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Cover Photo: Bellinger River estuary erosion survey

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CONTENTS

Executive Summary i
Introduction 1
Study aims and objectives 1
Report Structure 2
Study area 3

PART 1 BELLINGER-KALANG ESTUARY GEOMORPHOLOGY 4

1.0 Late Quaternary evolution of the Bellinger/Kalang River estuaries 4
2.0 Settlement history and landuse changes of the lower Bellinger/Kalang 6
3.0 Climate and hydrology of the lower Bellinger/Kalang Rivers 9
  3.1 Temporal trends in rainfall patterns 9
  3.2 Temporal trends in streamflow 11
    3.2.1 Historical flood stage-heights in Bellingen:1870-2009 11
    3.2.2 Identifying flood and drought dominated periods in the Bellinger/Kalang 13
    3.2.3 Synoptic drivers for temporal variations in rainfall and stream flow 14
4.0 Geomorphic process zones of the Bellinger/Kalang River estuaries 16
  4.1 Fluvial Dominated process zone 17
  4.2 Fluvial Transition process zone 19
  4.3 Marine Tidal Delta process zone 21
5.0 Historical channel changes of the Bellinger/Kalang River estuaries 22
  5.1 Comparison of current and historical bathymetry 22
  5.2 Photogrammetry analysis of 20th century channel migration 25
    5.2.1 Photogrammetry methodology 25
    5.2.2 Bend migration and bank erosion 26
    5.2.3 Historical channel changes on the Bellinger River 28
    5.2.4 Historical channel changes on the Kalang River 34
  5.3 Sites of accelerated channel change on the Bellinger/Kalang estuaries 36
  5.4 Implications of climate change on the Bellinger/Kalang River estuaries 38

PART 2 BELLINGER-KALANG 2009 BANK CONDITION ASSESSMENT 39

6.0 Current bank condition in the Bellinger and Kalang estuaries 39
  6.1 2009 field survey methodology 39
  6.2 Estuary bank erosion 40
    6.2.1 Summary of bank erosion - Bellinger River estuary 42
    6.2.2 Summary of bank erosion - Kalang River estuary 53
    6.2.3 Comparison of 1984 and 2009 channel erosion 67
  6.3 Riparian and estuary related remnant vegetation 69
    6.3.1 Riparian vegetation condition 69
    6.3.2 Remnant vegetation 71
  6.4 Estuary bank protection works 74
    6.4.1 Bank protection works - Bellinger River estuary 74
    6.4.2 Bank protection works - Kalang River estuary 76
    6.4.3 Effectiveness of bank protection works on the Bellinger-Kalang estuaries 77
    6.4.4 Best practice options for treatment of bank instability in estuaries 79
  6.5 Estuary access infrastructure 84
PART 3  RECOMMENDATIONS FOR MANAGEMENT OF BANK EROSION IN THE BELLINGER-KALANG ESTUARIES  86

7.0 Setting priorities for erosion management in estuarine systems  86
   7.1 General recommendations for erosion management  86
   7.2 Specific recommendations for erosion management  87

REFERENCES  90

APPENDICIES
Appendix 1 - Field survey GIS datasets provided to Bellingen Shire Council.  92
Appendix 2 - Photogrammetry cross sections 1942-2009.  93

LIST OF FIGURES

Figure 1  Locality diagram of the Bellinger and Kalang River estuaries.  3
Figure 2  Interpretation of late Pleistocene/early Holocene flooding of coastline associated with the post-glacial rise in sea level.  4
Figure 3  Transect showing age of floodplains at Bellingen township  5
Figure 4  Total monthly rainfall analysis 1899-2002  10
Figure 5  Historical flood heights on the Bellinger River at Bellingen Bridge  12
Figure 6  Cusum curve for mean daily discharge at Thora (2005002) from 1955 – 2009.  13
Figure 7  Frequency of east-coast lows since 1950  15
Figure 8  Distribution of geomorphic process zones in the Bellinger/Kalang estuaries  17
Figure 9  Bellinger longitudinal thalweg profile from Bellingen to Urunga  18
Figure 10  Kalang longitudinal thalweg profile from Brierfield to Urunga  18
Figure 11  Historical planform changes on the lower Bellinger River at Fernmount  21
Figure 12  Comparison between current bathymetric longitudinal profile and 1984/1985 bathymetric profile on the lower Bellinger River  22
Figure 13  Comparison between current bathymetric longitudinal profile and 1984/1985 bathymetric profile on the Kalang River  23
Figure 14  Location of focus reaches and river bends selected for photogrammetry analyses.  24
Figure 15  Mean bend migration rates for the Bellinger River  27
Figure 16  Mean bend migration rates for the Kalang River  27
Figure 17  Photogrammetrically derived high bank locations in the vicinity of Bends 1 to 4 downstream of Bellingen over the period 1943 - 2002.  28
Figure 18  Cross-sectional change for fluvial dominated reach A on the Bellinger River  29
Figure 19  Cross-sectional changes at the downstream end of Bend 4  30
Figure 20  Photogrammetrically derived high bank locations in the vicinity of Bend 5 and Bend 6 at Fernmount over the period 1943 - 2002.  31
Figure 21  Bank erosion/channel migration of Bend 6, upstream of Fernmount bluff  31
Figure 22  Photogrammetrically derived high bank locations in the vicinity of Bends 7 and 8 at “Hendersons” over the period 1943 - 2002.  33
Figure 23  Photogrammetrically derived high bank locations in the vicinity of Kalang Bends 1 and 2 downstream of Brierfield over the period 1942 - 2003.  34
Figure 24  Photogrammetrically derived high bank locations in the vicinity of Kalang Bends 3 and 4 near Urunga over the period 1943 - 2003.  35
Figure 25  Distribution and severity of reaches of active erosion mapped in the Bellinger and Kalang River estuaries, June 2009.  40
Figure 26  Distribution and severity of reaches of active erosion mapped in the Bellinger Fluvial Dominated A process zone between April and June 2009.

Figure 27  Distribution and severity of reaches of active erosion mapped in the Bellinger Fluvial Dominated B Process Zone, June 2009.

Figure 28  Distribution and severity of reaches of active erosion mapped in the Bellinger Fluvial Transition Process Zone, June 2009.

Figure 29  Distribution and type of existing bank protection and remediation works in the Bellinger Fluvial Transition Process Zone as at June 2009.

Figure 30  Distribution and severity of reaches of active erosion mapped in the Bellinger Marine Tidal Delta process zone, June 2009.

Figure 31  Distribution and type of existing bank protection and remediation works in the Bellinger Marine Tidal Delta process zone as at June 2009.

Figure 32  Distribution and severity of reaches of active erosion mapped in the Kalang Fluvial Dominated A process zone, June 2009.

Figure 33  Distribution and severity of reaches of active erosion mapped in the Kalang estuary Fluvial Dominated B process zone, June 2009.

Figure 34  Distribution and severity of reaches of active erosion mapped in the Kalang Fluvial Transition process zone, June 2009.

Figure 35  Distribution and type of existing bank protection and remediation works in the Kalang Fluvial Transition process zone as at June 2009.

Figure 36  Overall riparian vegetation condition in the Kalang Fluvial Transition process zone as at June 2009.

Figure 37  Distribution and severity of reaches of active erosion mapped in the Kalang Marine Tidal Delta process zone, June 2009.

Figure 38  Comparison of 1984 and 2009 erosion survey data

Figure 39  Overall condition of riparian vegetation in the Bellinger and Kalang River estuaries, June 2009.

Figure 40  Distribution of estuary-related remnant vegetation in the Bellinger-Kalang estuary study area.

Figure 41  Distribution and type of existing bank protection and remediation works in the Bellinger Marine Tidal Delta process zone as at June 2009.

Figure 42  Distribution and type of existing bank protection and remediation works in the Bellinger Fluvial Dominated A process zone as at June 2009.

Figure 43  Distribution and type of existing estuary access infrastructure in the Bellinger-Kalang estuaries as at June 2009.

Figure 44  Location of priority sites for erosion management in the Bellinger-Kalang River estuaries.
LIST OF TABLES

Table 1 Adopted Flood Frequency for the Bellinger River at Bellingen 12
Table 2 Annual and partial series for total discharge record at Thora 14
Table 3 Morphological and tidal attributes of the Bellinger/Kalang Estuary 16
Table 4 Dates of aerial photographs used in photogrammetry analysis 25
Table 5 Bend migration rates (bank erosion rates) for the Bellinger and Kalang Rivers 26
Table 6 Mean bankfull cross-sectional area and percentage change for Bends 1 – 8 32
Table 7 Mean bankfull width and percentage change for Bends 1 – 8 32
Table 8 Severity of bank erosion in the Bellinger River estuary, June 2009 41
Table 9 Severity of bank erosion in the Kalang River estuary, June 2009 53
Table 10 Comparison of 1981-84 and 2009 bank erosion data 67
Table 11 Overall condition of riparian vegetation in the Bellinger River estuary, June 2009 68
Table 12 Overall condition of riparian vegetation in the Kalang River estuary, June 2009 69
Table 13 Type and extent of bank protection works in the Bellinger River estuary, June 2009 73
Table 14 Type and extent of bank protection works in the Kalang River estuary, June 2009 76
Table 15 Snap-shot survey of effectiveness of bank protection measures in the Bellinger and Kalang River estuaries 77
Table 16 Summary of estuary access infrastructure statistics for the Bellinger and Kalang estuaries 83
Table 17 Recommended priorities for management of significant erosion in the Bellinger River estuary 88
Table 18 Recommended priorities for management of significant erosion in the Kalang River estuary 89

LIST OF PLATES

Plate 1 Upstream view of the lower Bellinger River from Marx Hill in 1902, 8
Plate 2 Downstream view of the lower Bellinger River from Fernmount, 1902. 8
Plate 3 Examples of erosion severity in the Bellinger Fluvial Dominated A process zone 43
Plate 4 Examples of severe erosion in the Bellinger Fluvial Dominated B process zone 46
Plate 5 Erosion in the Bellinger Marine Tidal Delta process zone 51
Plate 6 Examples of erosion severity in the Bellinger Marine Tidal Delta process zone 52
Plate 7 Erosion in the Kalang Fluvial Dominated A process zone 55
Plate 8 Erosion at Site 13 and Site 16, Kalang River estuary 56
Plate 9 Examples of erosion severity in the Kalang Fluvial Dominated B process zone 58
Plate 10 Erosion in the Kalang Fluvial Transition process zone 63
Plate 11 Examples of bank protection works, Bellinger-Kalang estuaries 78
Plate 12 Examples of best-practice rock revetment works 80
Plate 13 Examples of rock embayment works 80
Plate 14 Examples of fencing and revegetation on estuaries 81
Plate 15 Root ball revetment on the Kalang River estuary near Urunga 82
Executive Summary

The Bellinger/Kalang catchment has experienced a net reduction in large floods since 1977/78. This is a regional phenomena replicated in other coastal catchments of south-eastern Australia. This is despite 2009 having three moderate-large floods in February, March and May of 7.81, 8.58 and 8.38 m (AHD) respectively, corresponding to between the 20 and 10% annual exceedance probability (AEP) at Bellingen Bridge. This regional reduction in flood activity has resulted in an 11 – 26% decrease in flood magnitude for various recurrence intervals on the Bellinger River.

Comparison of the current (2008/2009) bathymetric longitudinal profile and the 1984/1985 bathymetric profile demonstrates the stability of macro-bedforms along the lower reaches of the tidal Bellinger River. Deep scour holes and major shoal crests have been in the same position for 25 years suggesting that the overall bed morphology is controlled by channel planform and resistant material at the channel margin (i.e. bedrock or old alluvium). The only major changes in bed elevation are around Raleigh Shoal and McGeary’s Island with the former showing 1 – 1.5 m of net bed lowering and with the latter showing the equivalent aggradation. Given that the Raleigh Shoal is actively dredged it is highly likely that the changes in bed elevation are a function of extractive operations. Patterns of sedimentation on the Kalang estuary also show stability of the form of channel profile with the only areas of demonstratable change being the lower areas of the Kalang River around Newry Island. In this case, both the south and north branch show aggradation of 1 – 1.5 m.

To aid the discussion of erosion processes, geomorphic process zones were delineated along the length of both estuaries. The process zones reflect underlying geomorphic characteristics including relative tidal fluvial energy dynamics, floodplain and channel morphology, sedimentary features, and vegetation attributes. Four process zones were identified;

- Fluvial dominated A process zone
- Fluvial dominated B process zones
- Fluvial Transition process zone
- Marine tidal delta process zone.

As with previous studies this report highlights that the steeper fluvially-dominated upper tidal reaches of the Bellinger River have eroded at a faster rate than the lower gradient fluvial-transition reaches on the Bellinger River. The data indicates that the Bellinger River at all sites erodes/migrates at a faster rate than the Kalang River. This is inferred to be a function of more cohesive bank material and quality and extent of riparian vegetation in the Kalang River estuary. The photogrammetry data also indicate that the cross-sectional changes and migration rates cannot be explained solely by the hydrological regime in a given time interval. Net increases in channel capacity are commonly recorded in addition to areas of net deposition. A 6 – 33% net increase in width has been documented to have occurred since 1942 in 6/8 bends examined, with the greatest changes occurring in the upstream fluvial dominated reach of the Bellinger River. Channel capacity (cross-sectional area) on the lower Bellinger River for 5/8 bends show a 2 - 75% increase. Two bends (Bends 2 and 3) both record a 12 – 14% net reduction in channel capacity as a function of deposition on the low floodplain. Sites of accelerated change are identified on both the Bellinger and Kalang Rivers.
Executive Summary

A comparison of digital GPS survey data of high bank location post the June 2009 floods to the 2002/2003 bank location showed that erosion rates were highest on the Bellinger River at Bends 5 (right bank upstream of Hydes Creek confluence), Bend 6 (opposite Fernmount on river left), and at Bend 4 (on river left approximately 500m downstream of Carlill’s Wharf). Erosion at these three sites is dominated by fluvial processes, with all sites having increased susceptibility to erosion due to the low cohesion of the alluvial bank soils, an almost complete lack of well structured riparian vegetation, and ongoing disturbance factors particularly associated with poorly managed stock access. On the Kalang River erosion rates were highest at Bend 1 in the upper fluvial dominated reaches of the estuary, followed by Bend 3 and Bend 4 on Newry Island opposite Urunga. Erosion processes at these three sites are also exacerbated by a lack of structurally diverse riparian vegetation, unmanaged stock access, and at Bends 3 and 4 wind and/or boat wave wash (relative contribution unknown).

A snap-shot survey of bank erosion undertaken in June 2009 (ie. post the early 2009 flood series) reveals that of the 60.3km of banks surveyed in the Bellinger River estuary, just over half (32.4 km or 54%) are stable with approximately 1/3rd of the remaining banks recorded with minor erosion (19.5km or 32%). Approximately 18% of stable banks were stabilised by erosion control works while 5% were naturally stable as a result of bedrock outcropping on the channel margin. This suggests that 41% of the alluvial river banks are naturally stable.

The summary statistics for the Bellinger estuary also show that:

- The Fluvial-dominated A process zone recorded the highest levels of moderate and severe erosion (13% and 10% respectively).
- The Fluvial-dominated A and B zones had similar proportions of stable bank. However, approximately 40% of the stable banks in the Fluvial-dominated A zone were either stabilised by bank protection works (21%) or bedrock (15%). Conversely, 99% of stable banks in the Fluvial-dominated B zone were alluvial with only 2% protected by works (rock revetment and revegetation).
- The Fluvial Transition zone had almost no active erosion, but almost a quarter of its banks were armoured by bank protection works (predominantly rock revetment) and 6% were protected by bedrock outcropping.
- 12 sites were identified as being significant in terms of the severity of erosion or potential to impact on the environment, social or economic values of the estuary.

In the Kalang River estuary, the 2009 survey results reveal that of the 60.5km of banks surveyed, just over two thirds (41.2 km or 68%) are stable, 21% have minor erosion (12.8km), 6% moderate erosion (3.8km), and 4% were mapped with severe erosion (2.7km). Bedrock outcropping (9% of banks recorded as stable) accounts for a greater proportion of stable banks in the Kalang than in the Bellinger. Also in contrast to the Bellinger estuary, a lesser proportion of stable banks are stable due to bank protection works (13%), with the vast majority of works located in the lower estuary around Newry Island and Urunga. This suggests that in the Kalang, approximately 53% of the alluvial river banks are naturally stable.

The summary statistics also show that:

- Bank erosion in the Kalang River estuary is concentrated in the Fluvial-dominated A and Fluvial Transition zones.
• The Fluvial Transition zone had almost 5.4km of bank protection works representing more than 20% of total bank length. Moderate and severe bank erosion was concentrated at the southern end of Newry Island on alluvial banks with essentially no riparian vegetation.

• The Fluvial-dominated B zone recorded the lowest levels of erosion of all process zones, mostly as a factor of the high level of bedrock control on the channel and the relatively continuous riparian vegetation strip in this zone.

• The Marine-tidal delta zone also recorded very low levels of bank erosion, however, 28% of stable banks in this zone were stabilised by bank protection works (mostly rock or rubble revetment and training walls). A further 12% were stable due to bedrock.

• 14 sites were identified as being significant in terms of the severity of erosion or potential to impact on the environment, social or economic values of the estuary.

A comparison of 2009 erosion severity and extent with results of surveys in 1981 and 1984 and reported in Cameron McNamara (1984) show a very large increase in minor bank erosion but a net reduction in moderate and severe bank erosion (26% and 68% respectively) in both the Kalang and Bellinger estuaries. The high proportion of minor erosion recorded in this survey is most likely a consequence of the proximity of the survey to the 2009 floods, although factors such as differing survey methodologies may also account for variations.

Riparian vegetation was generally poor throughout both estuaries, mostly as a consequence of historical land use but also influenced by contemporary management practices which continue to suppress native vegetation regeneration. Stock access and weed infestation were the two most common factors retarding native riparian vegetation recovery. The most common environmental weeds recorded were camphor laurel, small-leaved privet, coastal morning glory, cats claw creeper, white passion flower, and lantana. Four major types of remnants vegetation were mapped including remnant riparian forest, mangrove distribution, candidate coastal saltmarsh endangered ecological communities (EEC), and candidate swamp sclerophyll ECC. The distribution of remnant vegetation generally correlates with land capability. Two areas of remnant vegetation were identified as areas of significance that may be affected by erosion processes.

Bank protection measures have been implemented along 17km of waterway representing approximately 14% of the total length of bank surveyed. The most commonly used methods were rock revetment, rock training walls, revegetation and fencing, mixed (rubble, brick, concrete, timber, tyres), and tyre walls. It was estimated that 13% of works on the Bellinger were either only partially effective or failing. On the Kalang, 17% were partially effective or failing. The report recommends 4 examples of best-practice erosion control methods for estuaries in Section 6.4.4. In addition to protection works, the location, type and assumed tenure of estuary access infrastructure were also mapped. 170 access points were recorded of which 151 were assumed to be private structures on either private or foreshore reserve land. There was no observed correlation between bank erosion and estuary access structures.

The report recommends a set of guiding principles for erosion management that may be used to determine priorities for erosion control works. In is suggested that these principles be considered in conjunction with other factors such as economic (ie. funding and resource availability), social, and cultural considerations. The general principles recommended are;

• Protect existing infrastructure
Executive Summary

- Protect important conservation values
- Protect existing works
- Utilise best practice erosion control techniques
- Improve riparian vegetation
- Manage recreational boat use

Using the above principles, the 28 sites of erosion significance identified through the 2009 bank erosion survey have been allocated into three main priority groups. Five sites are recommended as Highest Priority, four sites as High Priority, with the remainder all considered to be Moderate Priority with the decision to work in these areas dependant upon factors such as landholder willingness, available resources, ability to remove disturbance factors, and social and political factors.
Introduction

Bellinger Shire Council, with the assistance of the Department of Environment, Climate Change and Water (DECCW) estuary management program, has prepared an Estuary Management Plan (EMP) for the Bellinger and Kalang Rivers. The EMP, which was adopted by Council in May 2008, included a number of prioritised implementation actions (BMT WBM, 2008). Of the identified actions, improving the knowledge and understanding of bank erosion processes in the Bellinger and Kalang River estuaries was identified as the highest priority. In particular, current and accurate mapping of erosion and a thorough investigation of erosion processes driving erosion in the two estuaries were identified as high priority actions (Strategy 5.1 and 5.3 respectively). In response, the Bellingen Shire Council has, with the support of NSW Department of Environment, Climate Change and Water, commissioned the Bellinger-Kalang Erosion Study. This report represents the findings of the study.

