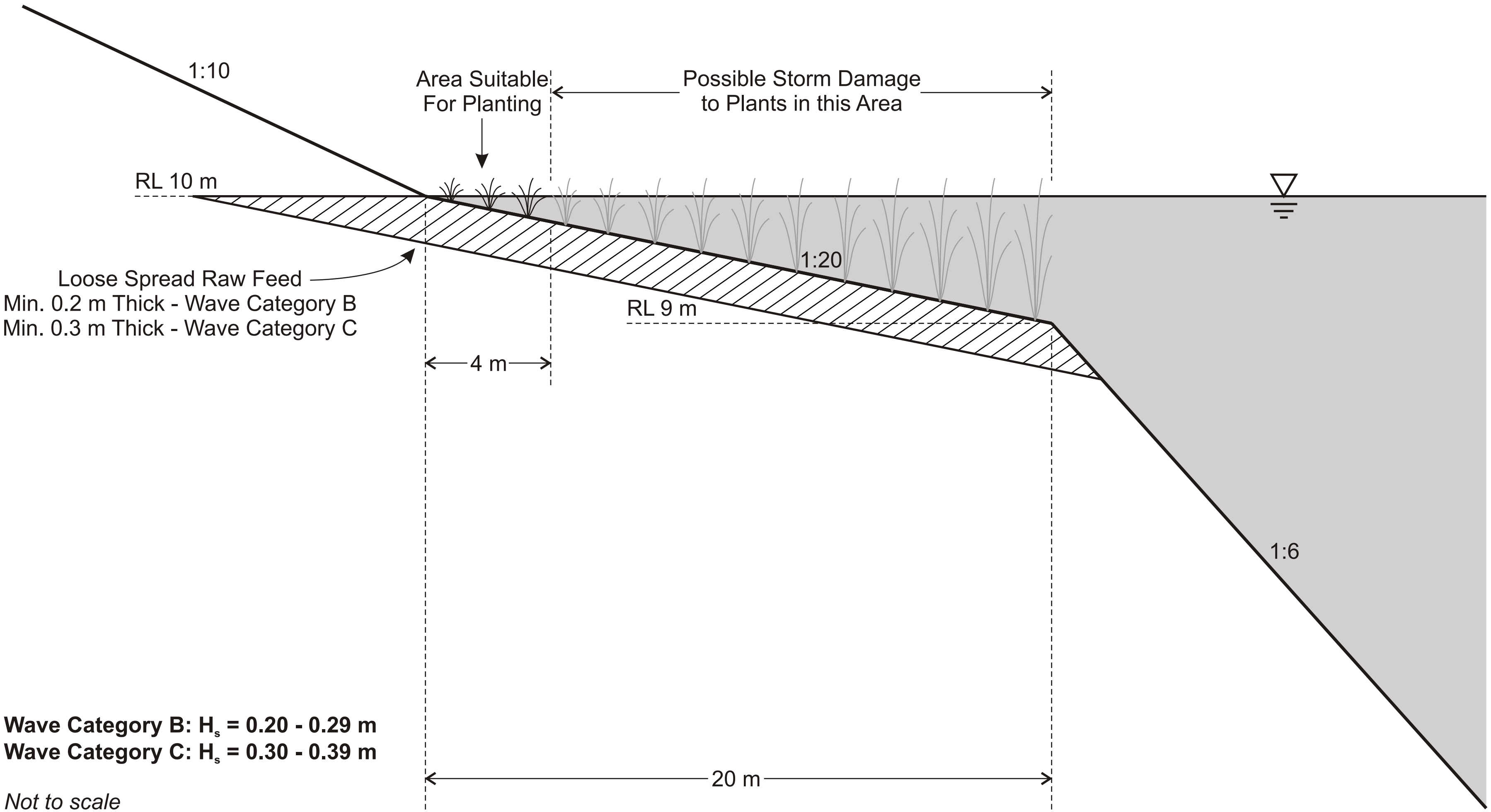
Not to scale

Figure
4.7

09030-4.7.cdr

WRL
Report No. 2009/09

SECTION C
WAVE CATEGORIES B AND C



Wave Category B: H_s = 0.20 - 0.29 m
Wave Category C: H_s = 0.30 - 0.39 m

Not to scale

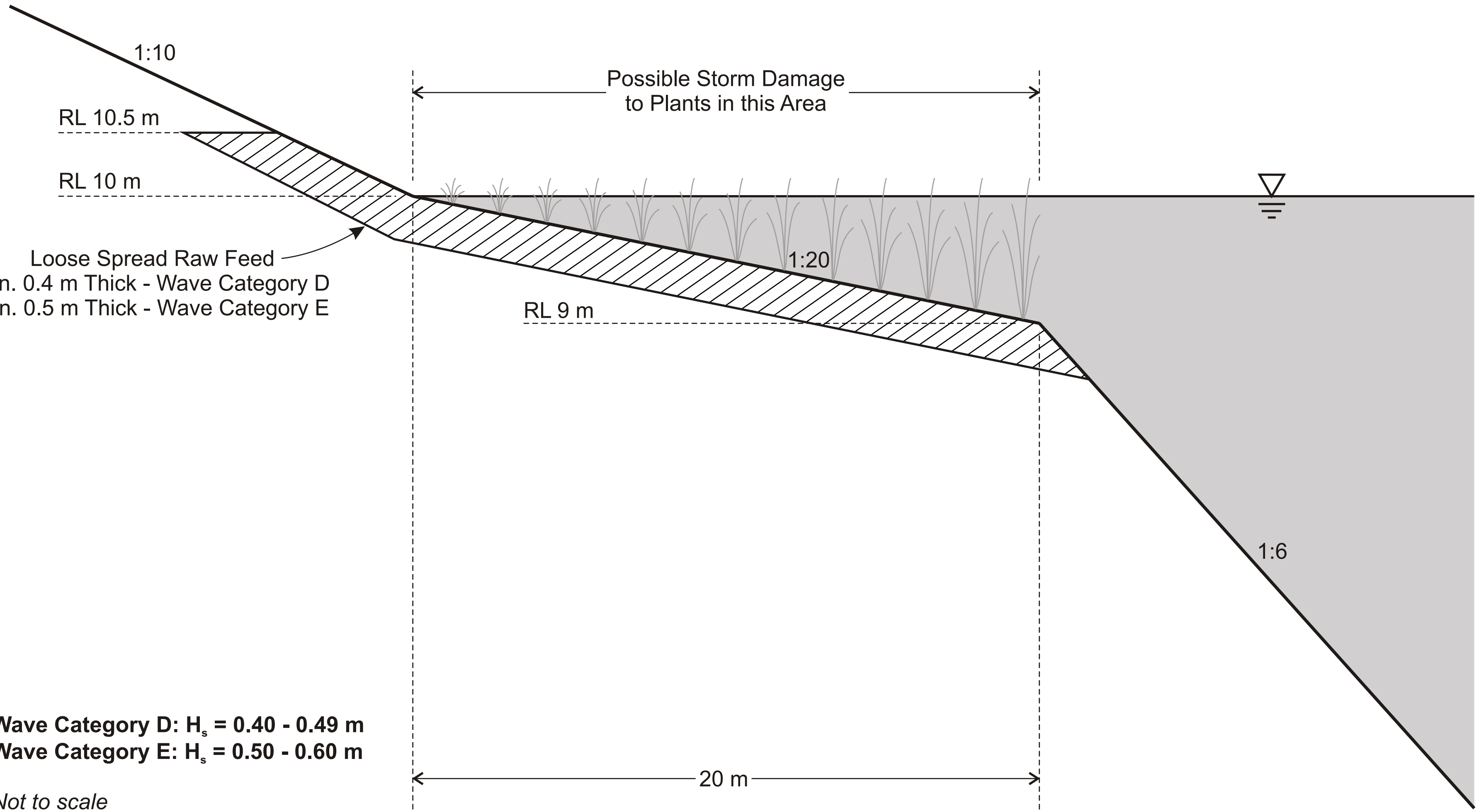
Figure 4.8

09030-4.8.cdr

WRL

Report No. 2009/09

SECTION C
WAVE CATEGORIES D AND E



Wave Category D: H_s = 0.40 - 0.49 m
