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CAUSEWAYS IN ESTUARIES: THEIR IMPACTS AND PROCEDURES FOR ENVIRONMENTAL PROTECTION

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ABSTRACT

1 Causeway crossings of estuaries have the potential to alter estuarine hydrodynamics. Reduced current velocities can increase siltation, and increased velocities can result in scouring. Tidal flushing of estuaries can also be affected, and this can markedly alter water salinities and stratification. Ecological impacts can involve changes in the distributions of estuarine animals and plants. Reduced tidal flushing may encourage eutrophication, and algal growth can be stimulated.

2 Using topographical maps 164 causeways were identified in New Zealand estuaries.

3 From analysis of aerial photographs a wide range of impacts were found in New Zealand estuaries, although there are many causeways which have had no obvious impact. Overall, causeways seem to have had little effect on saltmarsh vegetation or mangroves. There are several cases which demonstrate the problems which can arise when tidal flows are forced through very constricted openings; culverts have not been placed appropriately to maintain circulation and flow patterns; and where causeways trap large sediment inputs from catchments. In a few cases estuaries have been substantially altered or lost.

4 The relative merits and limitations of the different computational methods which can be used to assess hydrological impacts of proposed causeways are presented. Specific considerations regarding habitat, fisheries, birdlife, water quality, and construction activity are discussed.

1 INTRODUCTION

1.1 What are causeways?

Causeways are embanked carriageways, for pedestrian, road or rail transport, constructed across water or wetlands. Along the New Zealand coastline causeways are found in estuaries, where tidal areas are usually traversed by a length of causeway with a relatively short bridge spanning the main channel. Alternatively, or in addition to a bridge, culverts or pipes through the causeway are used to increase tidal water exchange. Causeways are generally built to shorten travel distances around a shoreline, and are often used to reduce the length of bridging necessary to cross a waterway.

1.2 Report outline

Despite the fact that causeways can have substantial effects on estuaries, the extent and nature of the impact of causeways on New Zealand estuaries has not been comprehensively documented. Criteria guiding causeway design have mainly aimed at maintaining some tidal flushing and, especially where freshwater runoff is significant, providing adequate bridging or culverting to allow flood waters to escape. Until recently, protection of estuarine ecosystems has not been an important concern in causeway siting or design.

In this report the overseas and New Zealand literature detailing causeway impacts is reviewed. Topographic map and aerial photograph analyses are used to gauge the extent and nature of the impact of causeways on New Zealand estuaries, and practical considerations for minimising impacts are offered.

1.3 Literature review

1.3.1 Physical impacts

Overseas studies have documented a range of causeway impacts. Several of these have dealt with descriptions of physical effects. For example, Xianze et al. (1988) reported major increases in siltation rates as a result of hindered tidal currents, and scouring from culvert flows, associated with a causeway in China. Similarly, rapid siltation was observed on the seaward side of a causeway in the Petitcodiac River estuary, New Brunswick (Galay 1983). Bray et al. (1982) found that the problems associated with the 21 km long causeway in the Petitcodiac River estuary included major geomorphological changes, annual changes in bed level near the causeway, beach formation upstream of the structure and net upstream sediment transport. Removal of a causeway, from the Sheepscot River estuary on the coast of Maine, was reported by McAlice and Jaeger (1983) to have increased tidal flows by almost 50%, and this was accompanied by substantial decreases in salinity stratification and increases in the strength of gravitational circulation. Goodwin (1987) modelled the hydrodynamics of Tampa Bay, Florida. He concluded that extensive physical changes due to the construction of causeways, islands, channels and shoreline fill had resulted in altered circulation patterns, a reduction of 6% in the amount of water entering the bay, but increased circulation and more rapid flushing of contaminants in some places.

1.3.2 Ecological impacts

Mulvihill et al. (1980) concluded in their major review of the impacts of shoreline structures in the United States of America, that causeways were among those structures which have the most potential for impact. Visel et al. (1989) found that a railway causeway across a river in Connecticut had reduced the river width and restricted tidal flushing and, as a result of increased siltation and decreased salinities, a local oyster fishery had been threatened. Roman et al. (1984) reported changes in the saltmarsh vegetation in six Connecticut estuaries as a result of causeways and dykes restricting normal tidal flushing. Reduction in soil water salinity, lowering of the water table and a relative drop in marsh surface elevation had lead to the establishment of less salt-tolerant vegetation. At Windsor in Nova Scotia, a causeway-induced mudflat was shown to contain finer sediment and have different benthic community structure compared with adjacent tidal flats unaffected by the causeway (Turk et al. 1980). In Ireland, the spread of cord grass (*Spartina anglica*) has been hastened in estuaries with causeways, and this is thought to have affected all birdlife which is dependent on mudflat feeding (Nairn 1986).

Buttermore (1977) described a small lagoon, east of Hobart, which had been cut off from a larger body of tidal water by a causeway. The combined effects of limited tidal exchange and a sewage discharge had accelerated eutrophication and had resulted in noxious odours from the decomposing algal mats. Stimulation of algal growth in a small estuary north of Dublin affected by a causeway was described by Fahy et al. (1975), who concluded that further spread of the algal mats would be damaging to wildfowl.