Study aims and objectives

The aim of this study to implement the following objectives from the Bellinger and Kalang Rivers Estuary Management Plan (EMP);

Management Strategy 5.1 by undertaking a comprehensive survey of bank erosion (including riparian vegetation) within the Bellinger and Kalang estuaries.

Management Strategy 5.3 by assessing and describing the broader geomorphic processes and characteristics of the Bellinger/Kalang estuaries investigating and describing current bank erosion processes and causal factors, and investigating and describing the estuary sedimentation characteristics including the role of fluvial sources.

Management Strategy 5.4 address partly by determining priorities for implementation of bank and riparian protection works based upon the findings of the erosion management study.
Bellinger-Kalang Estuary Erosion Study

Report Structure

Understanding the physical processes that drive estuarine erosion is essential if effective management solutions are to be found. The Bellinger and Kalang River estuaries, like other estuaries on the eastern seaboard of Australia have undergone accelerated rates of change since European settlement. This report is intended to provide a scientific basis for understanding the processes and underlying causes of erosion in the Bellinger-Kalang River estuaries.

Part 1 of the report seeks to assist the understanding of current day processes and the current day distribution of erosion in the two estuaries by;

Sections 1-3 documenting the historical changes that have occurred in the Bellinger and Kalang estuaries including late Quaternary estuary evolution and changes to land use and hydrological regime over the past century.

Section 4 identifying and describing geomorphic process zones within each estuary with a particular view to identifying the occurrence and extent of the main depositional environments (i.e. marine-tidal, fluvial transition and fluvial-dominated), using existing information (documents, reports and datasets made available by Bellingen Shire Council, New South Wales Department of Environment, Climate, Change and Water), aerial photography and bathymetric data.

Section 5 examining the rates and magnitudes of accelerated bank erosion in key areas by analysing historic and recent hydrographic data and photogrammetric analyses of bank erosion/channel migration in key areas over the period 1942 to current.

Part 2 of the report summarises the results of the 2009 field assessment of bank condition. It includes;

Section 6.2 an analysis of the current distribution of bank erosion within the Bellinger/Kalang estuaries including the identification of areas of current accelerated change with reference to the 2009 floods.

Section 6.3 a description of riparian vegetation condition throughout the estuary area and an explanation of the correlation between riparian vegetation condition and bank erosion severity.

Section 6.4 a summary of the distribution and effectiveness of bank protection works and options for future works that represent current best-practice.

Finally, Part 3 of the report provides management recommendation for future management of erosion within the two estuaries based on the findings of Parts 1 and 2 of the report.
Study Area

The Bellinger - Kalang estuary study area covers an area of approximately 160km$^2$. The Bellinger and Kalang Rivers join at Urunga and share a common entrance to the Pacific Ocean. In addition to the two river branches, the estuarine system includes Back Creek, Urunga Lagoon, and Picket Hill Creek and numerous areas of adjoining Saltmarsh and other saline wetlands such as those found on Urunga Island. The Bellinger is tidal to just above the Bellingen bridge while the Kalang is tidal almost to the Brierfield Bridge. This study focuses on the Bellinger and Kalang Rivers and the shared tributary system of Back Creek representing some 60km of estuary length and 120.8km of survey estuary bank.

The Bellinger and Kalang estuaries are referred to in technical terms as “Mature Barrier (Wave Dominated)” estuaries (Roy et al., 1980). In essence this means that the estuary behaves much like a freshwater river in its upper sections, runs through mostly fine-grained sediments in the mid to lower reaches (ie. cuts through an extensive floodplain with backwater and wetland features separated from the channel by natural levees on the bank), before running to the ocean over an entrance bar which is constantly replenished by sands drifting up the coast and being shunted into the mouth by waves and tides.

A locality map of the study area and important features is shown in Figure 1.

**Figure 1** Locality diagram of the Bellinger and Kalang River estuaries.
PART 1  BELLINGER KALANG ESTUARY GEOMORPHOLGY

1.0  Late Quaternary evolution of the Bellinger/Kalang River estuaries

Current sea level in south-eastern Australia was attained 7900 to 7700 years BP (before present) with sea levels continuing to rise to between +1 and +1.5 m between 7700 and 7400 years BP – termed the Holocene highstand (Sloss et al., 2007). This highstand lasted between 7500 years BP and 2000 years BP when it fell gradually to present level. The attainment of the Holocene highstand saw the drowning of embayed areas as the sea flooded previously exposed areas. It has been suggested for the Bellinger/Kalang estuaries that this marine incursion extended as far as the Repton and Raleigh area (PWD, 1983; Figure 2). This interpretation is generally consistent with the predicted distribution of acid-sulfate soils (ASS) for the lower Bellinger/Kalang River floodplains and with preliminary dating of the terraces on the lower Kalang River (7260 +/- 150 cal yrs BP). The risk assessment for ASS however, predicts high risk for the occurrence such soils (at depth) to Fernmount on the Bellinger and to the west of Newry Island on the Kalang River. Such acid sulfate soils are an indirect measure of previous estuarine extent with the pyrite-rich sediment indicating open water conditions or brackish estuarine conditions.

[Figure 2: Interpretation of late Pleistocene/early Holocene flooding of coastline associated with the post-glacial rise in sea level (Source: PWD, 1983).]
Recent work by Cohen and Nanson (2008) demonstrated that the attainment of sea level has been of secondary importance with regards to the timing of floodplain development on the lower Bellinger River at Bellingen with the floodplains accumulating from 4000 years BP. Regardless of the exact location of the previous estuarine extent, the existing chronology and ASS risk assessment suggests that the lower-most reaches of the estuary have been directly affected by the rise and the attainment of current sea level. In contrast, reaches closer to Bellingen township and the upper tidal reaches of the Kalang River have been dominated by ongoing fluvial erosion and deposition, continuing to the current day (Figure 3).

Figure 3  Transect at Bellingen township showing age of floodplains, modified after Cohen and Nanson (2008). Note the difference in size of the pre-1976 palaeochannel at Bellingen Island versus the contemporary channel. Downstream view, ka (thousands of years).
2.0 Settlement history and landuse changes of the lower Bellinger/Kalang

Unlike larger valleys to the north and south which were settled earlier in the 19th century (Daley, 1981, Birrel, 1987) the Bellinger valley was first ‘discovered’ by William Myles, a cedar getter moving north from the Macleay valley in either 1840 or 1841 (Braithwaite and Beard, 1978). With the notion that there was an unsettled valley with good water supply, Clement Hodgkinson led the first expedition from the Macleay valley in 1841.

Like many of the early descriptions of the floodplain forests of the mid-north coast region of NSW, Hodgkinson refers to the ‘brush’ — a euphemism used to describe dense rainforest — that they often had to cut through. Descriptions of the country-side using terms such as ‘choked’ or ‘impervious brush’ provide an indication of the density of some of the vegetation they were travelling through. Weingarth (1925) estimates that Hodgkinson and his party approached the Bellinger valley from the south, entering the main valley in the area of upper Thora. Hodgkinson in his second expedition in 1842 describes the nature of the floodplains around the coast as “dense brush, in which pines, palms and various kinds of myrtle trees bound together by a sort of climbing cane” occurred. He also describes broad-bladed grass plains with high reeds along with alluvial plains that contained cedar, rosewood, fig trees, nettle trees, and plum wood (Hodgkinson, 1844, p.57).

Hodgkinson (1844) describes the non-tidally influenced forests or ’brush’ to be finer than that found on the coastal plain. Other than brief descriptions of the dimensions of the tidal channel (‘280 feet wide’), and the presence of in-channel vegetation in a non-tidal tributary, Hodgkinson makes little mention of the character of the lower Bellinger River. Shortly after Hodgkinson’s second expedition a successful attempt to cross the bar at the river mouth was made by William Wright in 1842. This time interval saw the arrival of the first domesticated animals in the valley, along with the primary industry of cedar getting (Braithwaite and Beard, 1978). By 1843 there were 20 pairs of pit sawyers on the Bellinger River with the areas around the coast targeted first. The initial white settlement was between Raleigh and the coast, with the township of Bellingen originally known as Boat Harbour. Like many coastal catchments of NSW, the search for red cedar induced a rapid expansion into previously unsettled areas. Between 1843 and 1849 cedar getting and ‘squatter settlement’ was occurring throughout the lower valley, with logs rough dressed, chopped and floated individually down the river (Braithwaite and Beard, 1978).

The lower valley experienced more formal settlement with the first ship built on the lower reaches by 1849, while cedar getting moved further upstream by the end of the 1850s. Once cedar supplies became exhausted other rainforest species were progressively logged, with hoop pine (*Araucaria cunninghamii*), found in the plateau regions, being the most sought after (Lonie, 2000). The lower Bellinger River, downstream of Boat Harbour (now Bellingen), was used to transport timber with punts, shunting logs and goods from Boat Harbour to the coast, where they were shipped to Sydney. The development of sawmills both in Bellingen in the tablelands region from 1890 onwards resulted in forestry becoming a major industry in the valley.

In 1861 the NSW government passed legislation (The Crown Lands Act) which allowed settlers to take up to 320 acres of crown land, conditional upon the owner living on the land for three years and demonstrating that the land was cleared (Stevenson, 2001). This
legislation allowed for the controlling of the ‘squatters’ while also determining the character of agricultural development in the mid-late 19th century. This time interval within the Bellinger valley saw the development of schools, police stations and post offices, with the name of Boat Harbour changing to Bellingen in 1889 (Braithwaite and Beard, 1978). The mid-late 19th century also saw a succession of floods between 1864 and 1894. Braithwaite and Beard (1978) identified that the lower river was ‘shoaling’ up in the latter part of the 19th century. Soros-Longworth & McKenzie (1980) suggest that the shoaling of the river mouth at the start of the 20th century may have been caused by channel erosion in the preceding time interval. The exact nature of sedimentation in the lower reaches remains ambiguous with uncertainty as to where the estuary was shoaling and whether it was marine or fluvially derived sediment.

By the time J.H. Maiden journeyed through the valley in 1894 he noted that many of the alluvial flats had been cultivated for maize and that cedar getting was nearing an end (Maiden, 1894). Images from the early 20th century highlight the shift from sub-tropical rainforest in the 1840s with complete floodplain clearance by 1902. Plates 1 highlights the nature of the denuded banks at a watering point at Bellingen township indicating some locations had essentially little to no riparian vegetation at the turn of the 19th century (also Plate 2). The below-average rainfall in the early part of the 20th century resulted in drought conditions that saw a shift from maize to dairy and beef production, placing increased numbers of stock on the valley floor.

The onset of dredging to maintain navigation in the lower valley, the decrease in riparian and floodplain vegetation, along with the historical accounts of downstream aggradation suggest that the Bellinger River underwent a shift in the nature of sediment supply in the first 50–60 years of settlement. Swain (1912), a District Forester for the NSW Department of Forestry, noted that by 1905 53,000 acres of land had been taken up for farming, doubling by 1910 to 113,000 acres. This represents approximately 40% of the total catchment area and of this area Swain (1912) claims that half was cleared and the remainder on the ‘verge of denudation’. The reduction in vegetation on a catchment scale had profound impacts upon the freshwater reaches of both the Bellinger and Kalang Rivers (Cohen, 2003) and undoubtedly impacted on the current physical condition of the estuary. However, the extent of impact can only be hypothesised without extensive research which to date has not commenced.

Since the mid 20th century land use practices have shifted, with a reduction in rainforest logging, the declaration of National Parks, the decrease in dairy farming associated with major industrial de-regulation, a series of large floods in the 1950s, and a continuance of beef cattle. The reduction of the intensive dairy farming on the valley floor, along with an increase in hobby farming, agro-forestry and increased shared rural residential blocks (multiple occupancy) has resulted in a major shift in land-use patterns for the fluvial environment. Commercial shipping is no longer a feature of the estuary an instead has been replaced by recreational boating. A major challenge now in estuary management is how to provide safe boating while also maintaining river and estuary health. (HRC, 2003).

Dredging in the lower estuary commenced early in the 20th century and ceased around 1929 (PWD, 1983) with estimates of 150,000 m³yr⁻¹ dredged from the entrance and confluence of the estuary. Current dredging is restricted to the Raleigh Shoal, with an amount of 905,000 m³ able to be extracted from an 1100m stretch of estuary. Dredging is no longer undertaken as an
aid to navigation but rather as a source of construction materials for the rapidly growing Coffs Harbour region.

*Plate 1.*

*Plate 2.*

**Plates 1 & 2** Historical photos of the lower Bellinger River: 1) upstream view of the lower Bellinger River from Marx Hill in 1902, 2) downstream view of the lower Bellinger River from Fernmount, 1902. Note the limited riparian vegetation in both instances. (Source: Bellinger Valley Historical Society)
3.0 Climate and Hydrology of the lower Bellinger/Kalang Rivers

3.1 Temporal trends in rainfall patterns

Figure 4a presents a regional assessment of total monthly rainfall on the mid-north coast of New South Wales whilst Figure 4b shows the equivalent analysis for Bellingen Post Office. Residual mass curves (termed cusum curves from here on in) plot the cumulative departure from a given reference point, such as arithmetic mean and have been used previously to assess both rainfall (Kraus, 1956; Pittock, 1975, Riley, 1988) and streamflow (Smith, 1995). This technique is often used to assess directional trends away from the given reference point in time series data and to detect break-points within such series (Kraus, 1956). Rising limbs of a cusum curve indicate a time intervals where values are consistently above average, falling limbs indicate time intervals where values are below average, and horizontal limbs are where values are close to average.

As can be seen from this figure, the patterns in the long-term deviation for the mid-north coast are remarkably consistent between gauges suggesting a broad regional scale control on the patterns exhibited. The longest gauges (Casino and Port Macquarie) display rising limbs between 1885/87 and 1895/1900 highlighting an above-average rainfall pattern. In all of the gauges, bar Macksville, it appears that this above-average pattern was followed by a brief period of average rainfall conditions between 1895 and 1900, before exhibiting a clear below-average pattern for the early part of the 20th century. All gauges in Figure 4 exhibit falling limbs between 1900 and 1946/47. As noted by Pittock (1975) the rainfall patterns exhibited in Figure 3 all show a mid-late 1940s breakpoint, with the turning point occurring over a 12-month period. While the 1900 – 1946/47 period was characterised by below-average rainfall there is a 10 – 15 year period of average conditions between the early 1920s and mid 1930s. The second half of the 20th century shows a progressive rising limb, interspersed with short fluctuations lasting 2 – 5 years, with peaks (i.e. points of change) in 1964, 1977 and 1990. Since 1990, rainfall gauges show either an average or slight below-average condition.

The cusum curve for total monthly rainfall at Bellingen (Figure 4b) from 1899 until 2002 (station discontinued) demonstrates similar temporal trends to the regional analysis. The below-average trend for the first half of the 20th century is demarcated with a falling limb until 1920, where there is an average period of rainfall through to the late 1930s. The onset of this average rainfall period, also identified in the neighbouring Nambucca catchment (Lyall & Macoun, 1999), corresponds to the wettest year on record in 1921. The breakpoint in the 1940s is consistent with regional trends, occurring in October 1947. The post-1947 rainfall pattern in Bellingen, like other regional rainfall gauges on the mid-north coast, is characterised by quasi-periodic fluctuations within a broader above-average trend that extends until 1990. The post-1947 time interval is a period that contains nine out of the ten largest total annual rainfalls in the entire record. The percentage change in mean annual rainfall at Bellingen P.O. between the first and second half of the 20th century is in accordance with regional changes presented by Franklin (1999) with post-1947 increases of between 14 and 19%. Of these changes, Franklin (1999) identified that summer and autumn months experienced the greatest change of 23 and 16%, respectively, with winter and spring changing by 3 and 4%, respectively.
Figure 4  Total monthly rainfall analysis. a) Regional cusum curves for the mid-north coast of NSW; b) Cusum curve for Bellingen Post Office (stn 59001), 1899 – 2002 (station closed).
3.2 Temporal trends in streamflow

Flood frequency analysis for the Bellinger catchment draws on historical flood peak data, along with flood discharge records that have been recorded from approximately 1955 onwards. It draws on cusum curves for daily discharge, annual and partial series analyses for the longest gauges in the catchment whilst also synthesizing existing flood studies (Public Works Department, 1980; Public Works Department, 1991; Paterson Consultants, 2005).

3.2.1 Historical flood stage-heights in Bellingen: 1870-2009

The long-term historical flood data available for the catchment is essentially limited to stage-height records at Bellingen Bridge. This location has undergone changes in channel capacity, slope and sediment supply, yet provides the only location where flood height has been consistently recorded. While there are limitations to using stage-height data, it is essentially the only means to assess patterns of change in magnitude-frequency relationships between time intervals. The Public Works Department (PWD) (1980) in a comprehensive compilation of written and anecdotal records assessed the flood record at Bellingen Bridge. It has also been re-assessed recently by Paterson Consultants (2005) updating the PWD (1980) study including the 2001 flood data.

The gauge location at Bellingen has been the point of observation for flood levels since settlement (1842), although levels have only been referred back to a fixed point since 1912 when the first bridge was built (PWD, 1980). Bridge location has changed three times since 1912 within 100 m of the original location, with flood levels more consistently recorded after the current bridge was built in 1953. Hence, all flood levels prior to 1912 have been taken from landmarks near the bridge based on anecdotal evidence collated by PWD (1980). Figure 5 presents an annual and partial time series of floods > 6 m. The presence of seven floods over this threshold prior to 1900 and nine floods over the threshold between 1947 – 1977, in contrast to only four between 1900 and 1947 led Warner (1987, 1992, 1993) to suggest that these time intervals corresponded to periods of above and below-average discharge regimes (flood and drought-dominated regimes - FDRs and DDRs). It has been further suggested that the $Q_{2.33} - Q_{20}$ essentially doubled between 1901 – 1945 and 1946 – 1979 (Warner, 1992).

What is clearly apparent from Figure 5b, which shows a partial series of events >6 m in stage, is the period of high flood activity from 1948 – 1977 with 28 events greater than 6 m, including the third largest flood on record in 1950. In contrast, the same length of record between 1978 and 2009 has yielded 16 flood events > 6 m in stage. The partial series of flood stage-heights, shown in Figure 4b, highlights the clustering of floods not just in the 1948 – 1977 time interval, but in the previous time interval around 1920 – 1921, 1937 – 1939 and in the following time interval around 1988 – 1990. The first half of 2009 produced three floods in February, March and May of 7.81, 8.58 and 8.38 m (AHD) respectively. This corresponds to between the 20 and 10% annual exceedance probability (AEP) – Table 1.
**Table 1**  
*Adopted Flood Frequency, Bellinger River at Bellingen (log normal distribution)*

<table>
<thead>
<tr>
<th>Frequency (% AEP)</th>
<th>Return Period (years ARI)</th>
<th>Peak Flow (cu. m/sec)</th>
<th>Peak Level (m AHD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>4,510</td>
<td>11.13</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>3,466</td>
<td>10.33</td>
</tr>
<tr>
<td>5</td>
<td>20</td>
<td>2,335</td>
<td>9.38</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>1,644</td>
<td>8.65</td>
</tr>
<tr>
<td>20</td>
<td>5</td>
<td>1,074</td>
<td>7.57</td>
</tr>
</tbody>
</table>

Source: Paterson Consultants (2005)

**Figure 5**  
*Historical flood heights on the Bellinger River at Bellingen Bridge (modified from PWD, 1980 with supplemented stage height data from Paterson Consultants, 2005 and 2009 flood data. a) Annual stage heights > 8 m; b) Partial series for stage heights > 6 m.*
3.2.2 Identifying flood and drought dominated periods in the Bellinger/Kalang

Two gauges within the Bellinger basin (Basin No. 205) have been used to construct cusum curves of mean daily discharge. The Bellinger River (205002) at Thora and the Nambucca River at Bowraville (205006) have the longest records available, with the former providing a location within the Bellinger catchment to assess any changes in magnitude-frequency distribution pre- and post-1977/79. Figure 6 presents the cusum curves for daily discharge on the Bellinger River at Thora. Both gauges exhibit similar patterns throughout the record length matching the regional discharge cusum curves. Oscillating above-average trends are shown from the start of the record with a steep rising limb from 1971 until the breakpoint of 1977. This is followed by a below-average trend from 1977 until present with peaks in 1990 (matching the daily rainfall peak) and again in 2001 and 2009.