Wave Category E: H_s = 0.50 - 0.60 m

Not to scale

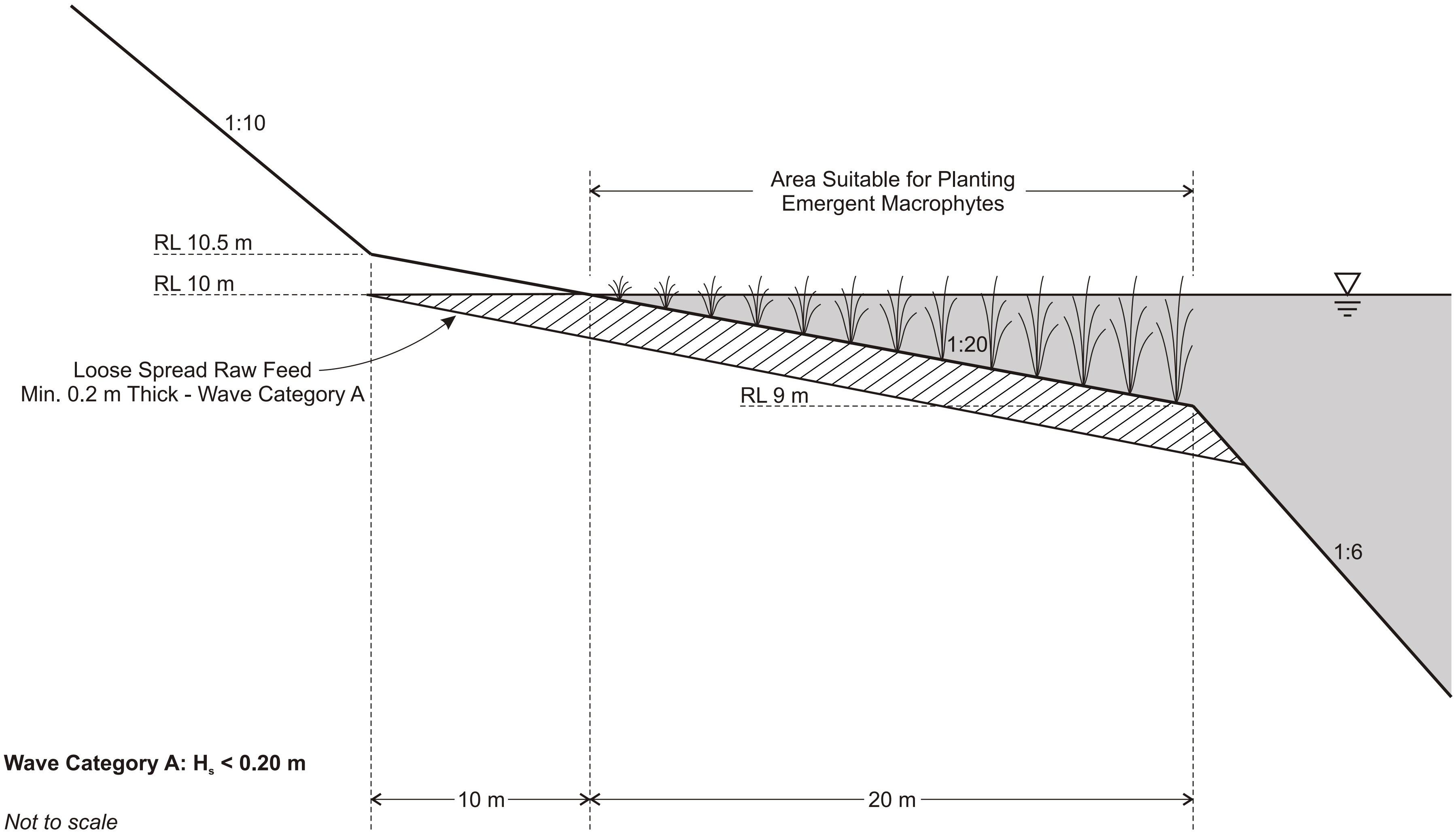
Figure 4.9

09030.4.9.cdr

WRL

Report No. 2009/09

SECTION D
WAVE CATEGORY A



Wave Category A: H_s < 0.20 m

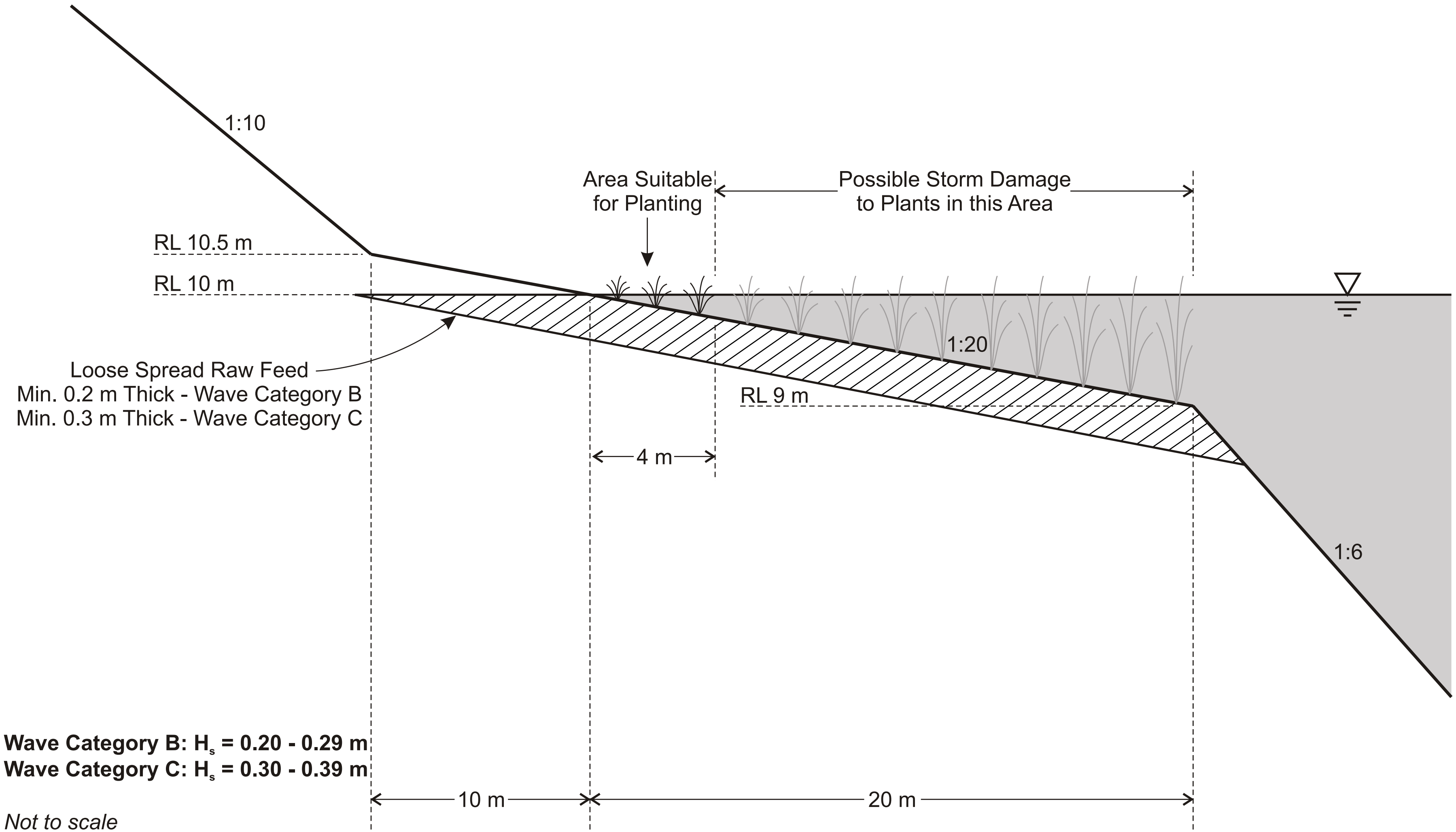
Not to scale

Figure
4.10

09030-4.10.cdr

WRL
Report No. 2009/09

SECTION D
WAVE CATEGORIES B AND C



Wave Category B: H_s = 0.20 - 0.29 m
Wave Category C: H_s = 0.30 - 0.39 m