In Tonga construction of causeways without any provision for water circulation has been identified as a chronic hazard (Chester 1984). Large solid fill coastal causeways associated with the oil and gas industry occurring off the Alaskan coastline have altered nearshore circulation, coastal geomorphology, and sediment transport, and have impacted on the nearshore fish habitat (e.g., Craig and Griffiths 1981, Robilliard and Colonell 1983, Levings 1985, Hale et al. 1989).

1.3.3 Causeway impacts in New Zealand

Many estuaries in New Zealand have causeway crossings, and there are some notable examples around the country of where, arguably, causeways have caused detrimental environmental impacts on estuaries. Despite this, there is little historical bathymetric, biological or water quality data against which to evaluate the impacts in a quantitative manner, and there have been very few studies of the impacts of causeways on New Zealand estuaries.

Knox and Kilner (1973) described conditions in McCormack's Bay which is separated from the rest of the Avon-Heathcote Estuary by a causeway. A mole across the middle of the bay also reduces tidal flushing and the bay is modified further by a substantial reclamation. The reduced flushing and impoundment of water in part of the bay has caused bottom muds to become anoxic, killing marine life, and dense algal growths have become a problem.

In Napier's Ahuriri Estuary, a causeway constructed between Westshore Lagoon and North Pond has resulted in the two water bodies developing distinctly different salinity and algal growth characteristics, and habitats. In this case the habitat changes are generally regarded as being beneficial, in that they now provide contrasting habitats for wildlife (AETC 1979). A more recent study of the Ahuriri Estuary (Hume et al. 1990) demonstrated that, despite popular belief and assertions to the contrary, construction of bridge and causeway crossings had not increased sedimentation, nor contributed to formation of large shoals and islands in the Outfall Channel. These features were, in fact, relics of the original estuary which had been raised about 2 m by an earthquake in 1931.

In Tauranga Harbour, numerical hydrodynamic and sediment transport models were used to predict the effects of a major harbour bridge and causeway in the estuary (Barnett 1985). Various options of bridge/causeway length and alignments were tested to design a structure that would minimise the impact on current patterns and velocities, and avoid scouring and sedimentation. Although the bridge and causeway has been completed, no attempt has been made to verify the model predictions.

Hume and Roper (1986) reported the effects of the construction in 1964 of a causeway for emergency access to Auckland airport at the entrance to Pukaki Creek, in Manukau Harbour. This causeway decreased the channel width from 370 to 90 m, and reduced the creek entrance cross-sectional area by about 45%. It produced sediment build-up in the immediate vicinity of the structure, and could also have temporarily affected tidal flushing, until the entrance scoured to larger dimensions. However, the authors found that it was difficult to attribute the reported general deterioration in water quality and siltation, and expansion of mangroves in the creek to the causeway alone, because these effects could also have resulted from catchment urbanisation and airport reclamations.

Hume (1991) described changes in channel morphology and hydraulics resulting from 6 causeways in estuaries in the Auckland region. In one case, a causeway was constructed in 1952 across an embayment at Waterview Inlet in the Waitemata Harbour, for Auckland's northwestern motorway (see Fig. 3.6). This resulted in a substantial (96%) reduction in the embayment entrance width from 1400 m to 60 m, and the causeway also sheltered the embayment from wave action. The new outlet channel was initially deepened by dredging and additional, but very limited, tidal exchange was achieved by directing flow through several small culverts in the causeway. Since causeway construction, very deep (5 m) scour holes developed at both the upstream and downstream bridge channel approaches, because the dredged channel's cross section was too small to accommodate tidal flows. The scouring continued for about 15 years until the bed stabilised.

1.3.4 Summary

Commonly, physical impacts arising from causeways are associated with changes in hydrodynamics. Water velocities can be increased where flows are forced through narrow bridge or culvert openings, or decreased where backwaters are created. Where current velocities are reduced, siltation can increase, and conversely increased velocities can result in scouring. Tidal flushing of estuaries can both increase or decrease, depending on the situation, and this can markedly alter water salinities and stratification.

Ecological impacts commonly involve changes in the distributions of estuarine animals and plants, and arise as a result of changes in sediment type, tidal ranges, and salinity. Reduced tidal flushing also encourages eutrophication, and algal growth can be stimulated. This in turn can cause a public nuisance as algal mats decompose, and estuarine organisms, especially wildlife, can be affected.

While it is clear that causeways can have profound effects on estuaries, it is difficult to obtain a comprehensive overview of impact because case studies tend to be restricted to situations where impacts have obviously occurred. It is also very difficult to separate impacts resulting from causeways from those due to other factors. For instance, changes in habitat, sediments becoming muddier, increased sedimentation rates, and deterioration in water quality can all result from general catchment development as well as from causeway construction.

2 CAUSEWAYS IN NEW ZEALAND ESTUARIES

2.1 Survey method

To provide some basic statistics on estuarine causeways in New Zealand, a survey was carried out using topographical maps (NZMS 260 series, 1:50,000 scale). For each causeway a note was made of its location, map reference, structure (i.e., whether it contains culverts or bridge), its purpose (i.e., whether for road, rail or pedestrian transport), the length of the total structure (and length of bridging), and the upstream length of impounded estuary. After an initial examination of all causeways it was possible to categorise them into one of three main types (Fig. 2.1). Full details are presented in Appendix 1.