![Cusum curve for daily discharge at Thora](image)

**Figure 6** Mass residual curve for mean daily discharge at Thora (2005002) from 1955 – 2009. Direction of curve indicates daily river discharge that is becoming either further above or further below the long-term average. Missing data indicated by horizontal line.

In order to assess differences between the inferred discharge regimes an annual and partial series analysis was carried out for the two gauges that contain data from 1956 onwards. Missing years on the Bellinger River were filled via a least squares regression with the Kalang River (205004 - $R^2 = 0.75$) and the Nambucca River at Bowraville (205006 – $R^2 = 0.71$). The correlation between neighbouring gauges provides a crude estimate of peak instantaneous discharge in missing years and yields a more complete time series in which to make comparisons between pre- and post-1977. A comparison was made between 1956 – 1977 and 1978 – 2001 and is summarised in Table 2. A two parameter log-normal distribution provided a more appropriate fit to the short annual maximum series, while a log Pearson Type III distribution was fitted to the partial series.
Table 2 highlights that there has been an estimated reduction of predicted discharge between the two time intervals on the annual series of 11 – 26% on the Bellinger River and 35 – 48% on the Nambucca River. The partial series on the Bellinger River shows a reduction of 54 – 25% post-1977 for the 2 and 5-year return period and increases of 4 – 40% for the 10 and 20-year return period, while the Nambucca River shows a reduction of 40 – 19% in estimated discharge for the four return intervals. The tabulated results concur reasonably well with the expected magnitude of changes between flood and drought regimes as presented in estimates by Warner (1992).

### Synoptic drivers for temporal variations in rainfall and stream flow in the Bellinger/Kalang

Rainfall and streamflow in the Bellinger catchment exhibit similar temporal variability to the regional trends with a 1947 breakpoint and a 14 – 19% increase in mean annual rainfall totals (1948-1977) as a function of equivalent increases in summer and autumn rainfall. Furthermore, the number of rain events in the Bellinger catchment >200 mm/48hours increased by 150 – 175% over the period 1948-1977. These changes have coincided with negative mean sea level pressure (MSLP) anomalies over eastern Australia (Speer, 2008) and sustained strong easterly zonal transport of Pacific maritime air onshore with resulting widespread high rainfall (Rakich et al., 2008). A change from negative to positive circulation anomalies over New South Wales since 1977/78 resulted in a decrease in east coastal low-pressure systems (east-coast lows) and accompanying rain (Figure 7). Negative pressure anomalies over eastern Australia, anomalous onshore low-level winds and larger NSW rainfall totals between 1947 and 1977, occur in the cool phase of the inter-decadal Pacific oscillation (IPO) index. Hence, it would appear that the shifts in rainfall and streamflow in 1945/48 and 1977 are intrinsically linked to broad-scale ocean-atmospheric interactions, with the indices such as the IPO providing a reasonably good measure of association between SST and periods of flood activity seen on the mid-north coast of NSW. The IPO has been shown to
modulate ENSO’s influence on Australia, with significant correlations when the IPO is negative (i.e. reduced tropical Pacific SST), but with poorer correlations when the IPO is positive (Power et al., 1999). This has been further substantiated by Verdon et al., (2004) who have shown that when the IPO is negative the frequency at which La Niña (wet conditions) occurs is significantly higher. Thus, it appears that ENSO extremes are dependent on the multi-decadal climatic state, with La Niña events being enhanced (i.e. wetter) when the IPO is negative and less severe when the IPO is positive.

**Figure 7**  Frequency of east-coast lows since 1950 (modified after Speer, 2008)
4.0 Geomorphic process zones of the Bellinger/Kalang River estuaries

The Bellinger/Kalang estuary can be classified as a wave-dominated filled (delta) system — equivalent to the mature barrier-dominated estuary of Roy et al., (1980). The system is river dominated by infilled mud basins west of Urunga and around Raleigh and Repton with only small areas of mangroves and intertidal flats (Table 3). The occurrence of palaeochannels on the coastal plain between the Pacific Highway and Mylestrom suggests that Bellinger and Kalang have migrated across the coastal plain, presumably in the last 2000 years since the current sea level was attained.

The distribution of marine and fluvial sediment has been previously assessed by the NSW Public Works Department in 1983. This work demonstrated the presence of well-sorted marine sediment extending from the mouth to just upstream of the v-wall on the Bellinger and to the entrance of Back Creek on the Kalang. Mixed marine-fluvial sediments extend to just upstream of the Back Creek entrance on the Bellinger River and to east of Newry Island on the Kalang River. Upstream of these points sediment within the Bellinger/Kalang Rivers were found to be dominated by moderately sorted sub-angular fluvially derived sediment.

Table 3 Morphological and tidal attributes of the Bellinger/Kalang Estuary (www.ozcoasts.org).

<table>
<thead>
<tr>
<th>Feature</th>
<th>Area (km²)</th>
<th>Feature</th>
<th>Area (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrier backbarrier</td>
<td>2.19</td>
<td>Tidal sand banks</td>
<td>0.41</td>
</tr>
<tr>
<td>Central basin</td>
<td>0</td>
<td>Rocky reef</td>
<td>0</td>
</tr>
<tr>
<td>Fluvial bayhead delta</td>
<td>0</td>
<td>Coral</td>
<td>0</td>
</tr>
<tr>
<td>Flood/ebb delta</td>
<td>0.51</td>
<td>Channel</td>
<td>4.48</td>
</tr>
<tr>
<td>Intertidal flats</td>
<td>0.99</td>
<td>Bedrock</td>
<td>0</td>
</tr>
<tr>
<td>Mangrove</td>
<td>1.05</td>
<td>Floodplain</td>
<td>2.25</td>
</tr>
<tr>
<td>Saltmarsh/saltflat</td>
<td>0.11</td>
<td>Bedrock perimeter</td>
<td>1.21</td>
</tr>
<tr>
<td>Water area</td>
<td>6.62</td>
<td>Entrance width</td>
<td>0.33</td>
</tr>
<tr>
<td>Perimeter</td>
<td>72.86</td>
<td>Entrance length</td>
<td>0</td>
</tr>
<tr>
<td>Maximum length</td>
<td>16.08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum width</td>
<td>0.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean wave height (m)</td>
<td>1.37</td>
<td>Mean wave period (sec)</td>
<td>7.14</td>
</tr>
<tr>
<td>Max wave height (m)</td>
<td>6.7</td>
<td>Max wave period (sec)</td>
<td>14.0</td>
</tr>
<tr>
<td>Tidal range (m)</td>
<td>1.2 – 1.8</td>
<td>Tidal period (sec)</td>
<td>Semi-diurnal</td>
</tr>
</tbody>
</table>

This report uses the current bathymetric data and current satellite imagery along with the 1984/85 cross-sectional survey data of the Bellinger/Kalang estuaries to determine the distribution of geomorphic process zones. Two fluvial dominated zones, a fluvial transition zone and a marine tidal delta process zone have been identified on each of the Bellinger and Kalang systems (Figure 8).
4.1 Fluvial Dominated Process Zone

Figures 9 and 10 present the longitudinal profiles of maximum depth (thalweg) for the Bellinger and Kalang Rivers. The distribution of sedimentation within the Bellinger/Kalang estuaries, along with bank morphology data allow for the identification of two fluvially-dominated reaches within both the Bellinger and Kalang Rivers, described briefly below.
Figure 9  Bellinger longitudinal thalweg profile from Bellingen to Urunga derived from 2008 bathymetric data.

Figure 10  Kalang longitudinal thalweg profile from Brierfield to Urunga derived from 2008 bathymetric data. Orange line indicates the north branch of the Kalang River at Newry Island.
Bellinger – Fluvial-Dominated A: Bellingen to Fernmount
The most-upstream fluvially dominated reach extends from the tidal limit at Bellingen to Fernmount. This reach is characterised by a channel with a mixed sediment load (bedload and suspended load), gravel bar formation and variable floodplain topography with the last gravel deposit occurring immediately downstream of Fernmount bluff. Maximum depth (inclusive of floodplain height) is 8 – 10 m, with the floodplains 4 – 7 m above mean tide level. Generally, depth of bed scour is < 8 m. In this reach there is a distinct macro-channel with a low (younger) floodplain inset within a higher older alluvial surface with valley floor widths up to 1 km. Collectively, the channel and low floodplain form the meander belt and zone of active overbank flow (300 – 500 m in width). This is a high-energy reach with the highest overbank velocities of all the tidal reaches.

Bellinger – Fluvial-Dominated B: Fernmount to McGeary’s Island
The reach from Fernmount is characterised by a significant reduction in grain size from gravel to sand, a maximum depth of 7 – 12 m but with lower floodplains (2.5 – 4 m above mean tide level). There less pronounced macro-channel and meander belt development with less floodplain topographic variability. Valley floor width increases to 1 km. Bar amplitude and occurrence is diminished with a subsequent increase in maximum bed scour (up to 10 m). Reduced channel dimensions and a reduction in stream gradient result in an increased proportion of discharge conveyed by lower velocity overbank flow.

Kalang – Fluvial-Dominated A: Brierfield Bridge to Pine Creek
The most upstream fluvially-dominated reach on the Kalang River extends from the tidal limit at Brierfield Bridge almost to the confluence of Pine Creek. Like the upstream fluvially-dominated reach on the lower Bellinger River, this reach exhibits variable floodplain topography with a maximum depth of 7 – 12 m and floodplains that are ~4 m above mean tide level. The variable topography is a function of a confined valley floor (< 0.5 km) producing high-energy overbank flow and discontinuous floodplain formation. Pronounced bed scour is apparent in the downstream end of this reach associated with the dominant role of bedrock and valley confinement

Kalang – Fluvial-Dominated B: Pine Creek to Newry Island West
This short reach of the Kalang River reflects a change in valley bedrock morphology with a straight 3 – 4 km length of channel in an area of reduced valley floor width. The confined nature of the valley floor (< 0.5 km) produces high energy stream processes with confined overbank flow. Maximum depth is 7 - 8 m with floodplains 2 - 3 m above mean tide level. This reach extends to the western margin of Newry Island.

4.2 Fluvial Transition Process Zone
The fluvial transition process zone reflects a reach of both the Bellinger and Kalang rivers, which exhibit a pronounced marine influence whilst still exhibiting a fluvial form. On the lower Bellinger River it extends from McGeary’s Island to Tuckers Island with a maximum depth of 7 – 10 m but with a considerable reduction in the elevation of the floodplains above mean tide level (1.5 – 2.0 m). Floodplain topography is reduced in this reach, a characteristic of the infilled mud basin. Bed material in this zone is still dominated by fluvially-derived sediment. The reduction in bank height results in an increased frequency of overbank flow.
On the Kalang River the north and south branches of Newry Island represent the fluvial transition zone. A large increase in valley width relative to the upstream reaches (1 – 1.5 km) results in a low relief floodplain with an anabranching channel form. The dominance of low stream gradients, a suspended load dominated channel with smaller and simpler channel geometry than upstream reaches results in an increased proportion of low-velocity overbank flow. This transitional zone is inferred to be occurring in the infilled mud basin with localised late Pleistocene terrace remnant sediment controlling channel planform position and the current rates of bend migration. Floodplains are 1 - 2 m above mean tide level with a maximum depth of 8 - 11 m. The channel along the south branch has more extensive scour than the north branch, with bed scour and bend migration being the dominant form of energy dissipation with a reduction in frequency and magnitude of bar formation.

4.3 Marine-Tidal Process Zone

The marine-tidal process zone reflects the component of the estuary dominated by marine processes (e.g flood and ebb-tide sediment transport). It extends from the east of Newry Island and from immediately upstream of the Back Creek confluence on the lower Bellinger River to the mouth at Urunga. PWD (1983) estimate that there is a 40,000 m$^3$yr$^{-1}$ net influx of marine sand (based on 1981 data) that is transported landward with the flood tide producing distinct shoals that occur to the Back Creek confluence and to immediately upstream of the Pacific Highway Bridge on the Kalang River. Maximum depth is 3 – 4 m but floodplain/mangrove plain height is only 1 – 1.5 m above mean tide level. The low floodplain height and low stream gradients results in tidal inundation of the salt marsh and mangrove flats. In locations such as the lower Bellinger, sediment supply is a function of flood tide transport and the direct supply from the adjacent coastal barrier. Whilst fluvial processes have been shown to be important for flushing the shoals during large flood events (PWD, 1983) the low frequency wave conditions at the mouth of the Bellinger have been shown to re-establish shoal formation soon after.
5.0 Historical channel changes of the Bellinger/Kalang River estuaries

Cohen (2003) demonstrated a 7% reduction in channel length between Thora and Bellingen township since settlement with 9 channel planform adjustments reducing channel length by 1.2 km. Despite the more alluvial setting of the lower Bellinger and lower Kalang Rivers exhibit little evidence of channel shortening/straightening since settlement. The only location that shows a reduction in channel length is on the Bellinger River immediately upstream of Fernmount (Figure 11).

Figure 11  Historical planform changes on the lower Bellinger River at Fernmount. 1909 Parish Map georeferenced to ortho-satellite image. Current channel position denoted by red line.

5.1 Comparison of current and historical bathymetry

Comparison of the current bathymetric longitudinal profile and the 1984/1985 bathymetric profile (Figure 12) demonstrates the stability of macro-bedforms along the lower reaches of the tidal Bellinger River. Deep scour holes and major shoal crests have been in the same position for 25 years suggesting that the overall bed morphology is controlled by channel planform and resistant material at the channel margin (i.e. bedrock or old alluvium). The only major changes in bed elevation are around Raleigh Shoal and McGearry’s Island with the former showing 1 – 1.5 m of net bed lowering and with the latter showing the equivalent aggradation. Given that the Raleigh Shoal is actively dredged it is highly likely that the changes in bed elevation are a function of extractive operations.
Figure 12  Comparison between current bathymetric longitudinal profile and 1984/1985 bathymetric profile on the lower Bellinger River. In each case, maximum channel depth (thalweg) has been used.

Equivalent comparisons on the Kalang River are also shown in Figures 13a and 13b. Differing cross-section resolution in the fluvial reaches of the Kalang make it difficult to draw firm conclusions about long-term changes in sedimentation patterns. The results for the fluvial transition reach (i.e. Newry Island North and South Branch) however highlight a more consistent pattern of bed aggradation (1 - 2 m) in the lower areas of both the north and south arms of the Kalang River around Newry Island.
Figure 13  a) Comparison between current bathymetric longitudinal profile and 1984/1985 bathymetric profile on the Kalang River. a) Kalang River with Newry Island, South Branch shown, b) Kalang River, North Branch of Newry Island. In each case, maximum channel depth (thalweg) has been used.
5.2 Photogrammetry analysis of 20th century channel migration

5.2.1 Photogrammetry methodology

Eight bends were selected for analysis on the Bellinger River between Bellingen and McGeary’s Island and four on the Kalang River (Figure 14). The selection of these sites was based on previously identified ‘actively’ eroding locations by Cameron McNamara (1985) and Warner and Paterson (1987). Six of the eight bends on the Bellinger River occur in the steeper fluvially-dominated process zone – Reach A, with the remaining two occurring in Reach B.

Figure 14 Location of focus reaches and river bends selected for photogrammetry analyses.

Four time intervals (Table 4) were chosen to assess changes in channel position/bend migration. These were 1942/43, 1964/67, 1982 and 2002/03. In the assessment of channel positions high and low bank position and water’s edge were identified in each time series and converted to ESRI shapefiles with a GDA/MGA 94 datum and projection. Tangents
perpendicular to high-bank polylines were created for each time series at regular intervals around each bend to measure distance eroded. Confirmation of the nature of bank erosion (i.e. erosion of a high outside bank) was provided by topographic cross-sections extracted for each time series.

Table 4  Dates of aerial photographs used in photogrammetry and hydrological interval represented

<table>
<thead>
<tr>
<th>Date of photo</th>
<th>Photo scale</th>
<th>Q at Thora on date of photo acquisition</th>
<th>Hydrological interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>07/11/1942</td>
<td>1:19,000</td>
<td>unknown</td>
<td>tail end of DDR</td>
</tr>
<tr>
<td>06/1943</td>
<td>1:19,000</td>
<td>unknown</td>
<td>tail end of DDR</td>
</tr>
<tr>
<td>08/1964</td>
<td>1:47,000</td>
<td>unknown</td>
<td>mid FDR</td>
</tr>
<tr>
<td>11/07/1967</td>
<td>1:47,000</td>
<td>1566 Ml/day</td>
<td>mid FDR</td>
</tr>
<tr>
<td>24/06/1982</td>
<td>1:16,000</td>
<td>112 Ml/day</td>
<td>Beginning of DDR</td>
</tr>
<tr>
<td>07/09/2002</td>
<td>1:25,000</td>
<td>44 Ml/day</td>
<td>DDR</td>
</tr>
<tr>
<td>03/09/2003</td>
<td>1:25,000</td>
<td>43 Ml/day</td>
<td>DDR</td>
</tr>
</tbody>
</table>

Q = Mean daily discharge. For total record at Thora (stn 205002) mean Q = 803 Ml/day

Positional changes documented between 1942/43 and 1982 essentially reflect changes in the time interval characterised by an increased flood frequency (flood-dominated period) whilst the changes documented between 1982 and 2002 reflect changes in the period of reduced flood frequency (drought-dominated period). In addition, post 2009 flood bank positions were collected with differential GPS to assess the relative effectiveness of the 2009 floods in initiating further bank erosion/channel migration.

The photogrammetry topographic cross-sections in each of the four time series provide a measure of channel capacity (channel cross-sectional area) in two drought-dominated time intervals (1942 and present) and the flood-dominated time interval of 1948-1977. Such cross-sections do not capture sub water surface topography and as such all derived cross-sections have been truncated at 0 m AHD and reflect gross changes in channel form above water level (locations and extent of aggradation).

5.2.2  Bend migration and bank erosion

Table 5 and Figures 12 and 13 summarise bend migration rates for the eight bends on the Bellinger River and the four bends on the Kalang River. What is apparent from the data is that mean bend migration and bank erosion is greatest in the Bellinger fluvial reach A with mean migration rates of 0.3 – 1.3 m/yr in contrast to bends 7 and 8 (Bellinger fluvial Reach B) where erosion rates have been lower with mean migration rates of 0.3 – 0.6 m/yr. What is also apparent is that bank erosion and bend migration is consistently lower on the Kalang River than the Bellinger River with rates < 0.4 m/yr. These values of bank erosion in the lower segments of the estuary are consistent with previously reported erosion rates of 0.75m/yr on both banks at Tuckers Island and 0.4 m/yr between Raleigh Road and Repton railway bridge (PWD,1983).
Table 5  
Bend migration rates (bank erosion rates) for the Bellinger and Kalang Rivers based on photogrammetry analysis

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean m/yr</td>
<td>Max m/yr</td>
<td>Mean m/yr</td>
<td>Max m/yr</td>
</tr>
<tr>
<td>B1</td>
<td>0.6 ± 0.2</td>
<td>0.7</td>
<td>0.8 ± 0.2</td>
<td>2.4</td>
</tr>
<tr>
<td>B2</td>
<td>0.4 ± 0.2</td>
<td>0.8</td>
<td>0.6 ± 0.2</td>
<td>1.4</td>
</tr>
<tr>
<td>B3</td>
<td>0.4 ± 0.1</td>
<td>0.7</td>
<td>0.8 ± 0.2</td>
<td>1.7</td>
</tr>
<tr>
<td>B4</td>
<td>0.7 ± 0.2</td>
<td>1.1</td>
<td>0.4 ± 0.1</td>
<td>0.6</td>
</tr>
<tr>
<td>B5</td>
<td>0.9 ± 0.2</td>
<td>1.5</td>
<td>0.8 ± 0.2</td>
<td>1.8</td>
</tr>
<tr>
<td>B6</td>
<td>1.4 ± 0.2</td>
<td>1.9</td>
<td>0.7 ± 0.2</td>
<td>1.5</td>
</tr>
<tr>
<td>B7</td>
<td>0.5 ± 0.1</td>
<td>0.9</td>
<td>0.3 ± 0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>B8</td>
<td>0.4 ± 0.1</td>
<td>1.0</td>
<td>0.3 ± 0.1</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Bellinger River

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean m/yr</td>
<td>Max m/yr</td>
<td>Mean m/yr</td>
<td>Max m/yr</td>
</tr>
<tr>
<td>K1</td>
<td>0.2 ± 0.1</td>
<td>0.3</td>
<td>0.4 ± 0.2</td>
<td>0.6</td>
</tr>
<tr>
<td>K2</td>
<td>0.3 ± 0.1</td>
<td>0.4</td>
<td>0.5 ± 0.2</td>
<td>0.8</td>
</tr>
<tr>
<td>K3</td>
<td>0.2 ± 0.1</td>
<td>0.8</td>
<td>0.2 ± 0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>K4</td>
<td>0.2 ± 0.1</td>
<td>0.8</td>
<td>0.3 ± 0.1</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Kalang River

Figures 15 and 16 demonstrate the variability in erosion rates between bends both within and between time intervals suggesting that the prevalent discharge regime in a given time interval itself is not the sole determinant on bank erosion rates. On the Bellinger River 50% of the bends eroded at a faster rate in the flood-dominated time interval between 1948 and 1977 with two of the other bends (Bends 1 and 2) eroding at much faster rates since 1982 and the other two eroding at rates that are within errors between the two time intervals. On the Kalang River three out of the four bends eroded at a faster rate during the flood-dominated time interval but all three are within the error measurements of each other. The following section outlines the nature of changes in channel capacity and bank position for the two fluvial reaches on the Bellinger River and the upstream fluvial reach and the fluvial transition reach on the Kalang River.
5.2.3 **Historical channel changes on the Bellinger River**  

**Bellinger – Fluvial-Dominated A: Bellingen to Fernmount**

Bend 1 has experienced a maximum erosion rate of 100 – 120 m in a southward direction since 1942 but with the greatest proportion occurring since 1982 (Figure 17). Despite the bulk of the erosion having occurred since 1982 this bend, which is immediately downstream of Bellingen bridge, had been progressively shifting south, eroding low alluvial surfaces since...
1942 (Figure 18). The last phase of active erosion at this bend was during the 2001 floods which saw widespread floodplain stripping, removing 10s of metres of alluvium.