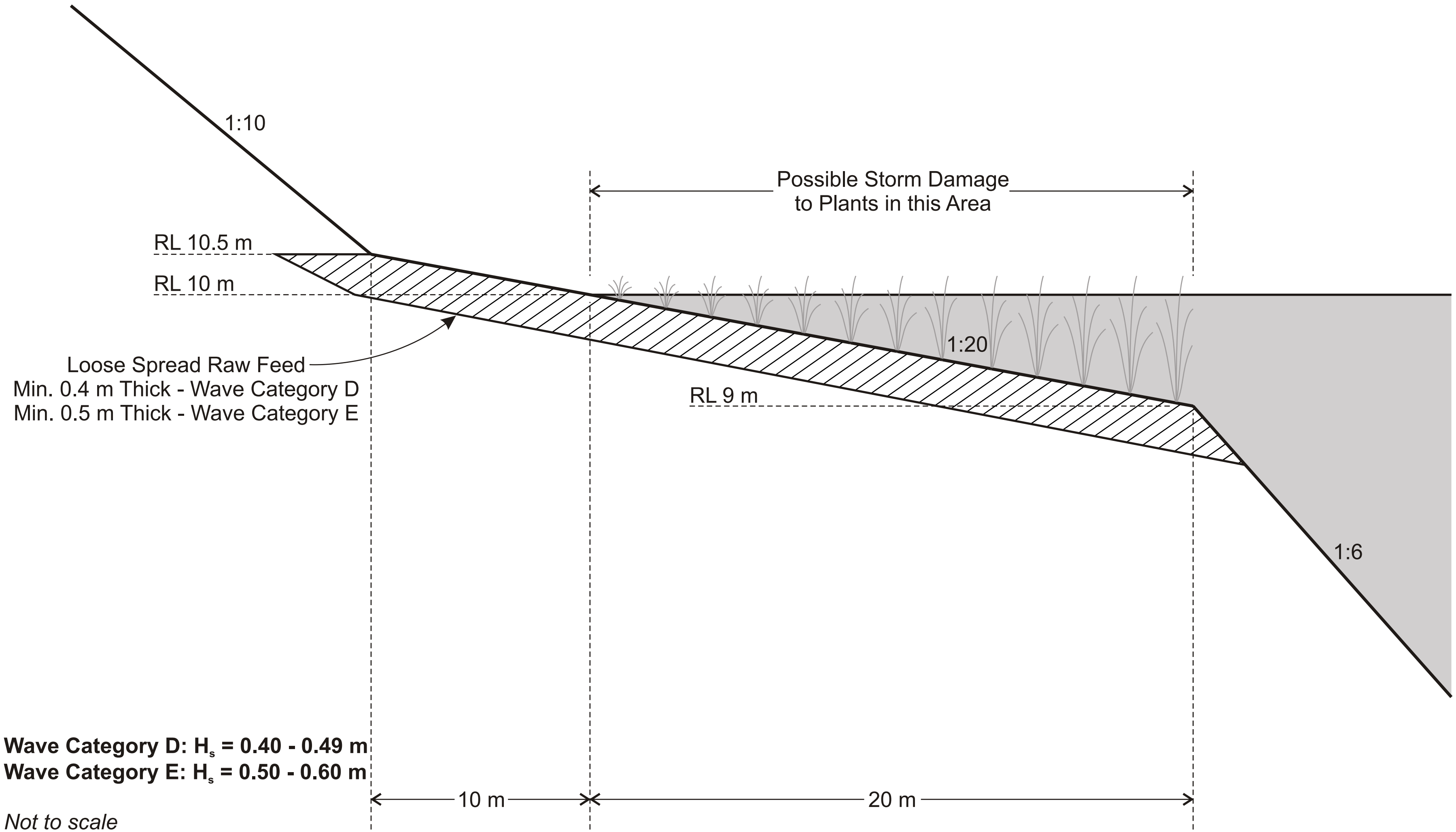
Not to scale

Figure 4.11

09030.4.11.cdr

WRL
Report No. 2009/09

SECTION D
WAVE CATEGORIES D AND E



Wave Category D: H_s = 0.40 - 0.49 m
Wave Category E: H_s = 0.50 - 0.60 m

Not to scale

Figure
4.12

09030-4.12.cdr

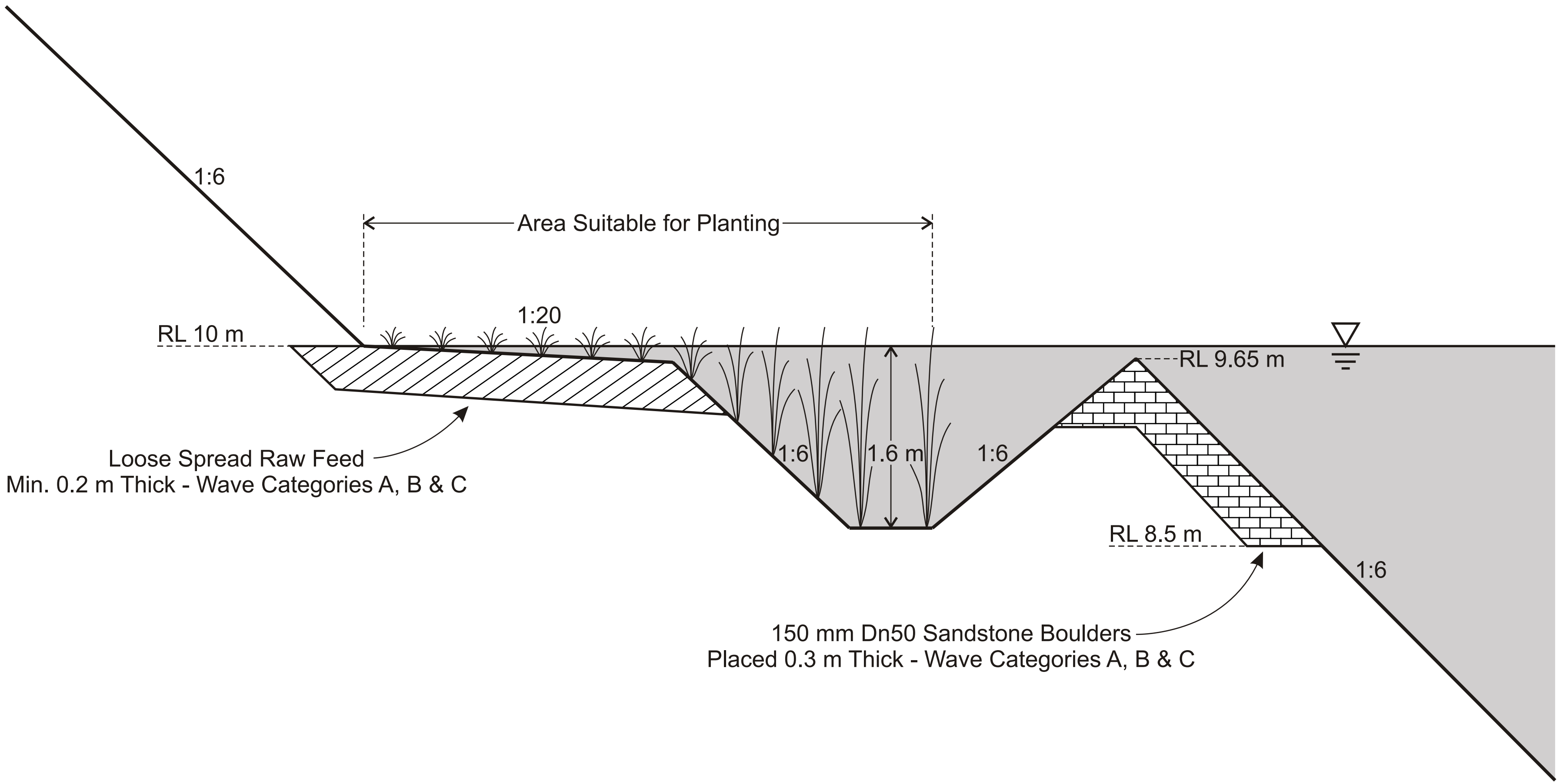
WRL

Report No. 2009/09

SECTION E - WAVE CATEGORIES A, B AND C
CONSERVATIVE DESIGN