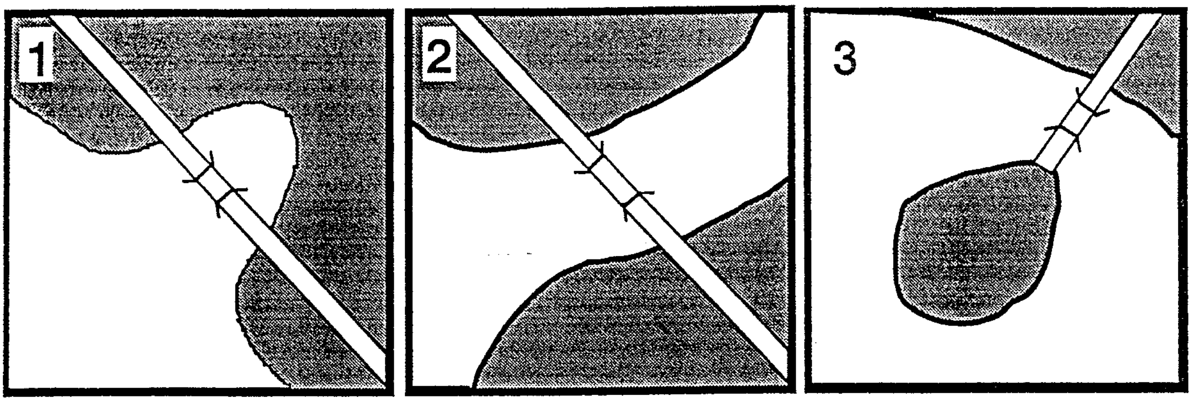


Figure 2.1: Types of causeways. 1. *Embayment* - where the causeway cuts off a small tidal embayment or creek, usually in the headwaters of an estuary, or along the margin of an indented shoreline (e.g., Fig. 3.13). 2. *Channel* - where the causeway crosses a major tidal arm or important flow path of an estuary or the main channel of a tidally influenced river (e.g., Fig. 3.2). 3. *Island* - where the causeway runs between the shore and an island in an estuary (e.g., Fig. 3.5).

2.2 Causeway Inventory

A total of 164 causeways were found in estuaries around the coastline of the North and South Islands, and islands in the Hauraki Gulf (Appendix 1). However, because the scale of mapping does not permit small features to be shown, this count is undoubtedly conservative.

Most causeways occur in the North Island (72%), and throughout the country they are concentrated around the northern half of the North Island, the north of the South Island, and in Southland and Otago (Fig. 2.2). Causeways are concentrated in those areas which have the most estuaries and a larger network of roads about the coast. The estuaries with the most causeways are in the South Island, being Moutere (10) and Whanganui (16).

Causeways have been constructed to serve as carriageways for road (143), rail (21), road/rail combinations (3), and pedestrian traffic (1). They are commonly several hundred metres long, and the longest structure (the main trunk railway causeway in Hobson Bay, Auckland) is 2100 metres.

The most common type of causeway crossing is the embayment type (76%). These mostly result from road straightening along the margins of estuaries. Crossings of the main flow tidal path make up about 17%, and island types 7%.