Figure 17 Photogrammetrically derived high bank locations in the vicinity of Bends 1 to 4 downstream of Bellingen over the period 1943 - 2002. The surveyed location of the post 2009 floods high bank is also shown as are the locations of derived cross-sections used to determine changes in channel capacity over the period.
Figure 18 Photogrammetry derived cross-sections for fluvial dominated reach A on the Bellinger River. Cross-section 4 and 5 highlight the net increase in channel capacity at Bend 1 whilst cross-section 9 highlights net aggradation and channel migration at Bend 2. The photo at top-right shows floodplain erosion following the 2001 floods at cross-sections 4 and 5. Downstream view for cross-sections and photo.

Bend migration and the active erosion of the concave bank should be coupled with bar/bank and low floodplain aggradation if there is to be mass balance in a given bend or in a given reach. The cross-sections in Bend 1 show an average net increase in channel capacity (cross-sectional area) since 1942 of 38% (up to 124%) whilst mean channel capacity at Bend 2 has decreased (i.e. aggraded) by only 14% (Table 6). This suggests that whilst both Bends 1 and 2 have actively migrated since 1942 (30 – 40 m for Bend 2) that channel capacity has experienced a net increase, but with some aggradation on the inside of Bend 2.

Bends 3 and 4 in the upstream fluvially-dominated reach of the Bellinger river show less severe erosion rates since 1942 (up to 20 m and 35 m respectively). Bend 4 is laterally constrained by bedrock on its northern margin restricting northward migration with the small area of historical bank erosion occurring on the upstream limb of the bend since 1982. It is in this section of the bend where channel capacity has experienced a net increase in contrast to cross-sections 19 – 22 that display reductions in cross-sectional area of up to 15%. This has been through the construction of a prominent depositional bench on the true left-bank (Figure 19). This depositional bench is an area that experienced active erosion in the 2009 floods (discussed in Section 7.3). Bend 3 has experienced a net reduction in channel capacity since 1942 of ~14% (Table 6) whilst Bend 4 has effectively remained of the same dimensions.
Bends 5 has been eroding at 0.7 – 0.9 m yr\(^{-1}\) (Table 5, Figures 15 & 20) with a maximum erosion of 65 m (equating to a maximum erosion rate of 1.8 m yr\(^{-1}\)). Bend 5 and 6 have both experienced the greatest rates of erosion in the flood-dominated time interval between 1942 and 1982. The cross-sectional data highlights that some sediment has been accumulating on the inside of Bend 5, on the low floodplain and channel margin, with a slight in channel size since 1982. However, net mean channel capacity at this bend has increased since 1942 by 17% (Table 6).

Bend 6 is constrained by bedrock on the outer margin (Fernmount bluff) but the channel margin immediately upstream of this has progressively migrated in an E-NE direction by up to 50 m (equating to a maximum erosion rate of 1.9 m yr\(^{-1}\)). Both these bends (5 and 6) experienced significant erosion (up to 20 m in the 2009 floods; Figure 21, discussed in Section 7.3). Some cross-sections such as XS35 and XS36 have experienced a net increase in channel capacity but as function of levee aggradation with an overall 75% increase in channel capacity since 1942 (Table 6).
**Figure 20** Photogrammetrically derived high bank locations in the vicinity of Bend 5 and Bend 6 at Fernmount over the period 1943 - 2002. The surveyed location of the post 2009 floods high bank is also shown as are the locations of derived cross-sections used to determine changes in channel capacity over the period.

**Figure 21** Bank erosion/channel migration of Bend 6, upstream of Fernmount bluff. Dashed line in cross-section and photo show up to 15 m of bank erosion.
Bellinger-Kalang Estuary Erosion Study

Table 6  Mean bankfull cross-sectional area and percentage change for Bends 1 – 8 on the lower Bellinger derived from the normalised photogrammetry cross-sections. Red denotes a net increase in channel capacity whilst yellow denotes a net decrease in channel capacity.

<table>
<thead>
<tr>
<th>Bend (average)</th>
<th>1942 XSA (m²)</th>
<th>1962 XSA (m²)</th>
<th>1982 XSA (m²)</th>
<th>2002 XSA (m²)</th>
<th>1942-1964 % change</th>
<th>1964-1982 % change</th>
<th>1982-2002 % change</th>
<th>1942-2002 % change</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>645.0</td>
<td>607.9</td>
<td>609.5</td>
<td>839.9</td>
<td>-1.7</td>
<td>0.0</td>
<td>39.8</td>
<td>37.5</td>
</tr>
<tr>
<td>2</td>
<td>852.7</td>
<td>683.1</td>
<td>686.2</td>
<td>739.8</td>
<td>-20.2</td>
<td>0.5</td>
<td>9.6</td>
<td>-12.9</td>
</tr>
<tr>
<td>3</td>
<td>784.7</td>
<td>733.2</td>
<td>721.2</td>
<td>668.4</td>
<td>-6.1</td>
<td>-0.8</td>
<td>-6.8</td>
<td>-13.8</td>
</tr>
<tr>
<td>4</td>
<td>583.7</td>
<td>525.0</td>
<td>547.1</td>
<td>600.8</td>
<td>-9.5</td>
<td>3.8</td>
<td>8.9</td>
<td>2.0</td>
</tr>
<tr>
<td>5</td>
<td>452.2</td>
<td>471.3</td>
<td>492.6</td>
<td>484.9</td>
<td>10.9</td>
<td>8.6</td>
<td>2.6</td>
<td>17.3</td>
</tr>
<tr>
<td>6</td>
<td>595.9</td>
<td>689.6</td>
<td>742.5</td>
<td>755.4</td>
<td>22.2</td>
<td>9.6</td>
<td>2.3</td>
<td>76.3</td>
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<td>7</td>
<td>345.5</td>
<td>269.9</td>
<td>288.8</td>
<td>250.0</td>
<td>-21.9</td>
<td>7.0</td>
<td>-13.4</td>
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<td>8</td>
<td>338.9</td>
<td>337.4</td>
<td>383.8</td>
<td>370.3</td>
<td>0.9</td>
<td>15.8</td>
<td>-2.8</td>
<td>18.5</td>
</tr>
</tbody>
</table>

XSA (m²) – Bankfull cross-sectional area

Table 7  Mean bankfull width and percentage change for Bends 1 – 8 on the lower Bellinger derived from the normalised photogrammetry cross-sections. Red denotes a net increase in channel width whilst yellow denotes a net decrease in channel width.

<table>
<thead>
<tr>
<th>Bend (average)</th>
<th>1942 QbW (m)</th>
<th>1962 QbW (m)</th>
<th>1982 QbW (m)</th>
<th>2002 QbW (m)</th>
<th>1942-1964 % change</th>
<th>1964-1982 % change</th>
<th>1982-2002 % change</th>
<th>1942-2002 % change</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>183.4</td>
<td>185.6</td>
<td>181.2</td>
<td>206.4</td>
<td>2.2</td>
<td>-3.1</td>
<td>35.1</td>
<td>33.1</td>
</tr>
<tr>
<td>2</td>
<td>238.8</td>
<td>242.6</td>
<td>237.1</td>
<td>257.9</td>
<td>2.4</td>
<td>-2.3</td>
<td>11.4</td>
<td>11.2</td>
</tr>
<tr>
<td>3</td>
<td>224.8</td>
<td>225.0</td>
<td>229.7</td>
<td>216.9</td>
<td>0.0</td>
<td>2.3</td>
<td>-5.6</td>
<td>-3.3</td>
</tr>
<tr>
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<td>141.8</td>
<td>136.4</td>
<td>148.6</td>
<td>151.6</td>
<td>-3.8</td>
<td>10.2</td>
<td>2.1</td>
<td>6.3</td>
</tr>
<tr>
<td>5</td>
<td>147.3</td>
<td>148.8</td>
<td>160.3</td>
<td>175.2</td>
<td>1.3</td>
<td>9.9</td>
<td>9.3</td>
<td>21.2</td>
</tr>
<tr>
<td>6</td>
<td>234.2</td>
<td>287.5</td>
<td>260.8</td>
<td>266.1</td>
<td>26.6</td>
<td>-10.1</td>
<td>1.7</td>
<td>14.9</td>
</tr>
<tr>
<td>7</td>
<td>158.9</td>
<td>179.5</td>
<td>131.9</td>
<td>128.7</td>
<td>13.0</td>
<td>-26.5</td>
<td>-2.4</td>
<td>-19.0</td>
</tr>
<tr>
<td>8</td>
<td>186.4</td>
<td>227.9</td>
<td>206.6</td>
<td>235.8</td>
<td>22.2</td>
<td>-7.7</td>
<td>23.2</td>
<td>28.2</td>
</tr>
</tbody>
</table>

QbW (m) – Bankfull width

Bellinger – Fluvial-Dominated B: Fernmount to McGeary’s Island

Bends 7 and 8 are the most slowly eroding bends of the analysis on the Bellinger River, eroding ~ 35 m over the 60 year period (equating to a mean erosion rate of 0.3 – 0.5 m yr⁻¹ and a maximum erosion rate of 1.0 m yr⁻¹, Table 5, Figure 15 & 22). Both bends appear to have eroded more quickly in the flood-dominated time interval from 1942 – 1982, however Bend 8 (locally known as Hendersons) is within measurement error. Both bends continued to erode in the 2009 floods with a maximum bank erosion of up to 5 – 6 m. Channel capacity and channel width at Bend 7 reduced by up to 60 and 19% respectively (Table 6 – 7). Photogrammetry cross-sections for both Bends 7 and 8 however should be treated conservatively given the large proportion of the cross-sectional area beneath the watersurface (8 – 10 m scour at Hendersons – Bend 8).
5.2.4 Historical channel changes on the Kalang River

Kalang – Fluvial-Dominated A: Brierfield Bridge to Pine Creek

Bends 1 and 2 on the Kalang River are E-SE migrating bends that have eroded 20 – 35 m respectively between 1942 and 2003. These bends occur in the steeper fluvial-dominated tidal reach and have migrated into erosion resistant high clay banks at 0.2 – 0.5 m yr\(^{-1}\) (Table 5, Figure 16 & 23). Both bends experienced little to no erosion in the 2009 floods but the low alluvial floodplain immediately upstream of Bend 1 on the concave bank experienced significant erosion in the 2009 floods (see Section 7.3). The low floodplains upstream of both bends have eroded 14 – 17 m over the period of investigation.
Figure 23  Photogrammetrically derived high bank locations in the vicinity of Kalang Bends 1 and 2 downstream of Brierfield over the period 1942 - 2003. The surveyed location of the post 2009 floods high bank is also shown at sites where active erosion was observed.

Kalang – Fluvial-transition: Newry Island

Bends 3 and 4 on the Kalang River occur in the fluvial-transition zone and have migrated more slowly than the two upstream bends (Figures 16 & 24). The given hydrological regime has not driven the rate of bend migration with mean erosion rates of $0.2 - 0.3$ m yr$^{-1}$ occurring in both the flood and drought-dominated time interval. Despite these bends forming a meander neck of $<100$ m the maximum distance eroded in 60 years has been $15 - 20$ m ($0.2 - 0.3$ m yr$^{-1}$) with a maximum erosion rate occurring between 1943 and 1964 ($0.8$ m yr$^{-1}$). This is equivalent to rates of erosion experienced in the 2009 floods (maximum erosion between 2002 and 2009, $0.9$ m yr$^{-1}$). Overall however, the slower rates of bend migration at
Bends 3 and 4 on the Kalang River are interpreted to be a function of clay-rich bank material and low stream gradients (hence low velocity floodwaters).

Figure 24 Photogrammetrically derived high bank locations in the vicinity of Kalang Bends 3 and 4 near Urunga over the period 1943 - 2003. The surveyed location of the post 2009 floods high bank is also shown at sites where active erosion was observed.

5.3 Sites of accelerated channel change on the Bellinger/Kalang River and the effectiveness of the 2009 floods

The lower Bellinger River throughout the tidal reaches has undergone significant increases in both channel width and channel capacity (cross-sectional area) throughout the 20th century. Whilst pre-European rates of channel migration and dimensions of the pre-European channel have not been documented in the tidal reaches it is presumed that the documented 20th century
rates would be far greater than equivalent pre-European rates. The dimensions of the non-tidal 20th century channel between Bellingen and Thora has been shown to be twice to three times that of pre-European channel remnants, abandoned at various locations along the valley. Cohen (2003) demonstrated that channel capacity between Bellingen and Thora increased by 7 – 12% in the flood-dominated time-interval between 1943 and 1973. Despite a reduction in flood frequency since 1977/1978 it was demonstrated that channel capacity has remained high.

Such dimensional changes have been documented for the tidal reaches but with considerable bend-to-bend variation. Bankfull width increases of 6 – 33% between 1942 and 2002 have been documented from the photogrammetry cross-sections for the upper fluvially-dominated reach of the Bellinger River. Some locations (such as Bend 1, adjacent to the Bellingen golf course) have increased their capacity by 37% whilst others (Bends 2 and 3) have decreased their capacity by 12 – 14%. This would suggest that some locations have undergone dramatic changes with a small proportion of that eroded material stored/deposited on bends downstream.

The 2009 floods, like the 2001 floods, have been efficient at de-stabilising a number of locations along the lower Bellinger and lower Kalang Rivers. In the case of the Bellinger, much of this erosion has occurred primarily as a function of little or discontinuous bank vegetation resulting in areas susceptible to rapid rates of bank erosion. The following locations are those that actively eroded in the 2009 floods, in order of severity:

Sites of accelerated change - Bellinger River
1. Bend 5: 20 – 25 m of bank erosion on right-bank
2. Bend 6: 10 – 15 m of bank erosion on left-bank
3. Downstream end of Bend 4: 10 – 15 m of bench erosion on true left-
4. Bend 3

When viewed as maximum erosion rates these bends have undergone accelerated rates of change with Bends 5 and 6 eroding at 2 – 3 times the previous maximum rates of erosion (Table 5). It must be stressed that the calculation and subsequent comparison of maximum erosion rates is governed by the short interval of investigation (e.g. 2002 – 2009) and that all bends that actively eroded were essentially bare of riparian vegetation prior to the 2009 floods.

Sites of accelerated change - Kalang River
1. Bend 1: Inside bend low floodplain, 5 – 10 m of erosion
2. Bend 1: Downstream end of bend, 5 m of low floodplain erosion
3. Brierfield Bridge to Bend 2

The Kalang River sites all have the appearance of ‘active’ erosion classified as either severe or moderate erosion in the field-mapping component. However, given the limited nature of photogrammetry on the Kalang River it is difficult to make comparisons with regards to rates of change.
5.4 Implications of climate change scenarios on bank erosion in the Bellinger/Kalang Rivers

Predicted 21st century climate change may well alter a number of parameters relevant to the ongoing management of the Bellinger and Kalang Rivers. Predicted sea level rise will ultimately modify the near-shore processes and the relationship between coastal sediment supply and near-shore estuary entrance dynamics. Other potential impacts of a predicted sea-level rise of 0.4 – 0.9 m is the co-occurrence of storm surges and large flood events. The implications for river management is that floodplain inundation frequencies will most likely change with the greatest impacts experienced near the coast. Predicted sea-level rise, coupled with large flood events, will ultimately shift the current position of the backwater effect in an upstream direction. The magnitude of this displacement will be governed by the nature of overbank flood dynamics, which in itself is a function of topography and flood magnitude. There is currently no such information for this on the Bellinger River.

The implications of climate change on the management of the lower Bellinger River will be determined by changes to the magnitude-frequency relationship of large flood events. Macadam et al., (2007) have estimated a reduction of 2 and 9% in spring and autumn rainfall by 2030 for Wooli Wooli Estuary, with a possible mean reduction by 20% in summer and autumn rainfall events between the 1 in 5 year and the 1 in 40 year recurrence interval. Macadam et al., (2007) however, also estimate a potential increase in summer rainfall events of 20%. Thus, the uncertainty with these predictions precludes and limits the predictive capability with regards to ongoing bank erosion on the Bellinger or Kalang Rivers. If the magnitude-frequency distribution changes so that more frequent large floods are experienced then management authorities can expect similar types of channel responses seen throughout the catchment in the previous flood-dominated time interval (1948 – 1977/78). This however, is dependent on the nature of the riparian zone when and if this change occurs. In contrast, an ongoing reduction in the frequency of large floods (as seen in the current drought-dominated time interval) would theoretically allow some currently unstable locations to become stabilised with riparian vegetation and/or remedial works.
PART 2 BELLINGER-KALANG 2009 BANK CONDITION ASSESSMENT

6.0 Current Bank Condition in the Bellinger and Kalang Estuaries

Current bank condition was determined by field assessment over an eleven day period in June and July 2009. The field assessment was conducted by boat and on foot in some locations. Bank erosion severity and probable failure mechanism were recorded for each location. In addition, bank erosion control works were also recorded as were natural channel features contributing to stability such as the presence and condition of native riparian vegetation and the presence of bedrock or resistant substrates in the bank profile. The location of infrastructure such as jetties, wharfs, and access points were also noted. All features were mapped using a handheld GPS unit and then transferred to an ArcGIS geographic database. Absolute locations of the recorded features are estimated to be accurate within ± 20 m.

The survey covered the main arms of the Bellinger and Kalang River estuaries (see Figure 26). The survey area included Back Creek, but not Picket Hill Creek or Urunga Lagoon. The total length of bank surveyed (calculating left and right banks separately) represents just over 120 km of riverbank.

The hydrological conditions immediately prior to the survey were dominated by a series of large floods occurring in February, March and May, all of which represented floods with an estimated recurrence interval of between 10 and 20 years (for the Bellinger River). Consequently, this snap-shot survey of bank condition must be viewed in the light of the extreme disturbance caused by these floods. The likely impact on the survey is that the extent of minor bank erosion is over-estimated in both estuaries.

6.1 2009 Field Survey Methodology

The factors that influence the distribution of erosion in estuaries are many and interrelated. They include the composition of bank soils (including the presence of resistant materials such as cohesive clays or, conversely, the presence of less consolidated material such as gravel seams in composite banks); the presence of bedrock outcropping on the channel margin; the presence or absence of riparian vegetation; disturbance factors such as unmanaged stock access or wind or boat waves; the presence of bank protection works (particularly hard structures that may divert high velocity flows onto adjacent unprotected banks); and, complex responses to changes in hydrological regime or sediment supply or distribution in the estuary.

In an attempt to further understand and describe the processes occurring in the Bellinger and Kalang estuaries, the 2009 field survey focuses on documenting the location and severity of bank erosion and the extent of factors that control bank erosion such as the location of bedrock outcropping, the distribution and condition of riparian vegetation, and the presence and types of bank protection works and estuary access infrastructure. These factors are discussed in detail in the sections below.