Figure
4.13

09030.4.13.cdr



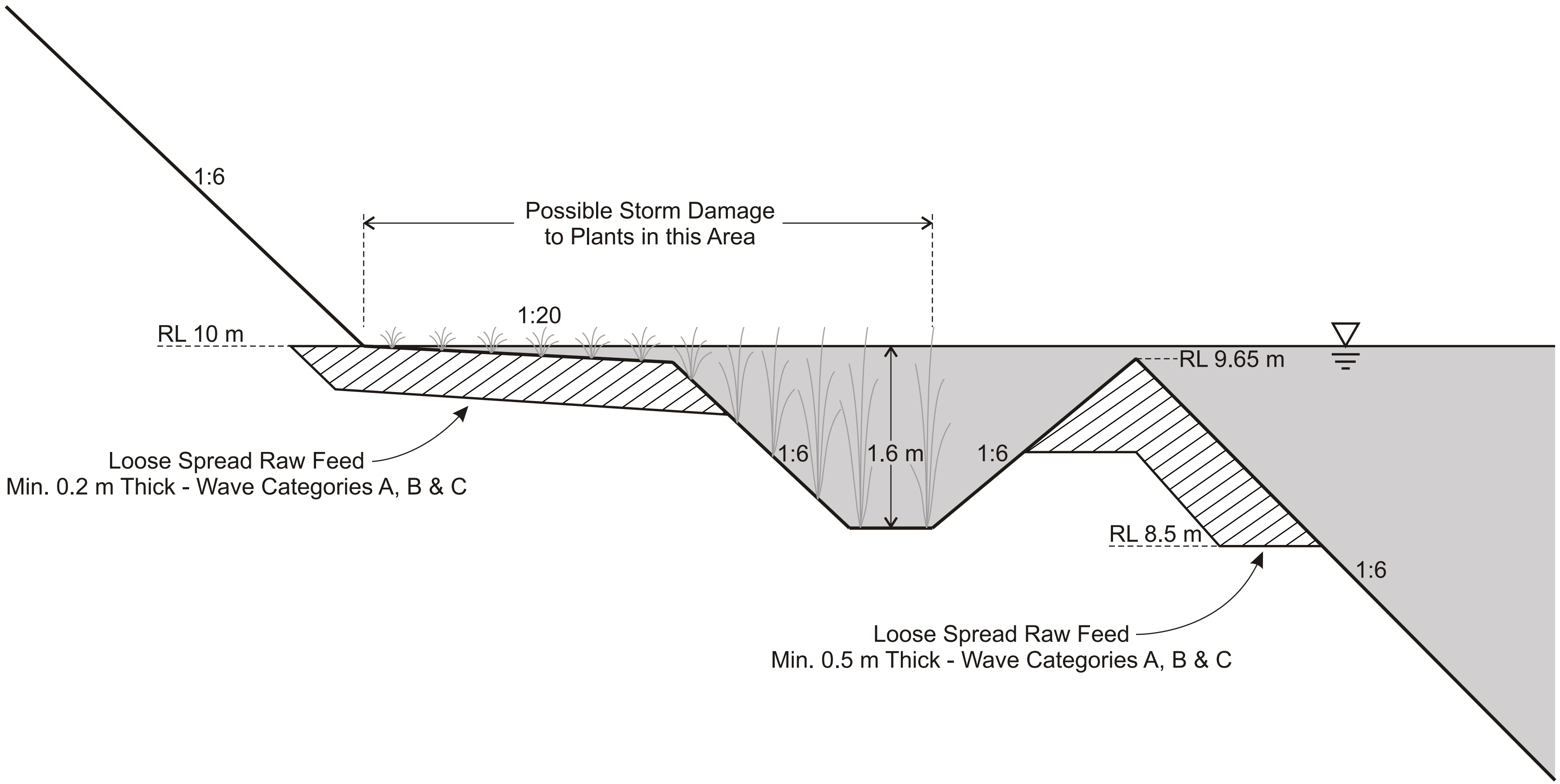
Wave Category A: H_s < 0.20 m
Wave Category B: H_s = 0.20 - 0.29 m
Wave Category C: H_s = 0.30 - 0.39 m

Not to scale

WRL

Report No. 2009/09

SECTION E - WAVE CATEGORIES A, B AND C
MONITORING AND POSSIBLE MAINTENANCE REQUIRED



Wave Category A: H_s < 0.20 m
Wave Category B: H_s = 0.20 - 0.29 m
Wave Category C: H_s = 0.30 - 0.39 m