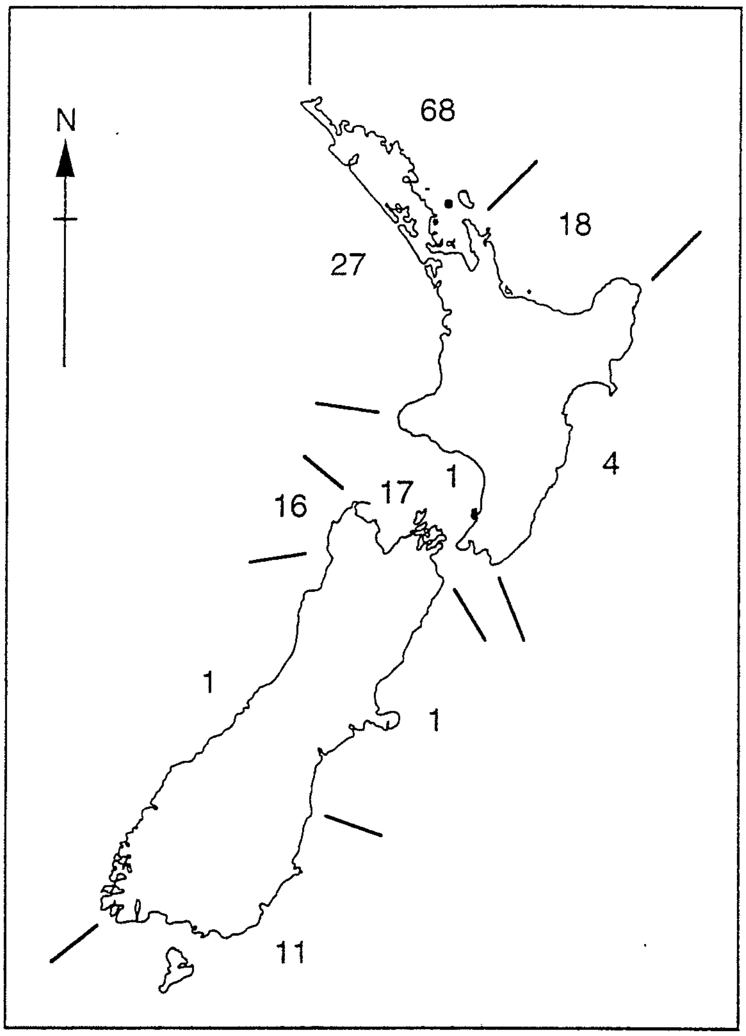


Fig. 2.2 The distribution of estuarine causeways around New Zealand

3 SURVEY OF CAUSEWAY IMPACTS

3.1 Survey method

Historical air photos were analysed to identify the range of impacts associated with causeways in New Zealand estuaries. This also gave some insight into the possible causes of impacts. Forty estuary causeways were selected for detailed examination from the list of sites given in Appendix 1, plus two sites where the estuary had been completely lost following construction of causeways. This selection was made to give wide geographic coverage and represent a range of estuary and causeway types, but was also influenced by availability of photographs. An attempt was made to find the earliest and most recent photos of a site, and where relevant, photos taken in the intervening years were also studied. Photos covering a period of about 40 years were usually available. Details of the aerial photographs used in the analysis are listed in Appendix 2.

The key features which were studied in the photos were the positions of channels, shoals and tidal flats, and type and coverage of vegetation. Vegetation in particular provides a sensitive indicator of estuarine conditions as the zonation of estuarine plants depends on sediment type, tidal inundation, salinity and water levels. Interpretation also had to allow for sun-angle and state-of-tide, both of which can alter the appearance of channels and shoals. In some cases the authors' personal knowledge allowed additional interpretation (e.g., regarding water quality and algal growth problems) to be made. While physical and habitat changes could be recorded from photographs it was not possible to assess the impact that causeways may have had on birdlife, through disturbance.

3.2 Site Descriptions and Causeway Impacts

This section presents a description of each of the sites followed by a discussion of the range of impacts observed and possible causes. Aerial photos of 14 of the 40 sites are reproduced at the end of this section.

Ryder Rd, Taipa (Fig. 3.1)
1948-1984: A causeway and short (20 m) bridge cross the mouth of Ryders Creek, a tributary of the tidal Taipa River. Mangroves have become established adjacent and parallel to the causeway. Mangroves in the area of the causeway have become denser and their aerial coverage has increased, but this has also occurred in parts of the Taipa River estuary well away from the causeway. A bridge spans the main channel, which has remained stable.

SH10, Taipa (Fig. 3.2)
1948-1984: A 350 m long roading causeway (bridge 100 m) crosses the main channel and intertidal area of the tidal Taipa River estuary. Interpreting the impacts of causeway construction is made difficult by the fact that the causeway and bridge were already constructed prior to the first aerial photo coverage in 1948. Since this time mangroves have colonised the area southeast of the causeway, but mangroves in the general area, well away from the causeway, have also increased.

SH10 & Kohumaru Rd, Mangonui
1948-1981: Roading causeways, about 500 m long, cut across the channel and mangrove covered intertidal areas near Paewhenua Island. To the south a 200 m long causeway cuts off a small embayment along the shores of Oruaiti Creek. Since causeway construction there has been little change overall. Mangroves have become more dense, but this has also occurred over the whole area. There have been no changes in the patterns of drainage channels in the estuary.

Otaika (1) & (2), Whangarei Hr (Fig. 3.3)
1942-1982: Two very long stretches (400 and 1100 m) of causeway for rail with relatively small stretches of bridge (150 m), cut off mangroved embayments in the upper Whangarei Harbour. The only changes associated with this major structure are a slight increase in the density of mangroves, especially along the flanks of the causeway. Drainage channels and overall coverage of mangroves have remained virtually identical over a forty year period.

Broadlands Dr, Whangateau Hr (Fig. 3.4)
1953-1982: An 800 m long roading causeway (bridge 100 m) crosses the main channel and sandy intertidal area of the southern arm of Whangateau Harbour. Construction of a major causeway and bridge has not altered channel position, but has resulted in scouring in the immediate vicinity of the bridge. It is possible this scouring and the associated changes in sedimentation have caused the loss of saltmarsh vegetation within about 500 m either side of the structure.

Herald Island, Waitemata Hr (Fig. 3.5)
1950-1988: A 350 m long causeway crosses muddy tidal flats to Herald Island in the upper Waitemata Harbour. Limited tidal exchange is achieved through the structure using culverts. Construction of the causeway has caused little overall change. Mangroves in the general area are slightly denser and have grown in narrow bands flanking the causeway. The small changes in mangroves have occurred away from the causeway as well as close too it. There is no perceivable change in channel morphology or sedimentation visible from the aerial photographs.

Whau River, Waitemata Hr
1940-1988: A 500 m long roading causeway (bridge 100 m) crosses the main channel and sandy intertidal area of Whau Inlet. Overall there has been little effect. Mangroves have grown adjacent to the flanks of the causeway, but there have been no obvious changes in the mangroves or wetland vegetation elsewhere.