The individual factors used in determining the estuary condition ratings have been recorded into a computer based mapping system (GIS or geographic information system) and are available through Bellinger Shire Council for viewing by arrangement. The results of the
survey are summarised in the sections below. Appendix 1 provides a list of the datasets created through this study.

### 6.2 Estuary Bank Erosion

As explained in the Geomorphic Process Zones section of this report, the geomorphic character and behaviour of the estuary is variable and consequently erosion rates and processes also vary.

In upper estuary reaches fluvial processes (ie. driven by freshes and floods) tend to predominate and processes such as sediment load, transport and deposition (for example gravel bar formation and meander migration) drive long term channel change. In middle to lower reaches, tidal influences change the energy environment producing different sedimentation patterns, flow dynamics, and erosion effects. In general, there are two main drivers of erosion processes in the middle to lower estuary reaches within which six main erosion types can be observed;

**Episodic or event-based processes...**

- Slab type block failure resulting from inundation and subsequent slumping, with material generally not remaining in situ.
- Rotational failures and slumps related to either subsoil drainage or draw-down effects as water level drops with rapidly receding flood levels, with material generally remaining in situ.
- Scour resulting from high velocity flows often acting on the bank toe. Material does not remain in situ. Scour associated with major flooding can remove the evidence of slab type block failures.

**Continuous processes...**

- Slab type block failure resulting from undercutting of the bank toe as a result of wave or wind action or scour, with material often remaining in situ.
- Notching of the bank toe or fretting as a result of wave action (wind or boat) and subsequent undercutting and failure.
- Disturbance of banks through unmanaged stock access, inappropriate land use, or the removal and/or suppression of riparian vegetation.

Although separating the types of processes facilitates explaining how erosion occurs in estuaries, in practice the processes are interrelated. For example, continuous effects such as unmanaged stock access can lead to suppression of the mangrove and river reed fringe which as a result of continuous wave wash from wind and boats can cause the banks to become undermined and susceptible to episodic damage from flood events. Similarly, the historic extraction of large quantities of gravel from middle to upper reaches of the Bellinger River, sometimes undertaken to alleviate sedimentation, can cause a series of responses in the estuary bed which actually exacerbates further bank erosion causing more serious sedimentation (see Cohen, 2003 and Nanson and Doyle, 1999).

The extent and severity of bank erosion recorded in the Bellinger and Kalang estuaries are provided in Figure 25. This figure shows that in the Bellinger River estuary the majority of erosion occurs in the Fluvial-dominated A and B process zones, between Bellingen and
Henderson’s bend. In the Kalang River estuary the major areas of erosion are located in the upstream *Fluvial-dominated A* process zone and the *Transition* process zone in the lower reaches. The reasons for the differing distributions of erosion in the two estuaries are discussed in sections 6.2.1 and 6.2.2 below.

In many respects the results reflect the fact that extensive flooding had occurred immediately prior to the survey period as most areas of minor erosion observed appeared recent and related to those flood events. This hypothesis is supported by the comparison of 1983-84 bank erosion extent to the 2009 results which shows very large increases in the extent of minor bank erosion but decreases in extent of moderate and severe bank erosion (discussed in detail in Section 6.2.3).

**Figure 25** Distribution and severity of reaches of active erosion mapped in the Bellinger and Kalang River estuaries, June 2009.
6.2.1 Summary of Bank Erosion - Bellinger Estuary

The extent of bank erosion in the Bellinger River estuary and its constituent process zones is summarised in Table 8. The data highlights that of the 60.3 km of banks surveyed, just over half (32.4 km or 54%) are stable with approximately 1/3rd of the remaining banks recorded with minor erosion (19.5 km or 32%). Approximately 18% of stable banks were stabilised by erosion control works while 5% were naturally stable as a result of bedrock outcropping on the channel margin. This suggests that 41% of the alluvial river banks are naturally stable.

The summary statistics for the Bellinger estuary also show that:

- The Fluvial-dominated A process zone recorded the highest levels of moderate and severe erosion (13% and 10% respectively).
- The Fluvial-dominated A and B zones had similar proportions of stable bank. However, approximately 40% of the stable banks in the Fluvial-dominated A zone were either stabilised by bank protection works (21%) or bedrock (15%). Conversely, 99% of stable banks in the Fluvial-dominated B zone were alluvial with only 2% protected by works (rock revetment and revegetation).
- The Fluvial Transition zone had almost no active erosion, but almost a quarter of its banks were armoured by bank protection works (predominantly rock revetment) and 6% were protected by bedrock outcropping.

Table 8 Severity of bank erosion in the Bellinger River estuary, June 2009

<table>
<thead>
<tr>
<th>Estuary or Process Zone</th>
<th>Total length surveyed (km)</th>
<th>Stable (km,%): Works</th>
<th>Minor (km,%): Works</th>
<th>Moderate (km,%): Works</th>
<th>Severe (km,%): Works</th>
<th>% Stable = Works</th>
<th>% Stable = Bedrock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bellinger River</td>
<td>60.3</td>
<td>32.4 (54%)</td>
<td>19.5 (32%)</td>
<td>4.8 (8%)</td>
<td>3.6 (6%)</td>
<td>18% (5.9 km)</td>
<td>5% (1.6 km)</td>
</tr>
<tr>
<td>Fluvial-dominated A</td>
<td>12.8</td>
<td>4.8 (37%)</td>
<td>5.1 (40%)</td>
<td>1.6 (13%)</td>
<td>1.3 (10%)</td>
<td>21%</td>
<td>15%</td>
</tr>
<tr>
<td>Fluvial-dominated B</td>
<td>15.5</td>
<td>5.3 (34%)</td>
<td>7.2 (46%)</td>
<td>1.1 (7%)</td>
<td>1.9 (12%)</td>
<td>2%</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>Fluvial Transition</td>
<td>15.5</td>
<td>15.0 (97%)</td>
<td>0.4 (3%)</td>
<td>-</td>
<td>-</td>
<td>22%</td>
<td>6%</td>
</tr>
<tr>
<td>Marine-tidal delta</td>
<td>16.5</td>
<td>7.3 (44%)</td>
<td>6.8 (41%)</td>
<td>2.1 (13%)</td>
<td>0.4 (2%)</td>
<td>21%</td>
<td>&lt;1%</td>
</tr>
</tbody>
</table>
**Bellinger estuary - Fluvial Dominated A Process Zone**

Figure 26 shows the spatial distribution of bank erosion in the Fluvial Dominated A process zone in the Bellinger estuary. Bank erosion in this zone is driven almost entirely by fluvial processes with the most recent floods in the first half of 2009 being a primary factor in the widespread distribution of erosion in this zone.

![Map of Bellinger Fluvial Dominated A Process Zone Distribution of Active Erosion June 2009](image)

**Figure 26**  Distribution and severity of reaches of active erosion mapped in the Bellinger Fluvial Dominated A process zone between April and June 2009.

As explained in the process zone descriptions (Section 4.1), the reach of estuary between Bellingen and Fernmount is characterised by a gravel bed channel with a distinct macro-channel with a low (younger) floodplain 4-7m high inset within a higher older alluvial surface. Collectively, the channel and low floodplain form the meander belt and zone of active overbank flow. The meander belt infrequently butts up against the bedrock valley margin or in some locations is controlled by old alluvial terraces which also provide relatively erosion resistant surfaces. In general, the areas between these bedrock or terrace controls are...
more susceptible to erosion, particularly where historical or contemporary land use practices have resulted in the loss of structurally diverse riparian vegetation and where disturbance factors such as unmanaged stock access continue.

Shallow slips are the dominant failure mechanism in most areas described as having minor erosion within this reach (Plate 3a). In contrast, areas of moderate erosion generally have larger areas of slippage with rotational slumps and slab-type block type failures occurring across the whole bank, or along extended sections of the bank toe (Plate 3b). In cases of severe erosion, the banks have a near vertical appearance as a result of a combination of undercutting, slab-type block type failures, and significant scouring (Plates 3c and 3d).

Plate 3  Examples of erosion severity in the Bellinger Fluvial Dominated A process zone, clockwise from top left: a) shallow slips resulting in minor erosion; b) moderate erosion as a result of a full bank slip and associated tree fall; c) severe erosion at Site 2 showing depth of toe scour; and, d) scour and associated undercutting and tree fall at Site 6.

Analyses of historical aerial photograph series and photogrammetrically derived cross-sections show that there has been a net increase in channel capacity throughout most of this zone over the last 60 years (see 5.2.3). As a consequence, a greater proportion of flood waters are able to be conveyed within the channel, in turn creating greater erosive forces. Although, the comparison of erosion rates between 1942 and 2009 show no clear trend across all the reaches analysed, it is likely that rates of erosion in all parts of the river are significantly above pre-European levels.
Of all the bends analysed, the 4 most actively eroding sites on the Bellinger estuary are all found within this process zone (see 5.3). They include in order of severity;

SITE 1. At Bend 6 on river left opposite Fernbank: approximately 140m of mass failure (including rotational slips and undercutting and subsequent tree fall) and 100m of scouring and stripping of the downstream low floodplain bench surface affecting approximately 0.3ha.

SITE 2. Downstream of Bend 4 on river left adjacent to North Arm Road: erosion of 370m of the low floodplain bench and including damage to a log crib wall and minor rock works. Approximate area damaged is 0.19ha

SITE 3. At Bend 5 on river right adjacent to waterfall way: approximately 330m of severe erosion of the bank and some associated floodplain stripping immediately before the point bar opposite Hydes Creek involving and estimated 0.13ha.

SITE 4. At Bend 3: 230m of bank erosion immediately downstream of the protection works at Carlill’s wharf (below the old Butter Factory at Bellingen), and erosion and stripping of the floodchute breakout and re-entry channels. Approximate area affected is 0.06ha.

Other areas of significant erosion include;

SITE 5. At Bend 1 adjacent to the golf course: moderate erosion of the bank face above the protective works (rock revetment of the bank toe, low mesh fencing, and revegetation installed in 2001). These works have mostly been successful in stabilising the toe location. However, some damage to the mesh fencing and revegetation along with minor floodplain stripping at flood breakout points on the golf course was observed.

Bellinger estuary - Fluvial Dominated B Process Zone

The Fluvial-dominated B process zone extends from Fernmount to McGeary’s Island (Figure 27). As with upstream reaches, fluvial processes are again the main drivers of channel change in this zone. However, the proportion of bedrock control on the channel is significantly less and the floodplains within which the channel is set are finer grained and lower in height (generally 2.5 - 4m above mean tide level). Bed material is composed of fine gravels and sands and bar formation is diminished.

Tidal variation increases throughout this zone and the floodplains are more susceptible to fretting and undercutting from wind and boat waves, particularly during mid-tides. In general, damage related to unmanaged stock access in this zone is less of an issue than in the upstream reaches of Zone A. This is particularly so on outside bends where the high eroded banks present a risk to livestock and many landholders had subsequently taken the precaution of fencing stock away from these areas. However, pugging and disturbance of lower banks on inside bends was frequently observed making these areas more susceptible to bank erosion.

Photogrammetry undertaken in the downstream half of this zone in the vicinity of Henderson’s shows mixed results in terms of changes to cross-sectional area and bankfull width (see 5.2.3). Consequently it is difficult to draw conclusions as to the effect of any historical changes to these two parameters. A comparison of the rate of erosion showed that this location was the most slowly eroding of all surveyed on the Bellinger (average of 0.3-
0.5 m yr\(^{-1}\)). Despite these statistics of historical change, up to 5-6 m of lateral erosion was experienced at both Bend 7 and 8 during the first half of 2009.

**Figure 27** Distribution and severity of reaches of active erosion mapped in the Bellinger Fluvial Dominated B Process Zone, June 2009.

The most significant erosion in this zone includes (not in order of severity):

**SITE 6.** Approximately 2.3 km upstream of Connor’s Creek confluence: 300 m of erosion of the concave bank on river left resulting primarily from flood scour but with signs of undercutting and block type failures at the upstream leading edges.

**SITE 7.** Approximately 2 km upstream of Connor’s Creek confluence: approximately 350 m of erosion of a low alluvial bench on the right bank (Plate 4a). This bank is relatively devoid of riparian vegetation and is being actively undercut resulting in extensive slab and block type failures. The erosion is most likely more rapid during flood events but is now also susceptible to wave action.
SITE 8. At Bend 7: approximately 450m of severe erosion on river right, driven primarily through fluvial scour but exacerbated by very poor bank vegetation cover (Plate 4b). Some evidence of mass movement through full bank slippage was observed and is likely related to drawdown effects (ie. mass slumping occurring after critical bank strength is exceeded by the mass of saturated soils as flood waters recede). Approximately 0.15ha were affected by the February-May 2009 floods.

SITE 9. At Bend 8 (Henderson’s): approximately 300m of severe erosion characterised by a vertical bank face and virtually no riparian vegetation. Failure types here are again predominately related to fluvial scour, undercutting and slab and block failure. Approximately 0.04ha of was affected during the February-May 2009 floods.

Plate 4 Examples of severe erosion in the Bellinger Fluvial Dominated B process zone, from left to right: a) Site 7, undercutting from scour and periodic wave action resulting in slab-type block failures; and, b) scour and associated undercutting and tree fall at Site 8.

Bellinger estuary - Fluvial Transition Process Zone

The Fluvial transition process zone represents the most stable process zone in the Bellinger estuary with 97% of banks rated as stable (Figure 28). The remaining 3% of the total bank length were considered to have only minor erosion. The most common erosion processes observed were the mid-tide fretting of the bank toe from wind and boat wave action (relative contribution unknown) and subsequent undercutting and shallow slips.

The relative stability of this zone in the Bellinger estuary can be attributed to the following factors;

- The Fluvial Transition zone has a fluvial planform but is subject to a pronounced marine influence. This in effect means that relative to upstream reaches this zone is a low energy zone. The deposition of large volumes of fluvially derived sediments on the Raleigh shoal demonstrates this fact, as does the presence of the two mid-channel deposits: McGeary’s and Tuckers Islands.
- The adjacent floodplains are low (1.5-2m above mean tide level) and wide, meaning that flood waters can quickly spread dissipating the erosive energy.
Almost the entire length of outside bank has either been artificially stabilised by bank protection works (22% of total bank length, see Figure 29 for distribution) or by bedrock outcropping (6% of total bank length).

There are no significant sites of erosion in this zone of the Bellinger estuary.

Figure 28  Distribution and severity of reaches of active erosion mapped in the Bellinger Fluvial Transition Process Zone, June 2009.
Figure 29  Distribution and type of existing bank protection and remediation works in the Bellinger Fluvial Transition Process Zone as at June 2009.

Bellinger estuary - Marine Tidal Delta Process Zone

Figure 30 shows the spatial distribution of bank erosion in the Marine Tidal Delta process zone. 7.3km (44%) of this process zone is stable with more than half of this length (3.9km) artificially stabilised with erosion control works (0.7km) or entrance training works (3.2km; see Figure 31 and Table 8). Less than 1% of banks are stable due to bedrock outcropping on the southern bank.
Of the remaining 9.3km of estuary banks, 6.8km (41% of total length) are considered to have minor erosion with over two thirds of this length (~ 4 km) occurring along the barrier dune that separates the estuary from the Pacific Ocean (Plate 5a). The sand dunes, which are characteristic of the barrier dune, have virtually no cohesion without vegetation and although wash from wind waves can cause localised areas of slip, most of the erosion observed in 2009 is suspected to have been related to the recent flood events and is not considered significant.
Figure 31  Distribution and type of existing bank protection and remediation works in the Bellinger Marine Tidal Delta process zone as at June 2009.

Figure 30 also shows that the incidence of moderate and severe erosion is almost exclusively concentrated around the northern and eastern portions of Urunga Island and north bank of Back Creek. On the eastern fringe of Urunga island, the presence of drain headworks protruding into the current day channel indicate that the bank has retreated some 20-30m over the last four decades (Plate 5b and 5c). The banks here have a shallow water profile and are composed mostly of sandy alluvium and marine-derived sands over basal clays. Consequently, the banks are highly susceptible to undermining and fretting of the bank toe, predominantly by wind waves during mid-tides, and then subsequent block failure. Unrestricted stock access on these banks is also a contributing factor as stock damage exacerbates the susceptibility of these banks to this style of erosion and the continual grazing of mangroves reduces the potential for vegetation to dissipate wave energy. Several failed attempts to stabilise areas of bank using tyres were noted during the survey.
Plate 5  Clockwise from top left: a) minor erosion of the barrier sand dune, left bank Bellinger estuary; b) exposure of drain headworks showing the extent of bank retreat on the eastern side of Urunga Island; and, c) Unmanaged stock access limits mangrove recolonisation.

Erosion processes within the Back Creek channel (including the northern portions of Urunga Island) are dominated by slab-type block failures resulting from undermining of the bank toe. Given the protected nature of these banks from both northerly and southerly winds, and the relatively low energy environment of the Back Creek system, it is reasonable to conclude that these processes are predominantly driven by boat wash. The alluvial nature of the banks here, the confined nature of the channel, the significantly reduced vegetation cover, and the time-savings afforded by using this channel as a short-cut to access the mid Bellinger estuary, all mean that the banks in this location are particularly susceptible to wave wash erosion.

In summary, the most significant erosion in this zone includes (in order of severity);

SITE 10. Back Creek: approximately 260m of discontinuous moderate bank erosion adjacent to Yellow Rock Road. Undercutting of the bank toe as a result of wave wash is destabilising sections of the bank in this location (Plate 6a).

SITE 11. Back Creek: approximately 350m of severe bank erosion on the northern tip of Urunga Island. Boat wash of the alluvial bank is the primary cause in this location. The deep water profile adjacent to this bank makes this bank particularly susceptible to wind and
boat wave wash. In addition, the almost complete absence of riparian vegetation and ongoing stock disturbances also contribute to instability at this site (Plate 6b).

**SITE 12.** Urunga Island: approximately 1800m of sporadic moderate erosion on the eastern side of the island adjacent to the Bellinger estuary. Erosion processes here are exacerbated by the shallow water profile, low floodplain, poorly consolidated bank materials, exposure to both north-easterly and southerly wind waves, and ongoing disturbance by stock to banks and fringing mangrove vegetation. An area of candidate coastal saltmarsh EEC is also impacted at this site.

![Plate 6](image_url)

**Plate 6**  Examples of erosion severity in the Bellinger Marine Tidal Delta process zone, from left to right: a) Site 10, moderate erosion on Back Creek adjacent to Yellow Rock Road; and b) Site 11, severe erosion at the north eastern tip of Urunga Island.

### 6.2.2 Summary of Bank Condition - Kalang Estuary

The extent of bank erosion in the Kalang River estuary is summarised in Table 9. Of the 60.5km of banks surveyed, just over two thirds (41.2 km or 68%) are stable, 21% have minor erosion (12.8km), 6% moderate erosion (3.8km), and 4% were mapped with severe erosion (2.7km). Bedrock outcropping (9% of banks recorded as stable) accounts for a greater proportion of stable banks in the Kalang than in the Bellinger. Also in contrast to the Bellinger estuary, a lesser proportion of stable banks are stable due to bank protection works (13%), with the vast majority of works located in the lower estuary around Newry Island and Urunga. This suggests that in the Kalang, approximately 53% of the alluvial river banks are naturally stable.

The summary statistics also show that;

- Bank erosion in the Kalang River estuary is concentrated in the Fluvial-dominated A and Fluvial Transition zones.
- The Fluvial Transition zone had almost 5.4km of bank protection works representing more than 20% of total bank length. Moderate and severe bank erosion was concentrated at the southern end of Newry Island on alluvial banks with essentially no riparian vegetation.

52.
The Fluvial-dominated B zone recorded the lowest levels of erosion of all process zones, mostly as a factor of the high level of bedrock control on the channel and the relatively continuous riparian vegetation strip in this zone.

The Marine-tidal delta zone also recorded very low levels of bank erosion, however, 28% of stable banks in this zone were stabilised by bank protection works (mostly rock or rubble revetment and training walls). A further 12% were stable due to bedrock.

A more detailed discussion of the results in each process zone is provided below.