Not to scale

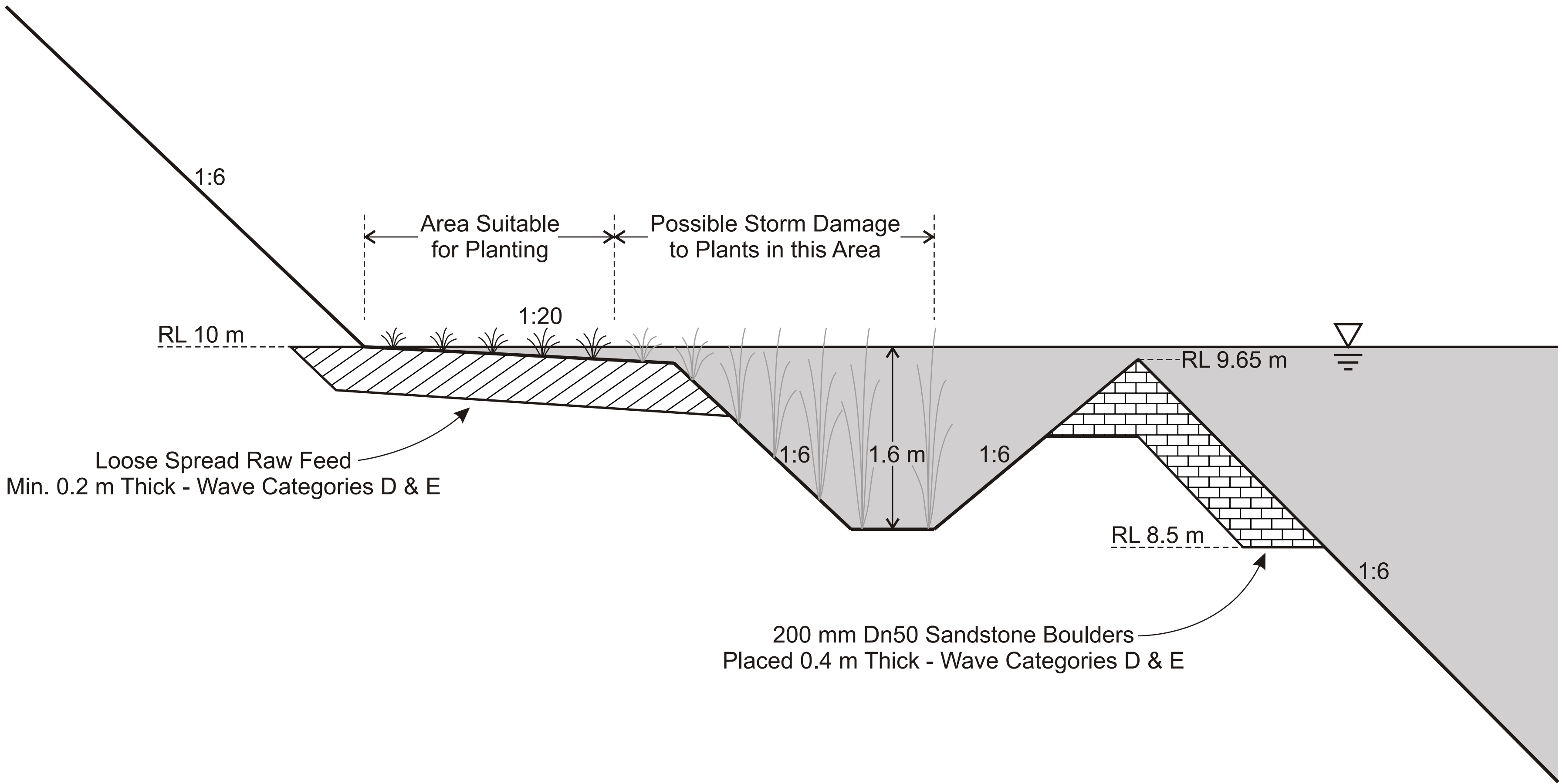
Figure 4.14

09030-4.14.cdr

WRL

Report No. 2009/09

SECTION E
WAVE CATEGORIES D AND E

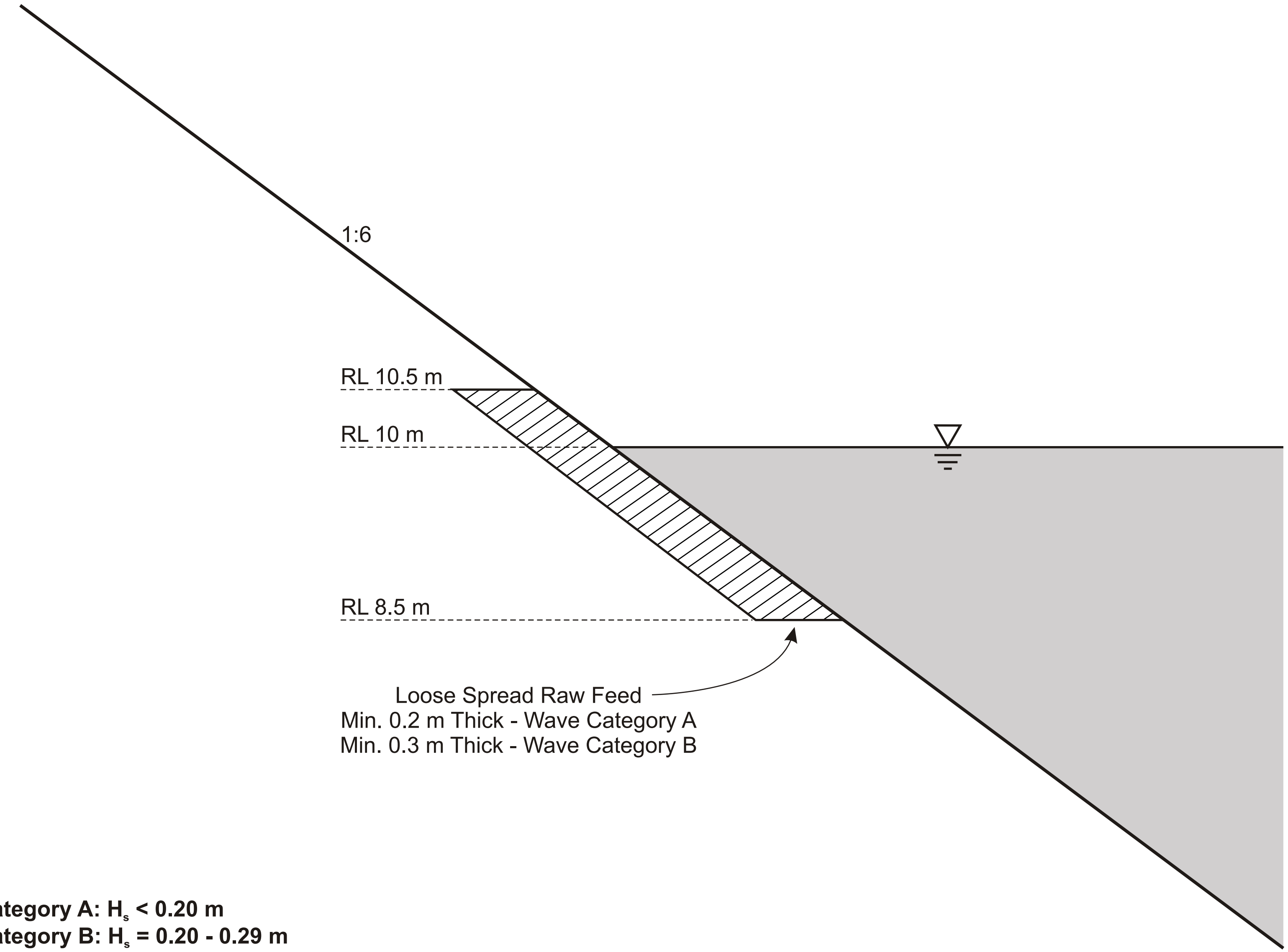


Wave Category D: H_s = 0.40 - 0.49 m
Wave Category E: H_s = 0.50 - 0.60 m

Not to scale

Figure 4.15

09030.4.15.cdr



Wave Category A: H_s < 0.20 m
Wave Category B: H_s = 0.20 - 0.29 m

Not to scale

WRL
Report No. 2009/09

SECTION F
WAVE CATEGORIES A AND B

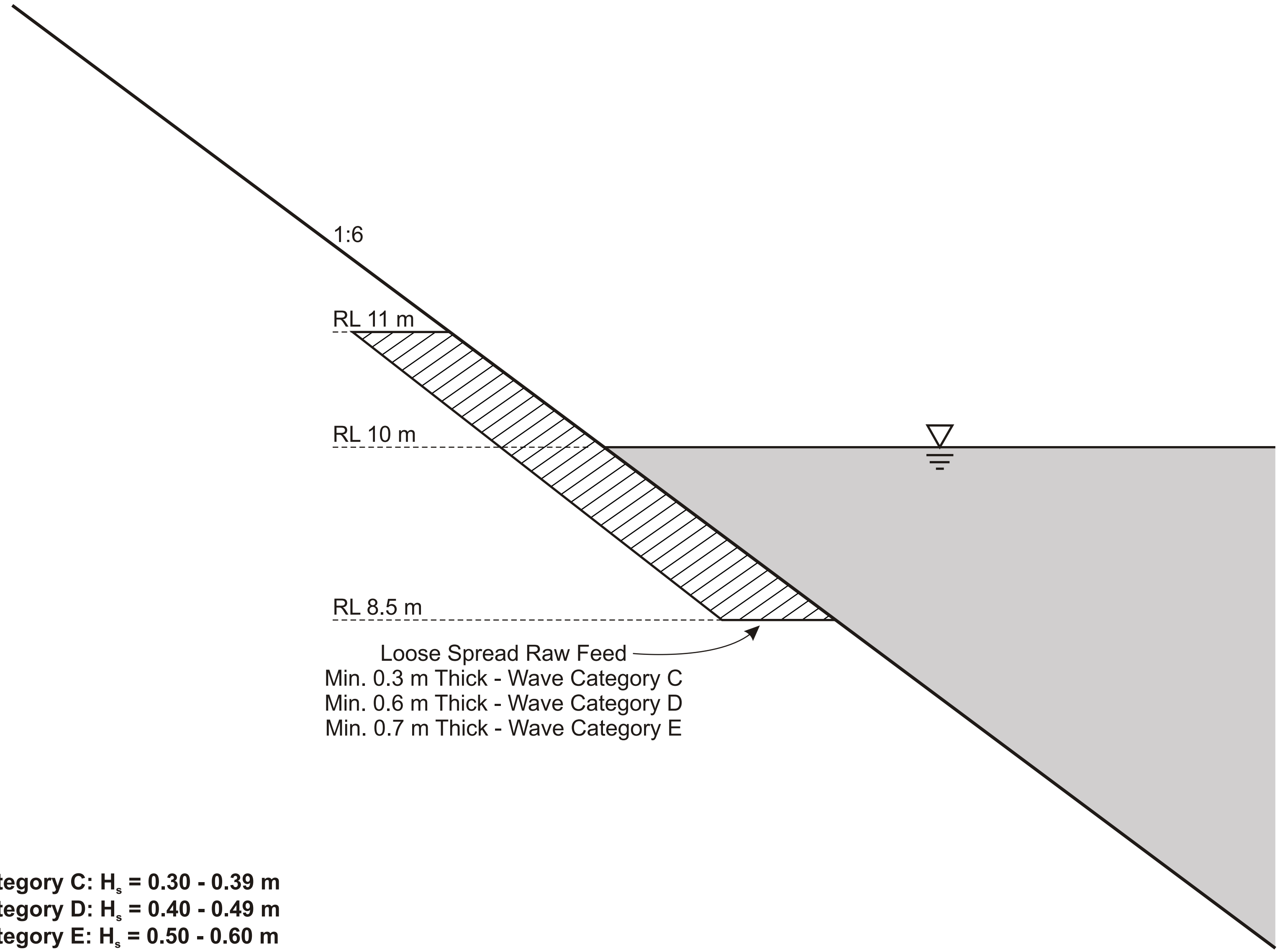
Figure
4.16

09030.4.16.cdr

WRL

Report No. 2009/09

SECTION F
WAVE CATEGORIES C, D AND E



Wave Category C: H_s = 0.30 - 0.39 m
Wave Category D: H_s = 0.40 - 0.49 m
Wave Category E: H_s = 0.50 - 0.60 m