Waterview Inlet (1) & (2), Waitemata Hr (Fig. 3.6)
1940-1988: Two stretches (200 and 1400 m) of causeway, part of Auckland's northwestern motorway, cut off mangroved embayments in the upper Waitemata Harbour. Despite construction of a major causeway, with only very limited bridging and culverting for tidal exchange; there has been little overall impact, and the inlet appears to be very stable. Mangroves have spread slightly and minor changes have occurred to the small drainage channels at the western headwaters end of the inlet. There are no major changes in the configuration of shell banks or channels, however, major scouring has occurred at the eastern-most opening, extending some 350 m beyond the causeway. (Refer Section 1: Causeway impacts - New Zealand).

Railway & Tamaki Dr, Waitemata Hr
1940-1987: Here the longest causeway system in New Zealand cuts across the intertidal mud flats of Hobson Bay. The outer road causeway now cuts off Judges Bay (550 m) and Hobson Bay (1400 m) from Waitemata Harbour. Long railway causeways (2100 & 700 m) bisect Hobson Bay. Interpretation of impacts is limited as the earliest photos were taken after major constructions had already occurred. The only obvious change since then is a slight increase in mangroves in the headwaters in the southwest of Hobson Bay, although this could have been because of nearby shoreline infilling.

Oturu Stream, Tairua Hr (Fig. 3.7)
1944-1983: Although the road was built when the earliest photos were taken, the road, with small bridges over the two creeks, was constructed through what was once wetland. Upstream the wetland vegetation has now virtually disappeared, being replaced by pasture. It is conservatively estimated that at least 36% of the original wetland has been destroyed.

Maheka Point, Waimapu Estuary, & Maungatapu, Tauranga Hr (Fig. 3.8)
1948-1986: These 3 long causeways (700, 700, & 1100 m) cut across channels and sand flats in the central and upper harbour. Despite their length they are well bridged over the channels and do not appear to have had any effect on the surrounding estuaries. Channels have remained stable and there is no evidence of increased sedimentation in the vicinity of the causeways.

Watchman Rd, Ahuriri Est (Fig. 3.9)
1936-1988: A short (150 m) culverted causeway severely restricts water exchange and has resulted in major changes in habitat and water quality upstream of the causeway. (Refer Section 1: Causeway impacts - New Zealand).

Road/rail Bridge, Ahuriri Est
1936-1988: The combination of a short 450 m causeway of which 400 m is bridge has resulted in very little impact. The extensive tidal flats in the area have remained stable, there is no evidence of increased sedimentation, and there have been no changes in channel morphology.

SH2, Ahuriri Est
1950-1988: A 350 m long causeway cut off minor channels, but appears to have had little effect on nearby shoals.

SH1 (1) & (2), Manukau Hr (Fig. 3.10)
1960-1991: Two sections of causeway (400 & 100 m) of the southern motorway cut across muddy intertidal areas and small channels in the headwaters of the Pahurehure Inlet. Mangroves in the general area have spread over the past 30 years, however this spread has been dramatically hastened near the causeways. The Pahurehure tidal creek upstream of the SH1 (1) causeway has completely filled with mangroves, and they have also become established outside the causeway. Although the causeway seems to have had a marked effect, there has been considerable land development which could have increased sedimentation and encouraged mangrove colonisation. There do not appear to have been significant changes in channel morphologies.

Pukaki Creek, Manukau Hr
1960-1991: A 350m long causeway with a 70 m bridge cuts across the channel at the entrance to Pukaki Creek. There has been a general increase in mangroves unrelated to the causeway, and construction activity and runoff from the airport has destroyed some mangroves. Apart from the growth of mangroves along the upstream flank of the causeway there appears to have been little change.

Kellys Bay Rd, Kaiapara Hr
1953-1987: A 600m long causeway with a small (50 m) section of bridge impounds a small mangroved area. Apart from increased density of mangroves, especially adjacent to the causeway, there have been no major changes associated with the causeway.

Rangi Point Rd, Hokianga Hr (Fig. 3.11)
1960-1984: Before a 400 m long causeway was constructed across the entrance of Waireia Creek, Hokianga Harbour, the area contained sparse mangroves. The causeway and its floodgate have completely changed the area, which now appears to contain either pasture or rushes.

Wharf Rd, Moutere In (Fig. 3.12)
1947-1985: A 900 m long culverted causeway cuts off the northern arm of the inlet. Interpretation is limited as the earliest photograph was taken after the construction of the causeway. Since then, however, there have been some slight changes in channel morphology, especially downstream. Overall the effect has been minor.

SH60 (1), Moutere In (Fig. 3.12)
1947-1985: A 700 m long roading causeway traverses tidal flats at the mouth of the Moutere River. In addition to any effects of causeway construction, there has been extensive shoreline infilling along the northern shore for pasture. However, the causeway has caused major changes in channel configuration of the Moutere River, both upstream and downstream, and large shifts in sandbank positions downstream.

SH60 (2) - (9), Moutere In (Fig. 3.13)
1947-1985: A series of small causeways occur along the indented southwestern shore of Moutere Inlet as part of road straightening. Overall the changes that have occurred due to the causeways are minor, and mainly involve small increases in saltmarsh vegetation. One embayment (SH60 (6)) appears to have limited tidal exchange and retains ponded water at high tide.