**Table 9  Severity of bank erosion in the Kalang River estuary, June 2009**

<table>
<thead>
<tr>
<th>Estuary or Process Zone</th>
<th>Total length surveyed (km)</th>
<th>Stable (km,%</th>
<th>Minor (km,)</th>
<th>Moderate (km,)</th>
<th>Severe (km,)</th>
<th>% Stable = Works</th>
<th>% Stable = Bedrock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kalang River</td>
<td>60.5</td>
<td>41.2 (68%)</td>
<td>12.8 (21%)</td>
<td>3.8 (6%)</td>
<td>2.7 (4%)</td>
<td>13% (5.2 km)</td>
<td>9% (3.9km)</td>
</tr>
<tr>
<td>Fluvial-dominated A</td>
<td>16.7</td>
<td>9.1 (54%)</td>
<td>4.7 (28%)</td>
<td>2.0 (12%)</td>
<td>0.9 (6%)</td>
<td>&lt;0.1%</td>
<td>18%</td>
</tr>
<tr>
<td>Fluvial-dominated B</td>
<td>11.6</td>
<td>9.5 (82%)</td>
<td>2.2 (18%)</td>
<td>0.03 (&lt;0.5%)</td>
<td>-</td>
<td>-</td>
<td>11%</td>
</tr>
<tr>
<td>Fluvial Transition</td>
<td>26.9</td>
<td>18.4 (69%)</td>
<td>4.9 (18%)</td>
<td>1.8 (7%)</td>
<td>1.7 (6%)</td>
<td>22%</td>
<td>4%</td>
</tr>
<tr>
<td>Marine-tidal delta</td>
<td>5.3</td>
<td>4.3 (81%)</td>
<td>1.0 (19%)</td>
<td>-</td>
<td>-</td>
<td>28%</td>
<td>12%</td>
</tr>
</tbody>
</table>

**Kalang estuary - Fluvial Dominated A Process Zone**

The most upstream fluvially-dominated reach on the Kalang River extends from the tidal limit at Brierfield Bridge to the acute bend south of the confluence of Pine Creek. Figure 32 shows the spatial distribution of bank erosion in this zone. As with the equivalent zone in the Bellinger, this zone has the most active areas of erosion in the Kalang estuary. Again, bank erosion in this zone is driven almost entirely by fluvial processes with the most recent floods in the first half of 2009 being a primary factor in the widespread distribution of erosion.

As with the fluvially-dominated reach on the Bellinger estuary, this reach exhibits variable floodplain topography with many inset benches and bank attached bar surfaces within the channel. The main floodplains are generally around 4 m above mean tide level. The meander belt is significantly narrower than in the equivalent zone in the Bellinger with the channel regularly abutting bedrock on the valley margin (18% of total bank length), or being variously controlled by old terrace features which are significantly more resistant to erosion than the lower (more recent) floodplain surfaces.
Figure 32 Distribution and severity of reaches of active erosion mapped in the Kalang Fluvial Dominated A process zone, June 2009.

In this zone, most reaches described as having minor erosion (28% of banks) have evidence of shallow slips or scour of the lower to mid banks. Areas of moderate erosion (12% of banks) generally have larger areas of slippage with rotational slumps and slab-type block type failures occurring across the whole bank, or along extended sections of the bank toe, often resulting in significant tree fall into the channel (Plate 7a). Both minor and moderate erosion are found on both inside and outside bends and along relatively straight reaches, indicating that the channel has responded to the large floods of early 2009 by significantly expanding its capacity (Plate 7b). In addition, poor riparian vegetation cover and unmanaged stock access is contributing to bank instability at many sites. Unfortunately, no historical cross-section information is available in these reaches so a comparison of pre-flood and post-flood channel capacity cannot be performed to confirm the field interpretations.

In cases identified with severe erosion (6% of banks), the main processes identified were generally a combination of scour, undercutting and slab-type block type failures, or mass...
failures such as full bank slips or rotational failures related to flood drawdown effects. Some sites, such as the most upstream example of severe erosion at the first acute bend below Brierfield Bridge, were obviously recent with numerous large trees with fresh rootballs within the adjacent channel and immediately downstream (Plate 7a). Other sites, such as the areas of severe erosion at Bends 1 and 2 have been progressively eroding at a rate of between 0.2 and 0.5 m per year since the early 1940s, but showed very little change after the early 2009 floods (see Section 5.2.4). The reasons for the discrepancies in rate of change at these two sites can be explained by the presence of highly resistant cohesive clays in the bank profile, indicating that the channel has eroded up against an old alluvial terrace (eg. see Plate 7c). Dating of a large hardwood log in the basal clays of one of the features indicates an age of approximately 7200 years.

Plate 7  Clockwise from top left: a) undercutting leading to tree fall, left bank upper Kalang estuary; b) erosion of the inside bend bank toe indicating channel expansion as a response to the 2009 floods; and, c) differences in susceptibility to erosion processes of different aged depositional units on the floodplain.

Erosion sites of significance in this zone include (in order of severity);

SITE 13. Right bank at Bend 1: approximately 150 m of severe erosion affecting 0.04ha. The upstream 70m of the bank is composed of a resistant terrace which nevertheless shows evidence of scouring at the toe and some mass movement related to drawdown effects (ie. where the mass of the saturated bank exceeds its cohesive strength as flood waters receded and slumping occurs). The downstream 80m is more erodible, being a lower floodplain surface composed of more recent alluvium, and is almost devoid of riparian
vegetation. Unmanaged stock access is also likely to be a contributing factor at this site. The major processes affecting the lower section are scouring of the bank toe followed by slab-type block failures (see Plate 8a).

SITE 14. Left bank, 600m downstream of Brierfield Road bridge: approximately 80m of the left bank has been scoured during the 2009 floods, resulting in undermining of the bank vegetation (mostly large camphor laurels and small-leaved privet) and subsequent collapse (see Plate 7a).

SITE 15. Right bank at Bend 2: similar to Site 13 in that this site also has an upstream terrace and a downstream low floodplain and also subject to the same processes. Approximately 100m of bank is affected, however analyses of the 2009 bank location to the 2002 location shows only minor change in the order of 0.5-1m.

SITE 16. Right bank immediately below Martels Road: much of the right bank in this location is composed of thin layer of colluvium over a bedrock base. A combination of scouring of the bank toe and subsequent slippage (also possibly exacerbated by drawdown effects) have resulted in undermining of a 25m section of Martels Road (Plate 8b). Relatively deep water below this site is likely complicate efforts to restabilise the bank.

SITE 17. Right bank: Moderate erosion on the convex bend upstream of bend 1 has damaged an area of recent (<5 years) revegetation works. Scouring of the bank toe has effected approximately 40-60m at this location.

SITE 18. Left bank, opposite and upstream of Bend 1: Severe erosion caused by bank scour affecting approximately 80m and 0.02ha.

SITE 19. Left bank, opposite and downstream of Bend 2: scouring of the bank toe and subsequent undermining and slab-type block failures has led to a length of approximately 80m of severe erosion.

SITE 20. Left bank, approximately 2km upstream of Pine Creek confluence: Approximately 80m of severe erosion at a flood breakout point that potential threatens an avulsion across a low floodplain surface into a previous channel location.

Plate 8 From left to right: a) Site 13, slab-type block failure occurring at the downstream extent of Bend 1; and b) scour and subsequent mass failure at Site 16 adjacent to Martels Road, Kalang estuary.

56.
Kalang estuary - Fluvial Dominated B Process Zone

The Fluvial Dominated B process zone represents the most stable process zone in the Kalang estuary with 82% of banks rated as stable (Figure 33). Of the remaining banks, the vast majority were described as having only minor erosion with only a 40m section of bank below South Arm Road rated as moderately eroded. The most common erosion processes observed were scour related to the 2009 floods which had resulted in numerous slips and slumps (Plate 9a), and the mid-tide fretting of the bank toe from wind and boat wave action (relative contribution unknown) and subsequent undercutting and shallow slips.

As mentioned in section 4.1, this reach of the Kalang River reflects a change in valley bedrock morphology. The estuary here becomes less sinuous with a wide and at times deep channel (7-8m). In the upper half of this zone, the left bank abuts the valley margin with bedrock outcropping controlling channel location in several reaches. Although the right bank
is entirely alluvial, the upper half of the zone is contained within Newry State Forest which has essentially allowed the maintenance of an almost continuous band of structural diverse native riparian vegetation. Where the channel emerges into floodplains and private ownership on both sides it is relatively straight and only minor areas of erosion were noted, mostly related to wave wash of the lower banks and subsequent undermining and slumping. The area is often utilised for skiing which may contribute to the fretting of the bank toe between low and mid tide levels.

Despite the numerous shallow slips, slumps, and areas of tree fall that occurred during the 2009 floods, there was only one site of erosion in this zone considered significant in a management context;

**SITE 21.** Left bank, immediately below South Arm Road upstream of the Pickett Hill Creek confluence: Approximately 50m of moderate erosion has undermined the South Arm Road (see Plate 9b). Likely processes include scouring of the bank toe and subsequent undermining and slumping, or slumping of the super-saturated bank during the receding phase of a flood event. As with the upstream Martells Road site, the deep water adjacent to the site will complicate any efforts to restabilise the banks.

**Plate 9** From left to right: a) Example of minor bank erosion in the Kalang Fluvial Dominated B zone, mass movement as a result of draw down effects on the receding phase of flooding; and b) scour and subsequent undermining and tree fall adjacent to South Arm Road, Kalang estuary.

**Kalang estuary - Fluvial Transition Process Zone**

The Kalang estuary Fluvial Transition process zone covers the two branches of the estuary that surround Newry Island. The morphology of Newry Island is complex being variously composed of aged terrace surfaces (including some Pleistocene 10,000 - 30,000 years old; PWD, 1983), younger floodplain surfaces, and minor bedrock outcrops. As a result, estuary bank morphology also varies.

This zone has the second highest rates of erosion in the Kalang estuary after the Fluvial Dominated A zone. Although more than two thirds (18.4km) of the banks are stable, 5.4km or 22% of total bank length is artificially stabilised by bank protection works. Of the remaining
one third of banks mapped with some degree of erosion, 18% had minor erosion, 7% moderate erosion, and 6% severe erosion. The distribution of erosion is presented in Figure 34 and shows that erosion is concentrated in the southern branch of the estuary, with two thirds of all moderate (1.2km of 1.8km total) and severe (1.1km of 1.7km total) erosion occurring on the Newry Island side of the southern channel.

Figure 34  Distribution and severity of reaches of active erosion mapped in the Kalang Fluvial Transition process zone, June 2009.

There is insufficient knowledge of the morphology of Newry Island to adequately explain the concentration of erosion on the southern bank of Newry Island. However, potential factors that may influence such a distribution include;

- The longitudinal profile for the Kalang estuary (Section 5.1) shows that the southern branch has a deeper water profile than the northern branch (maximum scour to -10m AHD as opposed to -6m), possibly indicating a preferential flow path with potentially higher erosive forces.
- Topographic variations across Newry island may also influence flood flows creating zones of localised scour at channel re-entry points such as at Sites 22, 23, and 24.
- Land use distribution: which has resulted in the northern sections of the island being developed for urban and rural residential purposes whilst the southern sections remain agricultural. In areas of rural residential and urban development, the proportion of estuary bank protected by stream works is 52% compared to 14% in the agricultural areas of the island (see Figure 35).

**Figure 35** Distribution and type of existing bank protection and remediation works in the Kalang Fluvial Transition process zone as at June 2009
Potential factors influencing erosion distribution on Newry Island continued from above…

- Riparian vegetation distribution and condition is also dependant upon landuse with agricultural areas showing a marked decrease in overall riparian vegetation condition compared to non-agricultural areas (Figure 36). Areas of bank erosion correlate closely with riparian vegetation condition in this process zone. In addition, very little of the estuary bank is protected from impacts related to unmanaged stock access.

- Estuary usage is also divergent. The southern branch is some 600m shorter than the northern branch meaning that it may be preferentially used to access the middle reaches of the Kalang. In addition, the shellfish industry is concentrated in the southern branch which may also influence rates and effects of wave wash erosion.

Figure 36  Overall riparian vegetation condition in the Kalang Fluvial Transition process zone as at June 2009
In terms of erosion rates, an analysis of the location of the high bank at Bends 3 and 4 showed comparatively slow rates of migration over the last 60 years (mean erosion rates of 0.2 – 0.3 m yr⁻¹). A survey of the bank location after the 2009 floods showed that Bend 3 had eroded a maximum of 6.2m (representing a rate of 0.9 m yr⁻¹), and Bend 4 a maximum of 2.7m (0.4m yr⁻¹). The rate for Bend 3 is roughly analogous to the maximum rates recorded during the flood-dominated regime from 1942 to 1964.

Erosion sites of significance in this zone include (in order of severity);

SITE 22. Left bank at Bend 3: 580m of severe erosion affecting 0.15ha since 2002 and threatening farm related infrastructure such as a road access and fencing. The bank here consists of approximately 1-1.5m of sandy-loam over a consolidated clay sub-layer. The sublayer is more resistant to erosion creating a narrow bench below the vertical eroded bank face. Severe scouring followed by slab-type block failure was observed after the 2009 floods (Plates 10a, 10b, and 10c). The sub-water surface bank profile is less steep than the bank face and so the bank toe is probably also susceptible to constant pressure from boat and/or wind waves with fretting and undermining occurring during mid-tides.

SITE 23. Left bank at the narrow meander neck on Newry Island: 200m of moderate erosion semi-protected by a failing tyre wall (Plates 10d). Continuing erosion of this bank will eventually lead to a meander cutoff and creation of a mid-channel island with the loss of 6.2ha of grazing land. The bank is almost completely devoid of vegetation and is subject to ongoing disturbance from stock grazing (see Plate 10e).

SITE 24. Left Bank at Bend 4: 660m of severe erosion affecting 0.12ha since 2002. In contrast to Bend 3, the bank here is mostly composed of aged material with a high cohesive clay content (Plate 10f). As such the banks are more resistant to bank erosion and erosion rates during the 2009 floods were almost half those recorded at Bend 3. The sub-water bank profile is also quite shallow, reducing the period of potential impact of wave wash on the bank toe to higher tides.

SITE 25. Left bank upstream and opposite of Bellinger Quays: approximately 360m of severe erosion. This site has very poor vegetation cover and is subject to scour and slab-type block failure, possibly exacerbated by undermining by boat and/or wind wave wash.

SITE 26. Left bank immediately upstream of the Newry Island bridge: a 30m stretch of bank slumping and associated tree fall potentially threatens the stability of the upstream eastern bridge abutment.
Plate 10  Erosion in the Kalang Fluvial Transition process zone, clockwise from top: a) Site 22, severe bank erosion at Bend 1; b) Site 22, high tide bank profile; c) Site 22, low tide bank profile showing bench formed by the resistant lower bank layer; d) Failing tyre wall at Site 23; e) isthmus at Site 23, tyre works (obscured) are on photo right; and f) Old coastal deposits forming the eroded bank profile at Site 24.
**Kalang estuary - Marine Tidal Delta Process Zone**

Figure 37 shows the spatial distribution of bank erosion in the Marine Tidal Delta process zone of the Kalang. Eighty-one percent of this zone (4.3km) is stable with the remaining 19% of banks all considered to show signs of only minor erosion.

The reasons for the high proportion of stable banks in this zone include:

- As much of the estuary bank here abuts private property in the township of Urunga, there has been a high degree of focus on artificial stabilisation of the foreshore using rock revetment, rubble debris, timber walls, and concrete block walls. There is just under 1km of bank protection works in this zone. Entrance training walls also protect an additional 1.45km of bank bringing the total length of bank with artificial stabilisation methods to 46% of banks. However, due some failure of works, only 28% of stable
bank are considered stable due to works, with the remaining 18% showing signs of minor erosion despite the presence of protection works (see Plate 11b, page 77).

- 650m or 12% of banks are protected by bedrock outcropping, all of which occurs on the left bank upstream of the Back Creek confluence.
- This process zone is generally a low energy zone with the low grade and tidal influence generally moderating erosive processes. Tidal currents can produce high flow velocities, however the highest velocities are generally focussed along the sections of heavily armoured training wall.

Although some damage to the right bank downstream of the railway bridge was observed after the May 2009 flood, this area was quickly repaired with rock revetment, and so doesn’t appear as erosion in Figure 37. Consequently, there were no significant sites of bank erosion identified within this process zone.
6.2.3 Comparison of 1984 and 2009 Channel Erosion

Figure 38 shows a comparison of bank erosion location and severity for the period 1981 to 1984 and the results of the 2009 bank erosion survey. The 1981-84 dataset is as reported in Cameron McNamara (1984) and represents a combination of two datasets, the first being the bank condition assessment undertaken during the Lower Bellinger Waterway Study (PWD, 1983), the second being the field inspection undertaken by Cameron McNamara (1984).

![Comparison of 1981-84 and 2009 bank erosion](image)

**Figure 38** Comparison of active bank erosion in the Bellinger and Kalang River estuaries as at June 2009 with the approximate locations of bank erosion mapped in 1981-84 by Cameron McNamara (1984).

A comparison of the 1981-84 figures with data presented in Section 6.2.1 and 6.2.2 above is provided in Table 10. Although caution needs to be exercised due to the likelihood of differing methodologies and the qualitative nature of the various assessments, the data primarily shows that in the Bellinger estuary there has been a marked increase in minor bank
erosion and a moderate decrease in both moderate and severe bank erosion. In the Kalang, due to differing survey extents, comparisons are only possible in the Fluvial Transition zone around Newry Island and in the Marine Tidal Delta zone around Urunga. The data here again shows a marked increase in minor bank erosion, with a more significant decrease in both moderate and severe bank erosion.

The very large increase in minor bank erosion can be explained by the proximity of the 2009 survey period to the recent series of floods in February, March and May 2009. Minor bank erosion can be expected to naturally recover provided disturbance factors are not ongoing and many of these sites may recover naturally over a relatively short period once vegetation recolonises. Moderate and severe erosion sites, however, experience much slower rates of natural recovery so are a more useful indicator of bank stability of decadal timeframes. Although as explained caution should be exercised, this data infers that moderate and severe bank erosion is less of an issue in both estuaries than reported in the early 1980s.

**Table 10**  Comparison of 1981-84 and 2009 bank erosion data (1981-84 data sourced from Cameron McNamara, 1984)

<table>
<thead>
<tr>
<th>Estuary</th>
<th>Process Zone</th>
<th>Survey Period</th>
<th>Minor (km)</th>
<th>Moderate (km)</th>
<th>Severe (km)</th>
<th>Total (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bellinger</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Fluvial-dominated A</strong></td>
<td>1983-84</td>
<td>0.94</td>
<td>0.25</td>
<td>1.23</td>
<td>2.42</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2009</td>
<td>5.14</td>
<td>1.62</td>
<td>1.33</td>
<td>8.09</td>
</tr>
<tr>
<td></td>
<td>Change (km)</td>
<td></td>
<td>+5.2</td>
<td>+1.37</td>
<td>+0.1</td>
<td>+5.67</td>
</tr>
<tr>
<td></td>
<td><strong>Fluvial-dominated B</strong></td>
<td>1983-84</td>
<td>0.31</td>
<td>2.87</td>
<td>1.49</td>
<td>4.67</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2009</td>
<td>7.18</td>
<td>1.09</td>
<td>1.90</td>
<td>10.17</td>
</tr>
<tr>
<td></td>
<td>Change (km)</td>
<td></td>
<td>+6.87</td>
<td>-1.78</td>
<td>+0.41</td>
<td>+5.5</td>
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<tr>
<td></td>
<td><strong>Fluvial Transition</strong></td>
<td>1983-84</td>
<td>-</td>
<td>1.28</td>
<td>0.51</td>
<td>1.79</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2009</td>
<td>0.42</td>
<td>-</td>
<td>-</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>Change (km)</td>
<td></td>
<td>+0.42</td>
<td>-1.28</td>
<td>-0.51</td>
<td>-326%</td>
</tr>
<tr>
<td></td>
<td><strong>Marine-tidal delta</strong></td>
<td>1983-84</td>
<td>1.21</td>
<td>1.34</td>
<td>1.89</td>
<td>4.44</td>
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<tr>
<td></td>
<td></td>
<td>2009</td>
<td>6.75</td>
<td>2.06</td>
<td>0.35</td>
<td>9.05</td>
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<td></td>
<td>Change (km)</td>
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<td>+5.54</td>
<td>+0.72</td>
<td>-1.54</td>
<td>4.61</td>
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<td></td>
<td><strong>TOTAL</strong></td>
<td>1983-84</td>
<td>2.46</td>
<td>5.74</td>
<td>5.12</td>
<td>13.32</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2009</td>
<td>19.49</td>
<td>4.77</td>
<td>3.57</td>
<td>27.83</td>
</tr>
<tr>
<td></td>
<td>% Change</td>
<td></td>
<td>+792%</td>
<td>-17%</td>
<td>-30%</td>
<td>+209%</td>
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<tr>
<td><strong>Kalang</strong></td>
<td></td>
<td>1983-84</td>
<td>0.89</td>
<td>6.89</td>
<td>4.86</td>
<td>12.64</td>
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<tr>
<td></td>
<td></td>
<td>2009</td>
<td>4.93</td>
<td>1.83</td>
<td>1.72</td>
<td>8.48</td>
</tr>
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<td></td>
<td>Change (km)</td>
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<td>+4.04</td>
<td>-5.06</td>
<td>-3.14</td>
<td>-4.16</td>
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<tr>
<td></td>
<td><strong>Marine-tidal delta</strong></td>
<td>1983-84</td>
<td>0.40</td>
<td>-</td>
<td>-</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2009</td>
<td>1.03</td>
<td>-</td>
<td>-</td>
<td>1.03</td>
</tr>
<tr>
<td></td>
<td>Change (km)</td>
<td></td>
<td>+0.63</td>
<td>-</td>
<td>-</td>
<td>+0.63</td>
</tr>
<tr>
<td></td>
<td><strong>TOTAL</strong></td>
<td>1983-84</td>
<td>1.29</td>
<td>6.89</td>
<td>4.86</td>
<td>13.67</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2009</td>
<td>5.96</td>
<td>1.83</td>
<td>1.72</td>
<td>9.51</td>
</tr>
<tr>
<td></td>
<td>% Change</td>
<td></td>
<td>+462%</td>
<td>-73%</td>
<td>-65%</td>
<td>-30%</td>
</tr>
</tbody>
</table>

1 Comparisons in the Kalang River are limited to the Fluvial Transition and Marine-Tidal Delta Process Zones due to differing survey extents.
6.3 Riparian and Estuary-related Remnant Vegetation

6.3.1 Riparian vegetation condition

Riparian vegetation is an integral component of river and estuary bank stability. Although factors such as composition of banks, sedimentation patterns, channel slope, wave climate, and contribution of underlying processes (ie. fluvial and tidal) also impact bank stability, it is no surprise that there is often a close correlation between the condition of riparian vegetation and bank stability in NSW estuaries.