Not to scale

Figure 4.17

09030.4.17.cdr

WRL

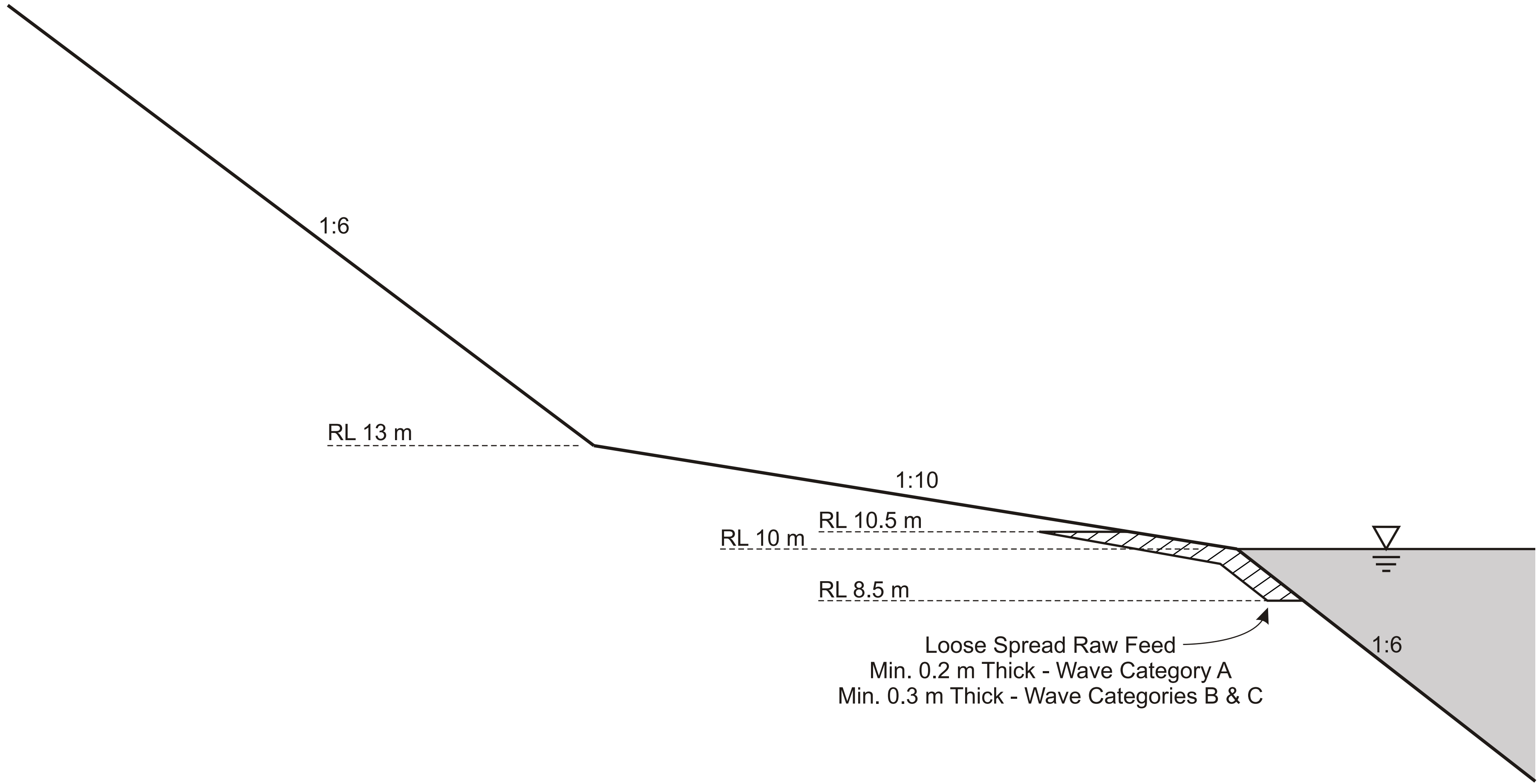
Report No. 2009/09

SECTION G

WAVE CATEGORIES A, B AND C

Figure 4.18

09030.4.18.cdr

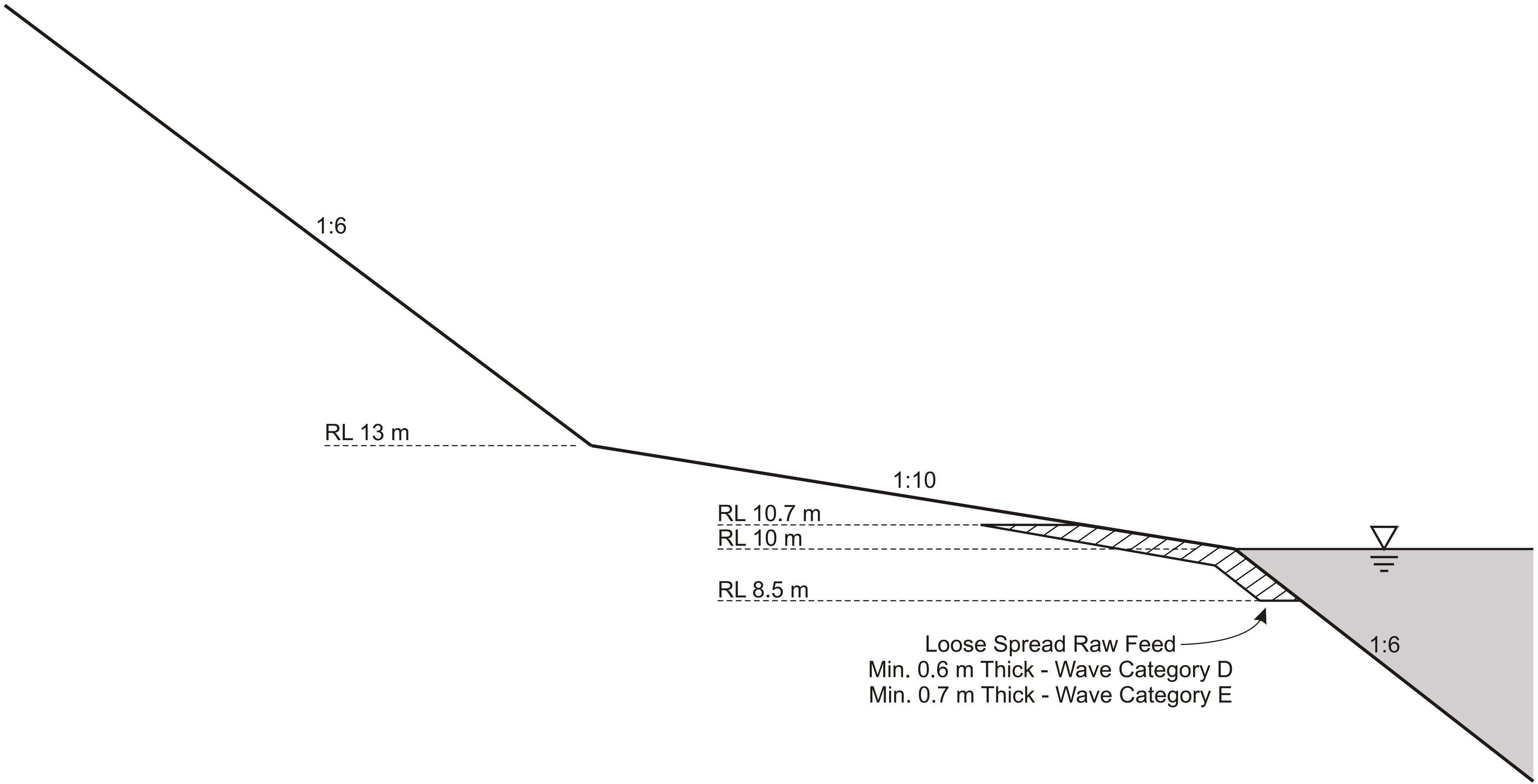


Wave Category A: H_s < 0.20 m
Wave Category B: H_s = 0.20 - 0.29 m
Wave Category C: H_s = 0.30 - 0.39 m