Rabbit Island, Bells Island, and Bests Island, Waimea In
1946-1985: Four causeways occur in the area where the Waimea River enters the estuary, cutting across channels and intertidal sandflats to link the mainland with islands in the estuary. Restricted flushing has resulted in lowered upstream salinities and weed problems in the channel between Rabbit and Rough Islands. Flows have been reduced between Bells and Bests Islands resulting in changes in channel morphology. Overall, major changes seem to have occurred in sedimentation, resulting in changed channel and shoal configurations where the Waimea River enters the estuary. These changes will have been affected to some extent by the construction of causeways, but other factors are probably involved, including shoreline infilling (to create pasture), stopbank construction, and the high sediment loads from the Waimea River.

McCormacks Bay, Avon-Heathcote Est
1950-1984: A small 600 m causeway cuts off an intertidal embayment from the main estuary. Interpretation is limited as the earliest photos were taken after causeway construction. There has also been substantial reclamation in the area impounded by the causeway, and a rock mole cuts across the middle of the bay. It is evident, however, that flushing is impeded and water is retained at low tide. Over the past 40 years the bay has developed water quality and algal growth problems. (Refer Section 1: Causeway impacts - New Zealand).

Main South Railway (3) & (4), Otago Hr
1947-1990: A series of small railway causeways occur along the indented northwestern shore of the harbour. Formation of flood tide deltas within these embayments indicate entrainment and trapping of sediment from the main harbour channel, but there do not appear to be any other major effects.

Anderson Bay Inlet, Otago Hr
1947-1990: A small 350 m causeway cuts off the upper reaches of the harbour. Interpretation is limited as the earliest photos were taken after causeway construction, and there has also been substantial reclamation. No obvious changes appear to be associated with the causeway.

Tiwai Rd, Awarua Bay, Southland (Fig. 3.14)
1951-1985: A very long (1200 m) road causeway cuts across the channel and intertidal area of the bay. There have been no obvious changes in channel morphology, shoals, or sandbanks and no evidence of changed sedimentation patterns associated with the causeway.

3.3 Discussion

The range of causeway impacts identified from aerial photographs are listed in Table 3.1. At several sites no changes could be directly attributed to the causeways, despite the fact that some of the structures were over 1000 m long, and major estuary channels carrying large flows were constricted (e.g., Tauranga Harbour, Fig. 3.8, and Awarua Bay, Fig. 3.14).

In the Northland and Auckland regions, where mangroves occur, it was common to find slight increases in mangrove density over time, although the total area covered by mangroves often remained the same. Because this effect was also observed well away from the causeways it was apparently the result of normal growth and was not attributable to the presence of causeways (e.g., Otaika (1) & (2), Whangarei Harbour, Fig. 3.3). In some southern estuaries (e.g., SH60 sites 4 & 5, Moutere Inlet, Fig. 3.13) small increases were noted in the coverage of saltmarsh vegetation, but it was impossible to determine if this was the result of normal growth, or had resulted from subtle changes in sedimentation patterns. At some sites substantial colonisation by new mangrove plants was seen (e.g., Fig. 3.1, 3.2, 3.10). To some extent this was associated with a general increase in mangrove coverage, but the SH1

Table 3.1: Summary of effects of causeways in estuaries identified from aerial photographs.

EFFECT	EXAMPLES*
No direct effect (although reclamation may be carried out after causeway construction).	Waimapu Est., Maungatapu, & Maheka Pt. (Tauranga); Road/rail Bridge, & SH2 (Ahuriri); Andersons Bay (Otago); Tiwai Rd. (Awarua Bay).
Small increase in saltmarsh vegetation, or slight increase in mangrove density.	SH10 & Kohumaru Rd. 1 & 2 (Mangonui Hr); Otaika 1 & 2 (Whangarei Hr); Herald Is., Whau R., Waterview 1 & 2, & Tamaki Dr. (Waitemata Hr); Kellys Bay Rd. (Kaiapara Hr); SH60 4 & 5 (Moutere).
Colonisation by mangroves (although this may have occurred in the general area).	SH10 & Ryder Rd. (Taipa); SH1 1 & 2 Pahurehure In, & Pukaki Cr. (Manukau).
Scouring and changes in channel morphology within a few hundred metres of the structure, and possibly loss of nearby saltmarsh.	Broadlands Dr. (Whangateau Hr); Waterview 1 & 2 (Waitemata Hr); Main Sth Railway 3 & 4 (Otago Hr).
Major changes in channel morphology and sedimentation, especially associated with large rivers.	Vicinity of Rabbit, Bests & Bells Is's (Waimea In); Wharf Rd. & SH60 1 (Moutere In).
Severely restricted water exchange resulting in habitat changes and water quality problems.	Watchman Rd. (Ahuriri); Rabbit Is. (Waimea In.); SH60 6 (Moutere); McCormacks Bay (Avon-Heathcote Est).
Estuary completely modified or lost.	Oturu (Tairua Harbour); Rangi Pt. Rd. (Hokianga Hr).