For this study, the assessment of riverbank (riparian) vegetation condition considered the following factors;

**Vegetation width**
Refers to the width of the riparian fringe (ie. the highest strata that could be expected for that vegetation community, for example there are obvious differences between a Saltmarsh community and a littoral rainforest).

**Vegetation structure**
Refers to the existence or otherwise of expected vegetation sub-strata (eg. canopy, shrub layer, ground layer, etc).

**Vegetation diversity**
Refers to what would be expected in a natural situation at that location, encompassing all structural layers.

**Integrity**
The presence and extent of environmental weed plants (the major weeds mapped were camphor laurel, small-leaved privet, bitou bush, maidera vine, cats claw creeper, white passion flower, and coastal morning glory)

Vegetation condition was mapped as relatively homogenous reaches with breaks in any of the recorded factors signalling a change in reach. Each factor was mapped on a scale of 1 to 5 with 1 indicating very poor and 5 indicating very good. These factors were then combined to form an overall riparian vegetation condition rating for the reach. A summary of the vegetation condition ratings for each estuary and component process zones is provided in Tables 11 and 12.

**Table 11** Overall condition of riparian vegetation in the Bellinger River estuary, June 2009.

<table>
<thead>
<tr>
<th>Estuary or Process Zone</th>
<th>Total length (km)</th>
<th>Not surveyed (km,%</th>
<th>Very Poor (km,%</th>
<th>Poor (km,%</th>
<th>Moderate (km,%</th>
<th>Good (km,%</th>
<th>Very Good (km,%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bellinger River</td>
<td>60.3</td>
<td>2.3 (4%)</td>
<td>10.9 (18%)</td>
<td>18.6 (31%)</td>
<td>21.1 (35%)</td>
<td>4.3 (7%)</td>
<td>3.1 (5%)</td>
</tr>
<tr>
<td>Fluvial-dominated A</td>
<td>12.8</td>
<td>0.3 (2%)</td>
<td>4.6 (36%)</td>
<td>5.2 (40%)</td>
<td>2.6 (20%)</td>
<td>0.2 (1%)</td>
<td>-</td>
</tr>
<tr>
<td>Fluvial-dominated B</td>
<td>15.5</td>
<td>0.6 (4%)</td>
<td>4.8 (31%)</td>
<td>5.8 (37%)</td>
<td>4.2 (27%)</td>
<td>0.1 (1%)</td>
<td>-</td>
</tr>
<tr>
<td>Fluvial Transition</td>
<td>15.5</td>
<td>-</td>
<td>0.7 (4%)</td>
<td>5.2 (34%)</td>
<td>6.5 (42%)</td>
<td>3.0 (20%)</td>
<td>-</td>
</tr>
<tr>
<td>Marine-tidal delta</td>
<td>16.5</td>
<td>1.4 (9%)</td>
<td>0.8 (5%)</td>
<td>2.4 (15%)</td>
<td>7.8 (47%)</td>
<td>0.9 (6%)</td>
<td>3.1 (19%)</td>
</tr>
</tbody>
</table>
Table 12  Overall condition of riparian vegetation in the Kalang River estuary, June 2009

<table>
<thead>
<tr>
<th>Estuary or Process Zone</th>
<th>Total length surveyed (km)</th>
<th>Not surveyed (km,%)</th>
<th>Very Poor (km,%)</th>
<th>Poor (km,%)</th>
<th>Moderate (km,%)</th>
<th>Good (km,%)</th>
<th>Very Good (km,%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kalang River</td>
<td>60.5</td>
<td>2.1 (4%)</td>
<td>7.3 (12%)</td>
<td>17.7 (29%)</td>
<td>17.3 (29%)</td>
<td>12.2 (20%)</td>
<td>3.8 (6%)</td>
</tr>
<tr>
<td>Fluvial-dominated A</td>
<td>16.7</td>
<td>0.5 (3%)</td>
<td>3.4 (21%)</td>
<td>4.0 (24%)</td>
<td>3.8 (23%)</td>
<td>3.1 (19%)</td>
<td>1.8 (11%)</td>
</tr>
<tr>
<td>Fluvial-dominated B</td>
<td>11.6</td>
<td>-</td>
<td>-</td>
<td>1.6 (14%)</td>
<td>2.0 (17%)</td>
<td>6.0 (52%)</td>
<td>2.0 (18%)</td>
</tr>
<tr>
<td>Fluvial Transition</td>
<td>26.9</td>
<td>0.8 (3%)</td>
<td>3.5 (13%)</td>
<td>9.7 (36%)</td>
<td>9.8 (37%)</td>
<td>3.0 (11%)</td>
<td>-</td>
</tr>
<tr>
<td>Marine-tidal delta</td>
<td>5.3</td>
<td>0.8 (15%)</td>
<td>0.3 (6%)</td>
<td>2.5 (47%)</td>
<td>1.7 (32%)</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

As is commonly the case, the more productive alluvial reaches of the estuary have a long history of intensive landuse development and associated clearing of riverbank areas. Not surprisingly, therefore, this pattern is repeated in the Bellinger and Kalang estuaries. Figure 39 shows that in the Bellinger estuary, the Fluvial Dominated A and B zones have both the worst riparian vegetation condition ratings and, with reference to Figure 25 on page 39, the most reaches described as being moderately or severely eroded. Similarly, in the Kalang estuary, the Fluvial Dominated A zone and the Fluvial Transition zone have the worst vegetation condition and erosion ratings.

It follows therefore that any attempt to improve the long-term stability of riverbanks must focus on improving riparian vegetation condition.
A comprehensive database of the vegetation condition ratings including the distribution of major environmental weed species has been provided to Bellingen Shire Council as a geographically linked database (in ArcGIS shapefile format).

### 6.3.2 Remnant Vegetation

Data on estuary-related remnant vegetation has been compiled from a variety of sources including:

- NSW DPI Fisheries Aquatic Habitats GIS data: used to derive an inferred distribution of Candidate Coastal Saltmarsh Endangered Ecological Community and Mangroves
- Comprehensive Regional assessment Air Photo Interpretation Project (CRAFTI) (DUAP, 1998): used to derive the inferred distribution of Candidate Swamp Sclerophyll Endangered Ecological Community
- 2009 field survey: used for the field mapping of potential riparian vegetation remnants. Riparian forest was mapped as a remnant where the vegetation was considered to be representative of the naturally occurring riparian vegetation at that location.

The distribution of estuary-related remnants in the study area and the relationship to areas of bank erosion are shown in Figure 40.

**Figure 40** Distribution of estuary-related remnant vegetation in the Bellinger - Kalang estuary study area.
In summary, the figure shows that;

- Almost without exception, the existence of remnant riparian forest is linked to the presence of bedrock outcropping on the channel margin. This means that remnant vegetation associated with the alluvial soils of the floodplain is very poorly represented.
- The Kalang estuary, with a significantly higher proportion of bedrock outcropping, and less floodplain and less associated agricultural development, had more remnant riparian forest than the Bellinger estuary.
- Mangrove communities are relatively widespread throughout the lower estuaries and are likely to be expanding. Saltmarsh, a threatened ecological community is more sporadic in its occurrence and mostly confined to Urunga lagoon and Urunga Island.
- Although not mapped as part of the field survey, Picket Hill Creek and Urunga Lagoon are likely to contain significant areas of mangroves and Coastal Saltmarsh and Swamp Sclerophyll Candidate EEC.

Although most remnants exist due to their inherent lack of suitability for landuse development (ie. either flood prone or steep bedrock landscapes), all are potentially threatened by weed invasion (particularly camphor laurel and small-leaved privet) and disturbances associated with landuse such as unmanaged stock access or drainage works. By comparing the location of remnants to the field data of bank erosion the following sites are considered to be of note;

**SITE 27.** Right bank lower Bellinger estuary: An area of supra-tidal flat containing the largest identified remnant of coastal saltmarsh in the study area is under threat from moderate erosion (see Site 12 above).

**SITE 28.** Right bank lower Kalang estuary: An area of candidate swamp sclerophyll forest EEC and a small area of coastal saltmarsh exist in this vicinity. There is presently no threat to these communities from erosion, however, they are located on the outside bend of the estuary and so may be vulnerable to future flood damage. These remnants have not been checked for condition or compatibility with respective EEC listings.
6.4  Estuary Bank Protection Works

6.4.1  Bank protection works - Bellinger Estuary

In total 8.93km of bank protection works were identified in the 60.3km of bank surveyed in the Bellinger River estuary. Table 13 provides information on the types of works used in each of the process zones and the estuary as a whole. The Marine Tidal Delta process zone had the greatest proportion of bank artificially stabilised (24%; see Figure 41). However, when entrance training walls are excluded from the equation (ie. 80% of the works undertaken in this zone), the Fluvial Transition process zone has the greatest proportion of banks stabilised with works (predominantly rock work on the northern bank adjacent to the old Pacific Highway; see Figure 30 in Section 6.2.1). The next highest proportion is found in the Fluvial Dominated A zone with 12% of banks protected by remedial works (Figure 42). The higher proportion of erosion control works in these two process zones infers that erosion has been more prevalent and/or perceived as more of an issue than in other process zones in the estuary.

Table 13  Type and extent of bank protection works in the Bellinger River estuary, June 2009

<table>
<thead>
<tr>
<th>Bank Protection Works Type</th>
<th>BELLINGER RIVER ESTUARY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fluvial Dominated A (12.8km)</td>
</tr>
<tr>
<td>Rock (km)</td>
<td>0.61</td>
</tr>
<tr>
<td>Rock &amp; Revegetation (km)</td>
<td>0.75</td>
</tr>
<tr>
<td>Concrete(^1) (km)</td>
<td></td>
</tr>
<tr>
<td>Gabions (km)</td>
<td></td>
</tr>
<tr>
<td>Logs (km)</td>
<td>0.03</td>
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<tr>
<td>Timber (km)</td>
<td></td>
</tr>
<tr>
<td>Root balls (km)</td>
<td></td>
</tr>
<tr>
<td>Tyres (km)</td>
<td></td>
</tr>
<tr>
<td>Revegetation &amp; Fencing (km)</td>
<td>0.06</td>
</tr>
<tr>
<td>Mixed(^2) (km)</td>
<td>0.13</td>
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<tr>
<td>Training Wall (km)</td>
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</tr>
<tr>
<td>TOTAL km (%)</td>
<td>1.59 (12%)</td>
</tr>
</tbody>
</table>

\(^1\) Includes concrete blocks, slabs, and walling

\(^2\) Includes mixed rubble, brick, timber, rock, and tyres.
Figure 41  Distribution and type of existing bank protection and remediation works in the Bellinger Marine Tidal Delta process zone as at June 2009.
6.4.2 Bank protection works - Kalang Estuary

In total 8.09km of bank protection works were identified in the 60.5km of bank surveyed in the Kalang River estuary. Table 14 provides information on the types of works used in each of the process zones and the estuary as a whole. The picture in the Kalang is similar to the Bellinger with the Marine Tidal Delta process zone having the greatest proportion of bank artificially stabilised (46%, or 18% when entrance training walls are excluded) followed by the Fluvial Transition process zone with 22% of banks stabilised with protection works. Figure 35 (page 59) shows that the majority of works in the fluvial transition zone are focussed around urban and rural residential development areas.
Table 14  Type and extent of bank protection works in the Kalang River estuary, June 2009

<table>
<thead>
<tr>
<th>Works Type</th>
<th>KALANG RIVER ESTUARY</th>
<th>Fluvial Dominated A (16.7km)</th>
<th>Fluvial Dominated B (11.6km)</th>
<th>Fluvial Transition (26.9km)</th>
<th>Marine-tidal Delta (5.3km)</th>
<th>Total Kalang Estuary (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock (km)</td>
<td></td>
<td>1.03</td>
<td>0.64</td>
<td></td>
<td></td>
<td>4.98</td>
</tr>
<tr>
<td>Rock &amp; Revegetation (km)</td>
<td></td>
<td>0.05</td>
<td></td>
<td></td>
<td></td>
<td>0.05</td>
</tr>
<tr>
<td>Concrete¹ (km)</td>
<td></td>
<td>0.06</td>
<td></td>
<td></td>
<td></td>
<td>0.06</td>
</tr>
<tr>
<td>Gabions (km)</td>
<td></td>
<td>0.03</td>
<td>0.03</td>
<td></td>
<td></td>
<td>0.06</td>
</tr>
<tr>
<td>Logs (km)</td>
<td></td>
<td>0.04</td>
<td></td>
<td></td>
<td></td>
<td>0.04</td>
</tr>
<tr>
<td>Timber (km)</td>
<td></td>
<td>0.12</td>
<td>0.05</td>
<td></td>
<td></td>
<td>0.17</td>
</tr>
<tr>
<td>Root balls (km)</td>
<td></td>
<td>0.18</td>
<td></td>
<td></td>
<td></td>
<td>0.18</td>
</tr>
<tr>
<td>Tyres (km)</td>
<td></td>
<td>0.34</td>
<td></td>
<td></td>
<td></td>
<td>0.34</td>
</tr>
<tr>
<td>Revegetation &amp; Fencing (km)</td>
<td></td>
<td>0.23</td>
<td>1.22</td>
<td></td>
<td></td>
<td>1.45</td>
</tr>
<tr>
<td>Mixed² (km)</td>
<td></td>
<td>0.02</td>
<td>2.32</td>
<td>0.26</td>
<td></td>
<td>2.6</td>
</tr>
<tr>
<td>Training Wall (km)</td>
<td></td>
<td></td>
<td></td>
<td>1.46</td>
<td></td>
<td>1.46</td>
</tr>
<tr>
<td>TOTAL km (%)</td>
<td></td>
<td>0.23 (&lt;0.1%)</td>
<td>0.02 (-%)</td>
<td>5.39 (22%)</td>
<td>2.45 (46%)</td>
<td>8.09 (13%)</td>
</tr>
</tbody>
</table>

¹ Includes concrete blocks, slabs, and walling
² Includes mixed rubble, brick, timber, rock, and tyres.

6.4.3 Effectiveness of bank protection works on the Bellinger - Kalang River estuaries

As can be seen from Tables 13 and 14, there has been a wide range of materials used in bank protection works in the Bellinger - Kalang River estuaries. Unfortunately this makes the objective assessment of the effectiveness of the different styles of bank protection works extremely difficult. For example a comparison of the effectiveness of rock revetment versus log walls versus dumped concrete would need to consider factors such as the goal of the works, the type of materials, workmanship, design, age of the works, individual geomorphic factors operating at a reach scale, and exposure to disturbance factors such as floods or wave wash. This scale of assessment was not possible for this study.

Nevertheless, a subjective assessment of the works based on a snap-shot survey has been undertaken. Table 15 provides a summary of the results of this survey. Effectiveness in this context is based upon the assumption that the aim of bank protection is limited to stabilising the bank, ignoring all other estuary management goals such as for example amenity and estuary health.
Table 15  Snap-shot survey of effectiveness of bank protection measures in the Bellinger and Kalang River estuaries.

<table>
<thead>
<tr>
<th>Effectiveness</th>
<th>Bellinger Estuary km (%)</th>
<th>Kalang Estuary km (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective</td>
<td>6.98 (87%)</td>
<td>6.71 (83%)</td>
</tr>
<tr>
<td>Partially effective or failed</td>
<td>1.06 (13%)</td>
<td>1.38 (17%)</td>
</tr>
</tbody>
</table>

The following observations of bank protection works within the study are also provided;

1. **Most bank protection works focus on bank stability only.**
   
   Most works in the estuary area are focussed on stability only and take little account of broader estuary goals (Plate 11a). The complex interactions between the estuary bank, the bank vegetation, water quality, and terrestrial and aquatic habitat are what make the estuary function ecologically and many industries such as oyster farming and tourism depend on a healthy estuary.
   
   Obviously where bank erosion threatens an important public asset such as a bridge, boat ramp, roadway, or other public facility, the focus of works is necessarily on asset protection and heavier engineering methods may be justified both in terms of public benefit and cost benefit. In these areas alternatives should be investigated that provide the maximum stability at the least cost to estuary health. Outside these areas the options for bank protection should equally consider estuary health and bank stability.

2. **The causes of partially effective and ineffective works.**
   
   Typical issues with partially effective and ineffective works include poor design, inappropriate use of materials, unsuitable materials, lack of maintenance, lack of vegetation, poor coordination of works between adjoining properties, and the lack of use of important materials which improve success rates such as geofabrics (Plate 11b and 11c).

3. **Bank protection works in urban and rural residential areas with foreshore frontage.**
   
   The most concentrated areas of bank protection works in the study area occur adjacent to urban and rural residential subdivision areas such as at Urunga, northern end of Newry Island, Bellingen Quays and at Raleigh. In these areas, residential lots front directly onto the estuary and landholders have in most cases undertaken a variety of works aimed at preventing erosion, protecting property, and in many cases facilitating river access. No formalised program exists to assist foreshore properties address erosion issues (except for speed controls on boating) and so landholders are left to use whatever limited resources are available to them to protect property. As a consequence, the works are ad hoc in nature and often poorly designed and maintained, or use inappropriate materials such as dumped bricks, old tyres, and concrete.

4. **Inappropriate materials**
   
   The following materials are generally inappropriate for use in bank protection works;
• Dumped building and construction wastes are unsightly and can be hazardous. Old bricks are easily removed by floods. Slabs of concrete can also be easily entrained by flood flows unless properly keyed together.
• Tyres are cheap to obtain but are also unsightly and may become a potential pollution risk if works fail.

Plate 11  Clockwise from top left a) Some methods of bank protection, whilst good for stability, ignore issues to do with estuary-bank connectivity, ecology, and flora and fauna; b) Partially failing mixed timber and rock works, lower Kalang estuary; c) Failing rock works that may have benefited from the use of geofabrics to reduce the removal of fines from behind the wall; and, d) Although vegetation has been damaged, the rock toe and mesh fence construction has generally held up well after the 2009 floods. This is partially due to the dense regeneration of vegetation on the site which acts to dissipate flow energy thus reducing erosion (Bellinger River adjacent to the golf course, Bellingen).