Not to scale

WRL
Report No. 2009/09

SECTION G
WAVE CATEGORIES D AND E



Wave Category D: H_s = 0.40 - 0.49 m
Wave Category E: H_s = 0.50 - 0.60 m

Not to scale

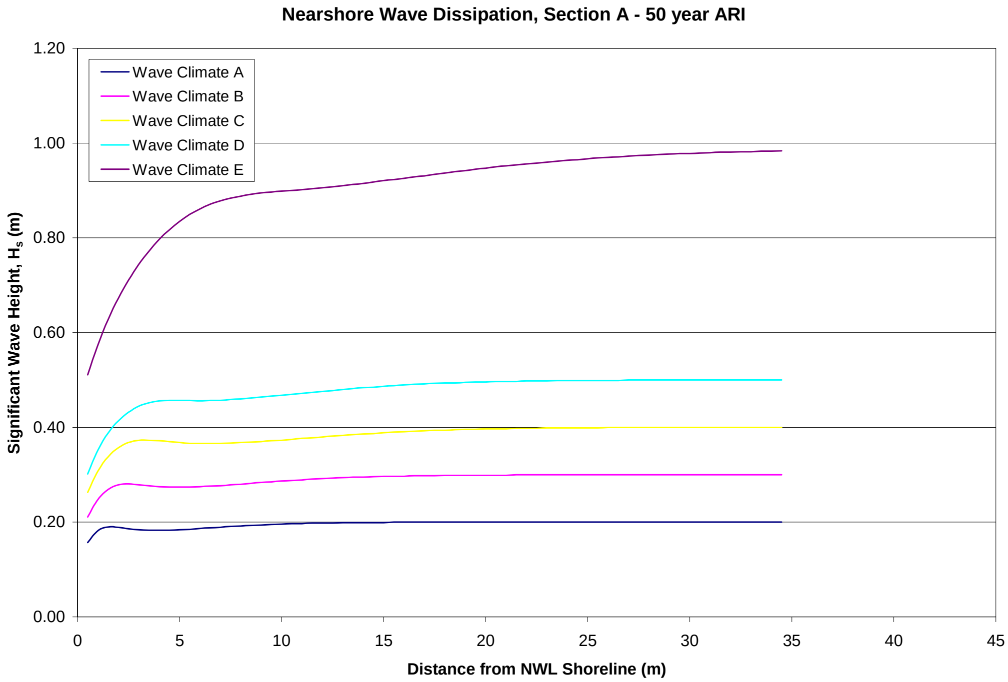
Figure 4.19

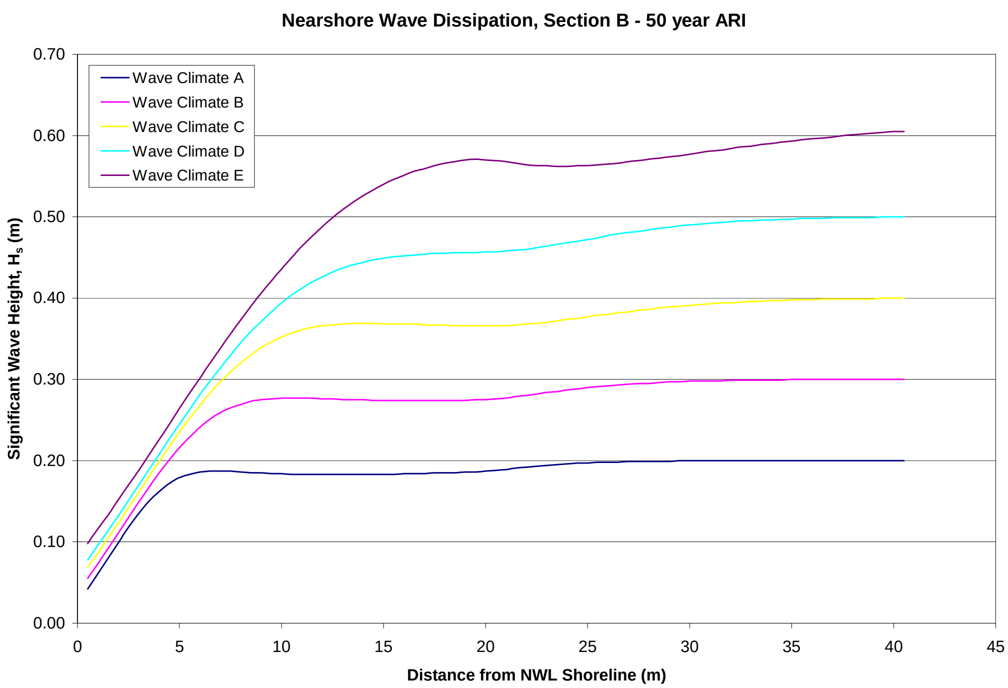
09030.4.19.cdr

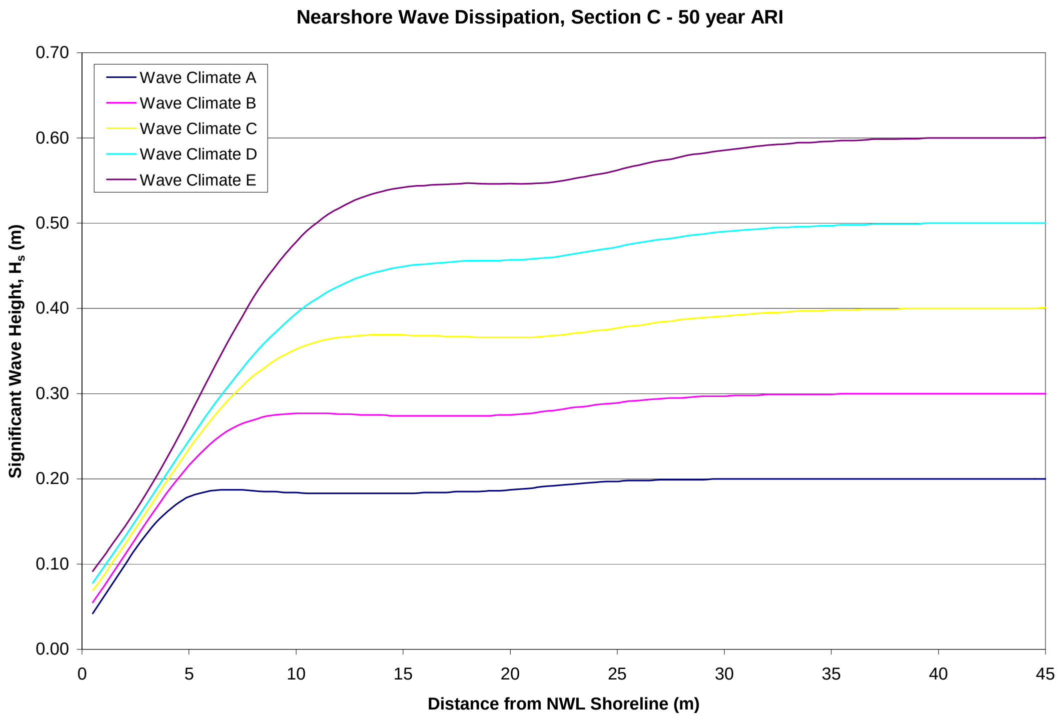
APPENDIX A
NEARSHORE SURFZONE WAVE MODELLING