* the underlined sites are illustrated by aerial photographs in this report

crossings of Pahurehure Inlet in Manukau Harbour (Fig. 3.10) appear to show that mangrove growth has been stimulated in the shelter afforded by the motorway crossings. At this site there has also been major catchment development, which could have increased sedimentation and thereby encouraged mangrove colonisation. It was also often observed that mangroves would colonise the higher bed adjacent to the flanks of causeway embankments.

Constriction caused by some bridges and culverts has resulted in scouring of the estuary bed and minor changes in channel morphology in the vicinity of the structures. Although this effect is usually localised and minor, in Whangateau Harbour scouring associated with Broadlands Drive (Fig. 3.4) has apparently destroyed the saltmarsh vegetation within a few hundred metres of the bridge. Major changes in channel morphology and sedimentation can occur where causeways intercept large river flows. Prior to the SH60 crossing of the Moutere River, in Moutere Inlet the river meandered over the sandflats in several channels (Fig. 3.12). With one centrally placed bridge, the river was constrained to a single channel as the southern channel silted up, and the positions of sandbanks downstream were altered. In Waimea Inlet causeways at the mouth of the river have had similar effects.

In a few cases the severely restricted water exchange resulting from causeways with insufficient bridging or culverts was found to have dramatically altered the estuarine habitat and resulted in water quality and algal growth problems. The Watchman Rd (Fig 3.9) and McCormacks Bay causeways are examples of this. At some sites, such as Oturu Stream on Tairua Estuary (Fig. 3.7), and Rangi Pt Rd in Hokianga Harbour (Fig. 3.11), the causeway has led to extensive alteration or loss of wetland area. Causeways extending out to islands appear to have had little impact on channel locations or saltmarsh distribution (e.g., Herald Island, Fig. 3.13).

3.4 Conclusions

A wide range of impacts can be found in New Zealand estuaries, although there are many causeways which have had no obvious impact. Overall, causeways seem to have had little effect on saltmarsh vegetation or mangroves. Mangroves in Manukau Harbour and saltmarsh in some southern estuaries may have increased as a result of changed sedimentation. There are several cases which demonstrate the problems which can arise when tidal flows are forced through very constricted openings, culverts have not been placed appropriately to maintain circulation and flow patterns, and where causeways trap large sediment inputs from catchments. In a few cases estuaries have been substantially altered or lost.

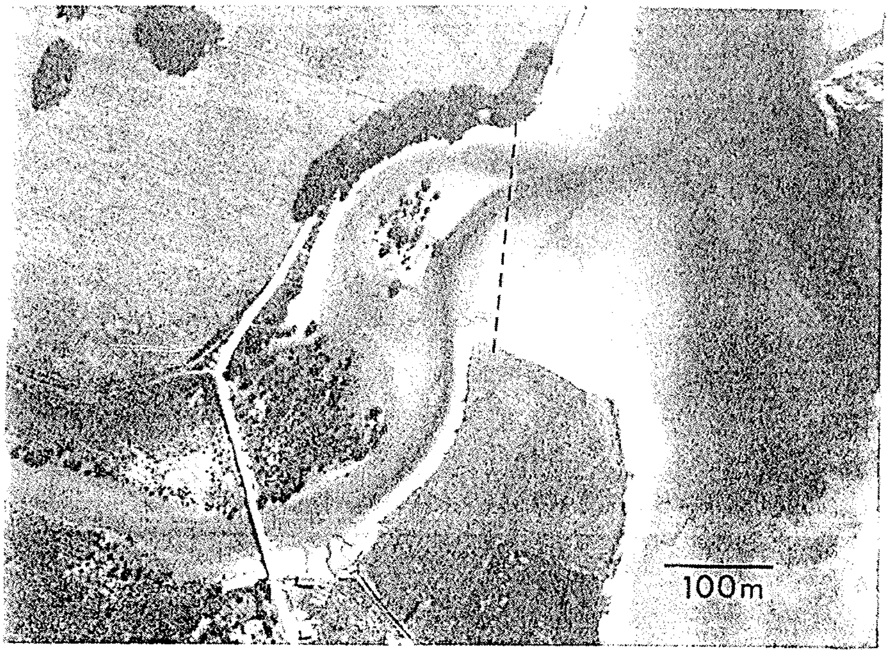
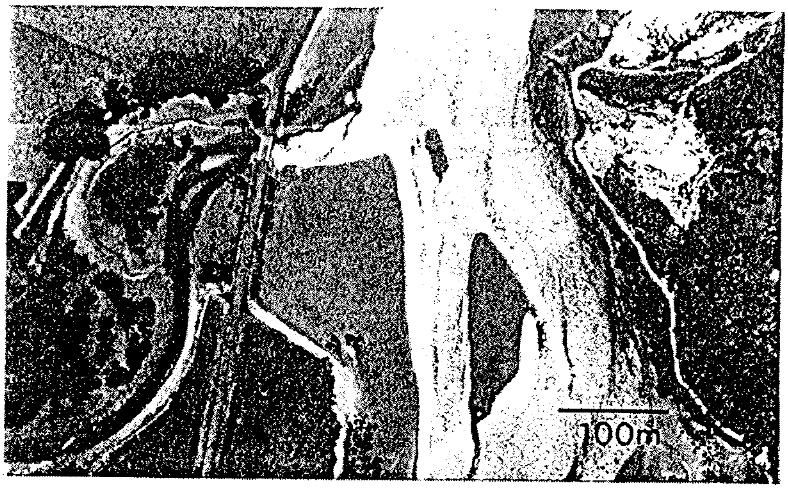


Figure 3.1: Ryder Creek, Taipa, in 1948 (above) and 1984 (below) showing the changes associated with the Ryder Rd crossing. Mangroves upstream of the causeway have become denser, and their aerial coverage has increased, but this has also occurred in the general area, well away from the causeway. Mangroves have become established alongside the causeway. The main channel in the creek has remained stable, and the subsidiary channel has become smaller.