6.4.4  Best practice options for treatment of bank instability in estuaries

Over the last 12-15 years with the advent of government funded programs for land rehabilitation and conservation (eg. landcare, Natural Heritage Trust, Envirofund, Cooperative Research Centres, NSW Estuary Management Program, Catchment Management Authorities, etc), a great deal of research, effort and experimentation has been directed towards developing more effective and river health orientated methods for addressing bank

78.
erosion. In addition to developing assessment tools designed to assist responsible authorities to determine priorities for action, practical alternatives which encompass broader river health goals have also been demonstrated. In general, this means incorporating vegetation into works designs, using appropriate materials, and modifying the management of sites to minimise disturbances for example by reducing stock access or boating activities to allow natural regeneration to occur on river banks.

Importantly, prior to the construction of any works in any part of the estuary, it is crucial that the processes occurring at a site are correctly identified and understood. Many works fail as a result of poorly understood erosion processes or the failure to differentiate between symptoms and causes of erosion.

The following examples of alternative and “best-practice” techniques have proven to be effective in other estuary areas and have broad practical application in the Bellinger and Kalang estuaries.

**Example 1: Best-practice rock revetment.**

Rock revetment is a high cost treatment for bank protection which generally is most suitable for protecting expensive assets such as roads or bridge abutments. Traditionally, rock has been dumped or placed over the entire bank face. This method of treatment is generally unnecessary, provided the mid to upper banks are adequately revegetated, as the most common forms of bank erosion attack the bank toe resulting in undermining and subsequent removal of material from the bank (for example wave wash or scour during flooding).

Plate 12 illustrates the incorporation of vegetation into rock works which not only assists in binding the rock together with the roots but also provides resistance during floods, thus slowing down erosive energy. Geofabric (eg. Bidum) has been used under the rock which was placed by excavator. The geofabric prevents finer bank materials being washed from between the rocks thus preventing slumping (a common cause of failure with rocks works). Fencing has been used in both cases to minimise damage from stock grazing while the vegetation recovers.

**Example 2: Rock embayments and mangrove/river reed regeneration**

Plate 13 illustrates a technique of rock revetment that is designed to reduce the effect of waves on susceptible river banks. The technique also allows mangroves to recolonise the toe of the bank providing important habitat elements and maintaining riverbank-estuary connectivity.

Rock embayments are constructed to the height of the mean high tide and have openings at the downstream end of the rock wall to allow water to flow behind the structures and deposit mangrove and other seed and debris. They are most suitable in reaches of river where wave action is the primary source of undermining and where a suitable bench is available upon which to construct them. The cost is similar to standard rock revetment works and an excavator must be used to place the material.
Plate 12  Examples of best-practice rock revetment works clockwise from top left a) Clybucca Creek, Macleay Valley, NSW; b) Taylors Arm, Nambucca Valley, NSW; c) Bellinger River below the golf course, Bellingen; and, d) Bellinger River adjacent to the Butter Factory, Bellingen.

Plate 13  Examples of rock embayment works from left to right a) On the Macleay River, Rainbow Reach, Macleay Valley, NSW. Showing early river reed (Phragmites sp.) colonising; and, b) Rock embayment works showing mangrove colonisation after approximately 4 years, Manning River near Taree, NSW. Bank revegetation works also visible (Photo: Tim Elder, 2004).
Example 3: Fencing and natural regeneration

A low cost method of improving bank stability and estuary health is simply to manage stock access to allow natural regeneration to occur. Plate 14 shows an example of the suppression effects of stock grazing on mangroves at the toe of a susceptible bank. Fencing in such areas has an immediate effect on bank vegetation and mangrove growth and reduces the bank’s susceptibility to wave wash and other forms of erosion. Fencing of the estuary does not necessarily mean complete exclusion of stock but may be appropriate in cases where the timing, duration and intensity of grazing on the riverbank needs to be more effectively managed.

In the lower estuary, the weed issue becomes less prevalent and fencing to promote natural regeneration is thus a more viable option due to reduced weed control issues.

Plate 14  From left to right a) An example of an area that could benefit from more effective stock management. Note the pruned mangroves in the foreground; and, b) Fencing and revegetation at this site has been successful with plants now beginning to naturally regenerate along the bank toe, Kalang River, Urunga.

Example 4: Innovative approaches - Hardwood root ball revetment

Root ball revetment represents an experimental, soft engineering approach to bank revetment or direct bank protection. As hardwood has a limited lifespan in estuaries due to copra and other biological organisms, the technique must be integrated with the re-establishment of an effective riparian vegetation zone, to be successful in the long-term. The root balls are very effective at dissipating wave wash from both wind and boats in the mid to high tide range. The tangle of roots are also likely to be an effective trap for mangrove seed which combined with the reduced wave climate should result in mangrove recolonisation of the bank toe, further enhancing bank stability. An example of this form of treatment on the Kalang River is shown in Plate 15.
Plate 15  An example of root ball revetment on the Kalang River upstream of Urunga, from left to right a) Root balls with regenerating mangroves in the foreground; and, b) Same works showing revegetation and fencing behind the bank face.
6.5 Estuary Access Infrastructure

The brief for this erosion study requested that information be collected on the distribution and types of infrastructure used for accessing the Bellinger and Kalang River estuaries. The information was collected during the field survey in June 2009 and involved recording the type of infrastructure observed, the likely tenure, and the location using a handheld GPS unit. The results of the infrastructure survey are summarised in Table 16 with the geographical distribution shown in Figure 43. The positional accuracy of the locations of the identified structures and access points is estimated to be ± 40 m.

Of note, more than ¾ of the infrastructure recorded occurs in the Kalang estuary, most of which occurs in the vicinity of Urunga, Bellinger Quays, and the northern parts of Newry Island (Figure 43). Only 15 structures out of the 151 privately owned structures displayed a Department of Lands Licence number.

The two estuaries have a similar number of public facilities although the Kalang’s are more focussed on boating facilities while the Bellinger has more public access points and a public jetty and swimming enclosure at Mylestrom. The majority of commercial structures on the Kalang are related to Oyster operations. In both estuaries there was evidence of recent flood damage to a number of structures, most of which were privately owned. There was little evidence showing that structures had contributed to erosion at any particular site.

Table 16  Summary of estuary access infrastructure statistics for the Bellinger and Kalang estuaries.

<table>
<thead>
<tr>
<th>Ownership*</th>
<th>Infrastructure Type</th>
<th>Bellinger estuary</th>
<th>Kalang estuary</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Private</td>
<td>Access point</td>
<td>15</td>
<td>29</td>
<td>44</td>
</tr>
<tr>
<td></td>
<td>Boat facility</td>
<td>4</td>
<td>33</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>Jetty</td>
<td>9</td>
<td>40</td>
<td>49</td>
</tr>
<tr>
<td></td>
<td>Pontoon</td>
<td>1</td>
<td>13</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>Wharf</td>
<td>1</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Public</td>
<td>Access point</td>
<td>3</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Boat facility</td>
<td>1</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Jetty</td>
<td>1</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>Commercial</td>
<td>All types</td>
<td>3</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>Unknown</td>
<td>Wharf</td>
<td>-</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td>38</td>
<td>132</td>
<td>170</td>
</tr>
</tbody>
</table>

* Ownership details were inferred from site characteristics and adjacent land tenure and have not been checked against cadastral information or Dept Lands databases.

A geographic information database of the recorded infrastructure locations has been provided to Bellingen Shire Council (in ArcGIS shapefile format).
Figure 43  Distribution and type of existing estuary access infrastructure in the Bellinger - Kalang estuaries as at June 2009.
PART 3  RECOMMENDATIONS FOR MANAGEMENT OF BANK EROSION IN THE BELLINGER-KALANG ESTUARIES

7.0 Setting priorities for Erosion Management in estuarine systems

In many settled river catchments, there are more river management issues than there are resources available to resolve them. As a result, a system for setting priorities is necessary if the available resources are to be used as effectively as possible to improve overall estuary health.

From a purely river health perspective, protection of reaches in good condition through the removal of threatening processes, and appropriate rehabilitation and preventative actions in easily restored or high value reaches should be considered the highest priority. However, it is recognised that many of these reaches are on private land which, depending on circumstances, may limit the practical implementation of any management actions.

From the same perspective, undertaking rehabilitation works solely in reaches that are in poor condition should be avoided as such works are likely to have little effect on the overall health of the system, are likely to be high cost and high risk, and may take up valuable resources that may be better utilised preventing areas in good condition from becoming degraded.

Whilst, these principles form a logical framework for assisting the priority setting process, it is recognised that other factors such as social, economic, cultural, and political considerations also play influential roles in estuary management decisions. For example, the protection of important community assets such as roads and bridges is an obvious example of where social and economic considerations may override river health objectives.

Section 7.1 below outlines a series of general recommendations for management of erosion in the Bellinger and Kalang River estuary systems. These recommendations apply to the management of erosion of the estuary systems as a whole. In terms of priority sites for remediation, Section 7.2 recommendations priority ranking for all 28 of the sites identified as having significant erosion in the process zone analyses. Outside of these 28 sites, all remaining reaches of erosion recorded in the 2009 field survey are considered to be low priority for management action. It is recommended that the priorities be reviewed periodically. For instance, flood events, changes to estuary use, or the construction of new public infrastructure adjacent to the estuary may result in a reassessment of the priorities presented below.

7.1 General recommendations for erosion management

The following general principles for erosion management are recommended for the Bellinger and Kalang River estuaries;

1. Protect existing public infrastructure: Roads and bridges are particularly at risk from damage during flood events. Within the Bellinger-Kalang study area, bank erosion has been recorded as a primary risk factor to public infrastructure at four sites. Actions to
remediate erosion in these areas can save many thousands of dollars of damage and can
generally be considered to have a high benefit to cost ratio.
2. Protect important conservation values. Coastal saltmarsh EEC, swamp sclerophyll forest
ECC, mangrove communities, and remnant riparian forests are just some of the high value
ecosystems that occur on estuaries on the North Coast of NSW. With the exception of
mangrove forests, the distribution of many vegetation communities has been significantly
reduced over the past 150 years (see Section 2.0). Protection of any remaining remnants
should therefore be a priority for erosion management.
3. Protect existing works: There are some 17km of estuary bank protection works in the
study area representing a huge investment of effort and resources. Three sites have been
identified in the study area where existing works have been damaged by recent flooding.
In one site, the consequence of failure of the works is a likely meander neck cutoff and the
subsequent creation of a 6.2ha island in the lower Kalang River (Site 23). Other sites such
as at the Bellingen Golf Course require minor maintenance works to assist the ongoing
rehabilitation of the sites.
4. Utilise best-practice erosion control techniques: this includes using appropriate materials,
incorporating estuary health goals, and re-establishing native riparian vegetation.
Examples of best-practice techniques are provided in Section 6.4.4 of this report.
5. Improve riparian vegetation: There is a high correlation between the presence/absence of
structurally diverse native riparian vegetation and absence/presence of bank erosion (see
Section 6.3.1). This suggests that in order to decrease erosion rates in the estuary it will be
necessary to improve the condition of riparian vegetation. Removing disturbance factors
such as unmanaged stock access and controlling invasive environmental weeds (such as
Camphor laurel, small-leaved privet, cats-claw creeper, madiera vine, and white passion
flower) can assist natural regeneration. However, considerable effort is required to
achieve long-term success and follow-up maintenance is essential. The locations of
reaches of riparian vegetation in good and very good condition are shown in Figure 39
(p.69). Incentive funding for landholders could be targeted towards these areas to ensure
that they remain in good condition. Planning controls may also assist in this regard.
6. Manage recreational boat use: There are a plethora of signs indicating boat speed limits
in areas deemed susceptible to boat wash erosion in the lower reaches of the estuary.
Despite this, there are still areas which are being impacted by boat wave wash. In
particular, the southern branch of the Kalang around Newry Island and Back Creek are
impacted. In other areas, the contribution of wind waves versus boat wave wash is less
certain but boat wash is still likely to be a contributory factor. Bellinger Council has
recently (late 2009) initiated a Recreational Boating Use survey (engaging Jetty Research
of Coffs Harbour), which will provide important data to assist in addressing this issue.

7.2 Specific recommendations for erosion management
In accordance with the general principles recommended for management of erosion in the
Bellinger and Kalang River estuaries (as outlined above), Highest Priority sites are those that
threaten existing community infrastructure or property, or high value ecological systems
including riparian and remnant vegetation. High priority sites include those sites where bank
protection measures have already been implemented but where flooding or other identified
factors are threatening the works and future stability of the banks. Moderate Priority sites are
those where erosion is considered to be serious but where significant and ongoing
commitment is required by both landholders and responsible government agencies and funding bodies. Many moderate priority sites have very poor riparian vegetation and ongoing disturbance factors such as wind or boat wave wash or impacts from unmanaged stock access. These factors would need to be addressed in any erosion mitigation strategy to justify expending resources on these sites.

Figure 44 shows the location of priority sites for erosion management within the study area (Highest priority sites indicated in red, moderate priority in blue, and lower priority in black).

**Figure 44** Location of priority sites for erosion management in the Bellinger-Kalang River estuaries as at June 2009.

**Bellinger River estuary sites**

The analysis of erosion in the Bellinger River estuary identified twelve sites of erosion significance of which two are considered to be highest priority for remedial action (Table 17).
**Table 17  Recommended priorities for management of significant erosion in the Bellinger River estuary.**

<table>
<thead>
<tr>
<th>Priority</th>
<th>Site</th>
<th>Justification</th>
<th>Page reference*</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIGHEST</td>
<td>10</td>
<td>Continued erosion may eventually threaten Yellow Rock Road. The primary cause of erosion here is most likely to be wave wash causing undermining and subsequent bank collapse.</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>12/27</td>
<td>Continued erosion at the downstream end of this Site 12 is threatening Candidate Coastal Saltmarsh EEC at Site 27. Ongoing disturbances associated with wave wash (primarily wind generated) and unmanaged stock access require management.</td>
<td>51/71</td>
</tr>
<tr>
<td>HIGH</td>
<td>2</td>
<td>Flood damage to existing bank protection measures threatens the loss of a small alluvial flat.</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Flood damage to existing protection works adjacent to the Bellingen Golf Club. The majority of works have survived the 2009 floods well, however, revegetation and weed control and some repair of mesh fencing on the site may assist in reducing scour at the site and on the adjacent golf course.</td>
<td>43</td>
</tr>
<tr>
<td>MODERATE</td>
<td>1</td>
<td>All adjacent sites listed here as Moderate Priority are in agricultural landscapes and would require a significant commitment from landholders, responsible government agencies, and funding bodies to actively remediate. All sites except Site 9 (which had fencing on the top bank) are subject to stock impacts with sites 7 and 11 also affected by wave wash.</td>
<td>43, 43, 44, 44, 45, 45, 50</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>11</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Further detail on individual sites and processes can be found in the main body of the report at the listed page reference.

**Kalang River estuary sites**

The analysis of erosion in the Kalang River estuary identified sixteen sites of erosion significance, three of which are considered to require immediate attention (Table 18).

**Table 18  Recommended priorities for management of significant erosion in the Kalang River estuary.**

<table>
<thead>
<tr>
<th>Priority</th>
<th>Site</th>
<th>Justification</th>
<th>Page reference*</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIGHEST</td>
<td>16</td>
<td>Erosion at this site has undermined a section of Martels Road. The deep water profile limits potential bank stabilisation methods. Further site investigation is recommended to determine appropriate methods of stabilisation and approximate costs.</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>21</td>
<td>Erosion at this site has undermined a section of South Arm Road. The deep water profile limits potential bank stabilisation methods. Further site investigation is recommended to determine appropriate methods of stabilisation and approximate costs.</td>
<td>57</td>
</tr>
<tr>
<td></td>
<td>26</td>
<td>Erosion on the left bank (Pacific Highway side) upstream of the Newry Island bridge may threaten upstream eastern bridge abutment if not treated.</td>
<td>61</td>
</tr>
</tbody>
</table>

88.
<table>
<thead>
<tr>
<th>Priority</th>
<th>Site</th>
<th>Justification</th>
<th>Page reference*</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIGH</td>
<td>17</td>
<td>Flood damage to an existing riparian revegetation project should receive priority assistance to ensure the success of the works. Landholder commitment has already been demonstrated.</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>23</td>
<td>A tyre wall in this location has contributed in part to the stability of this site, however, the wall is in a poor state of repair and is being progressively undermined. Works here should aim to stabilise the banks using best practice techniques, although the deep water profile adjacent to the site will complicate and increase the costs of construction. Remove of disturbance factors such as unmanaged stock access and wave wash (primarily from boats in this location) will also be important factors in long-term stability.</td>
<td>61</td>
</tr>
<tr>
<td>MODERATE</td>
<td>13</td>
<td>All adjacent sites listed here as Moderate Priority are in agricultural landscapes and would require a significant commitment from landholders, responsible government agencies, and funding bodies to actively remediate. All sites except Site 20 are subject to stock impacts with sites 22, 23, 24 and 25 also affected by wave wash.</td>
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<td>20</td>
<td>Sites 24 and 25 may be suitable for rock embayment construction due to their relatively shallow water profiles and proximity to the lower estuary and therefore mangrove seed sources.</td>
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<td>28</td>
<td>This site covers two separate remnant vegetation communities which occur on outside bends in the lower Kalang estuary opposite Newry Island. The condition of the remnants has not been established and erosion is not currently occurring adjacent to the remnants. Further assessment and monitoring is recommended.</td>
<td>71</td>
</tr>
</tbody>
</table>

* Further detail on individual sites and processes can be found in the main body of the report at the listed page reference.
References


Hodgkinson, C., 1844. Port Macquarie to Moreton Bay, with descriptions of the natives, their manner and customs. T. and W. Boone, 1-70.


NSW DPI Fisheries. 2006. Aquatic Habitats - GIS Dataset.


Field Survey GIS Datasets provided to Bellingen Shire Council

The following datasets were collected as a result of this study. All datasets were created in ArcGIS shapefile format (Projection: MGA94 Zone 56). Contact Bellingen Shire Council for access enquiries.

Bank Erosion
This dataset contains a line shapefile indicating assessed condition of riverbanks on the Bellinger and Kalang River Estuaries. Classification of severity is on a scale of 0-3, “0” indicating no erosion, “1” minor erosion, “2” moderate erosion, and “3” severe erosion.

Bank Protection Works
This dataset contains a line shapefile of locations of erosion protection works in the Bellinger and Kalang River Estuaries. General works type information is included as well as a limited assessment of effectiveness at the time of survey.

Bedrock outcrops
This dataset contains a line shapefile of locations of bedrock outcrops in riverbanks in the Bellinger and Kalang River Estuaries.

Bellinger-Kalang River Estuary Outline
This dataset contains a polyline shapefile of the Bellinger and Kalang Estuaries’ waterway boundary, onscreen digitised at 1:5000 from the 2006-2008 Quickbird 4 satellite imagery.

Bellinger-Kalang River Estuary Polygon
This dataset contains a polygon shapefile of the Bellinger and Kalang Estuaries’ waterway boundary, onscreen digitised at 1:5000 from the 2006-2008 Quickbird 4 satellite imagery.

Bellinger-Kalang Estuary Process Zones
This dataset contains a polygon shapefile indicating process zones of the Bellinger and Kalang River Estuaries. Process zones have been delineated using broad geomorphic criteria. The process zones are intended to be used to assist management by providing a framework to understand the physical character and behaviour of different reaches of the estuary.

Estuary Access Infrastructure
This dataset contains point locations of all identified public and private access points in the Bellinger and Kalang River Estuaries. Access points are grouped into general type of access and associated structure if any.

Riparian Vegetation Condition
This dataset contains a line shapefile indicating assessed condition of riparian vegetation on the Bellinger and Kalang River Estuaries. Vegetation width, structure, integrity and diversity were rated (1-5 indicating a scale of very poor to very good) and combined to give an overall vegetation condition rating (1-5 indicating a scale of very poor to very good condition). The presence of major environmental weeds was also recorded with the level of infestation on a scale of 1 (low) to 3 (dominant) noted.
Appendix 2 - Photogrammetry Cross-sections 1942-2009

XS1

XS2

XS3

XS4

XS5

XS6

BEND 1
Appendix 2 - Photogrammetry Cross-sections 1942-2009

BEND 2
Appendix 2 - Photogrammetry Cross-sections 1942-2009

BEND 3

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Appendix 2 - Photogrammetry Cross-sections 1942-2009

XS16

XS17

XS18

XS19

XS20

XS21

XS22

BEND 4
Appendix 2 - Photogrammetry Cross-sections 1942-2009

BEND 7
Appendix 2 - Photogrammetry Cross-sections 1942-2009

BEND 8