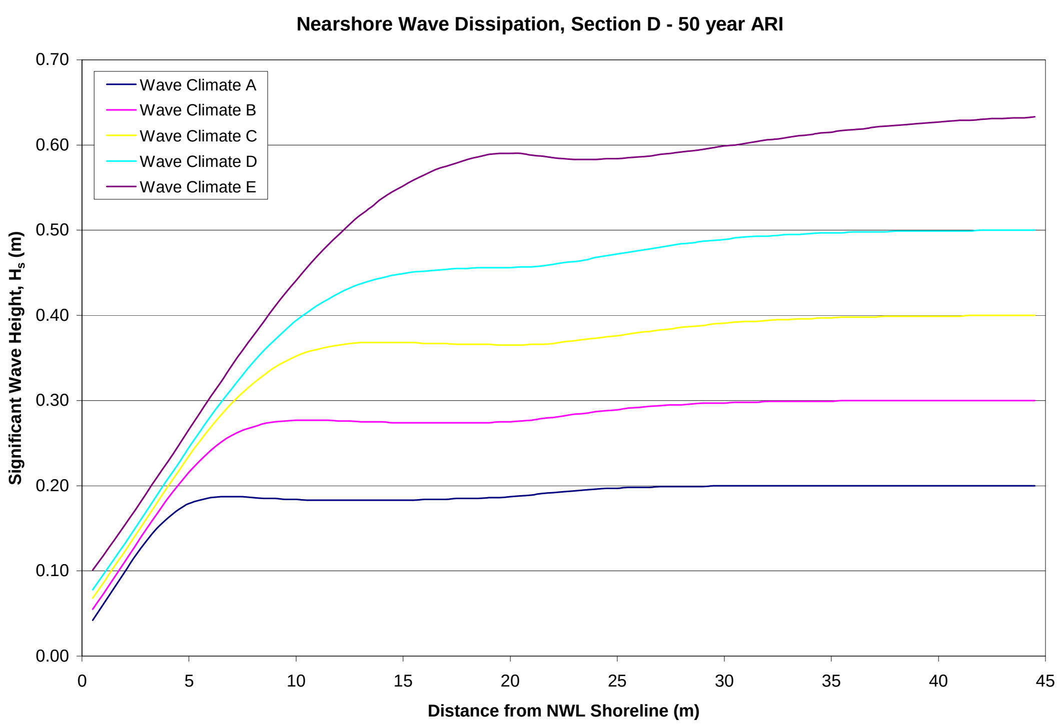
APPENDIX A. NEARSHORE SURFZONE WAVE MODELLING

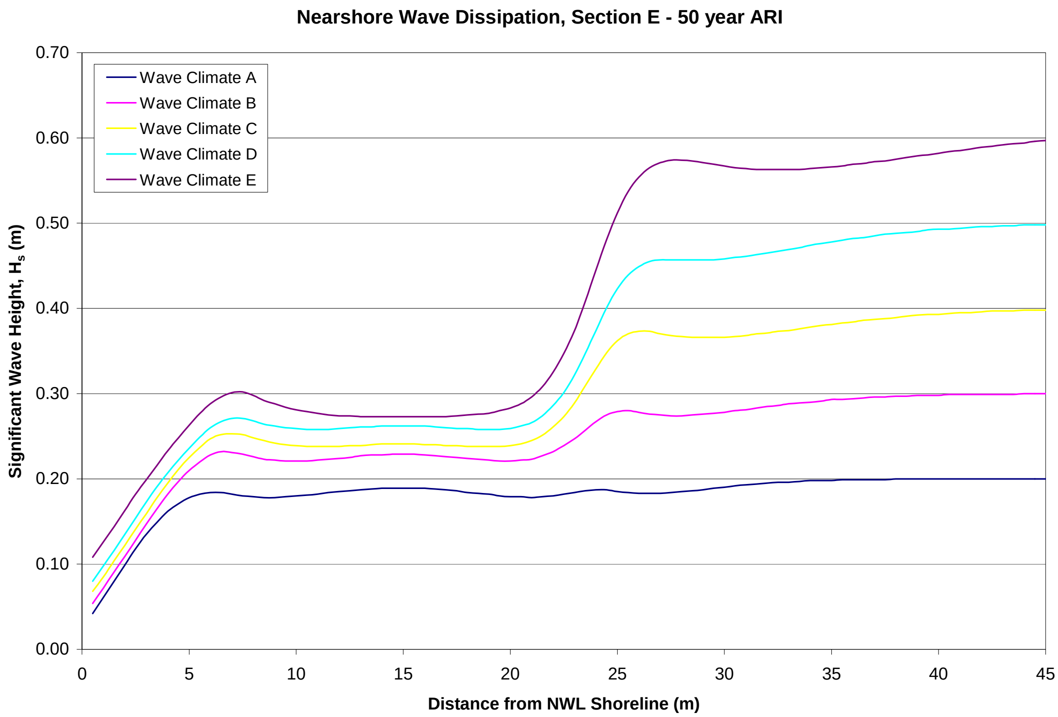
The following plots show the decay of wave height from breaking and dissipation as waves travel over the foreshore profiles. These charts can be used to identify the nearshore wave heights during a 50 year ARI storm event. The shoreline for this analysis is the Normal Water Level (NWL) shoreline at RL 10 m on foreshore sections.

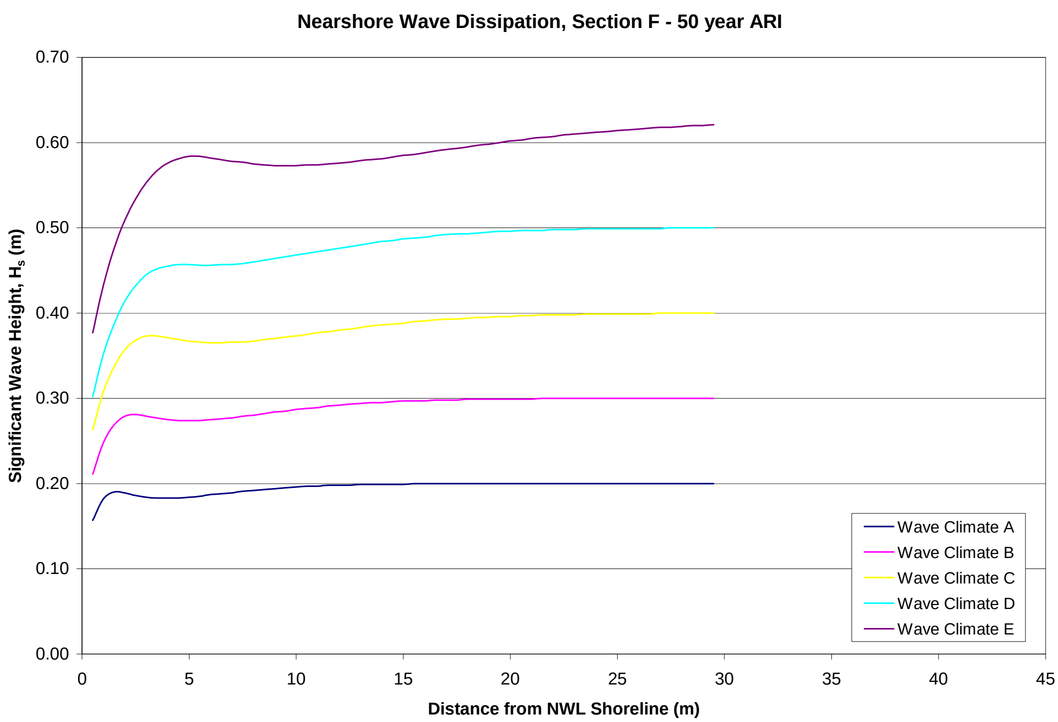





Nearshore Wave Dissipation, Section C - 50 year ARI
Wave Climate A
Wave Climate B
Wave Climate C
Wave Climate D
Wave Climate E
Significant Wave Height, Hs (m)
Distance from NWL Shoreline (m)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0
5
10
15
20
25
30
35
40
45


Nearshore Wave Dissipation, Section D - 50 year ARI
Wave Climate A
Wave Climate B
Wave Climate C
Wave Climate D
Wave Climate E
Significant Wave Height, Hs (m)
Distance from NWL Shoreline (m)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0
5
10
15
20
25
30
35
40
45


Nearshore Wave Dissipation, Section E - 50 year ARI
Significant Wave Height, H_s (m)
Distance from NWL Shoreline (m)
Wave Climate A
Wave Climate B
Wave Climate C
Wave Climate D
Wave Climate E
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0
5
10
15
20
25
30
35
40
45


Nearshore Wave Dissipation, Section F - 50 year ARI
Significant Wave Height, H_s (m)
Distance from NWL Shoreline (m)
Wave Climate A
Wave Climate B
Wave Climate C
Wave Climate D
Wave Climate E
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0
5
10
15
20
25
30
35
40
45