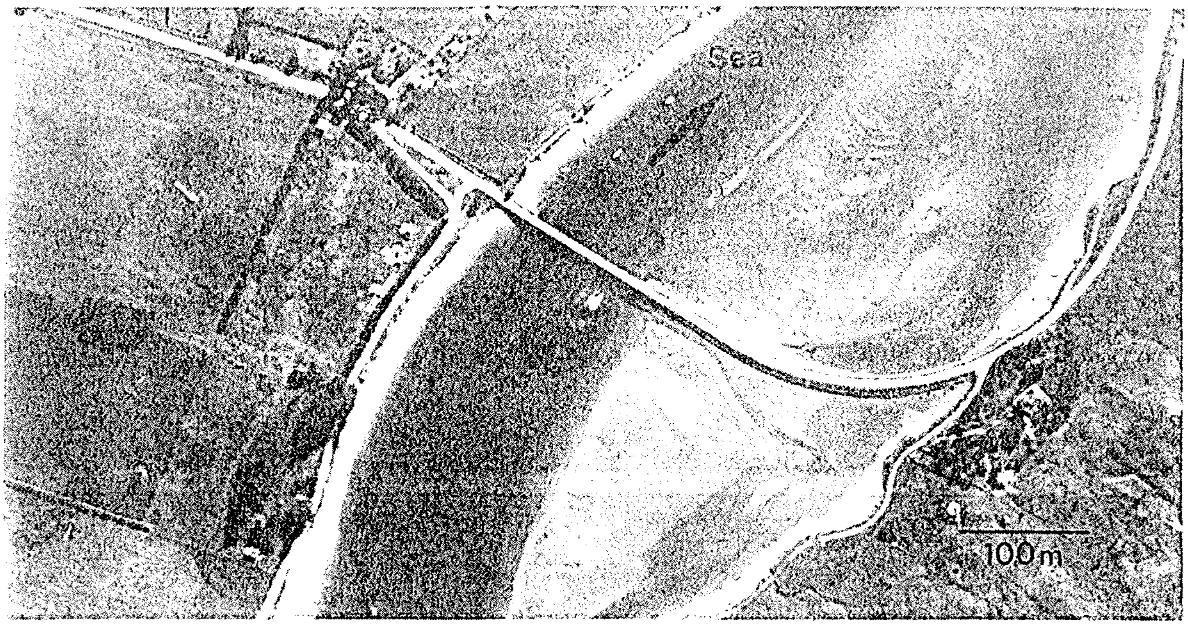


Figure 3.2: SH10 crossing of the tidal Taipa River estuary in 1948 (above) and 1984 (below). Over this period mangroves have colonised the right bank, upstream of the causeway, but mangroves in the estuary well away from the causeway have also increased.

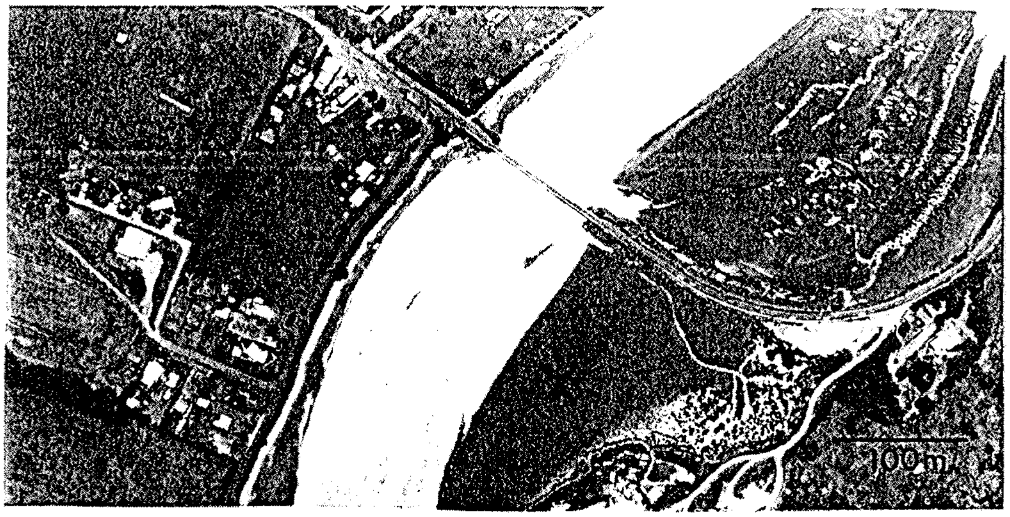
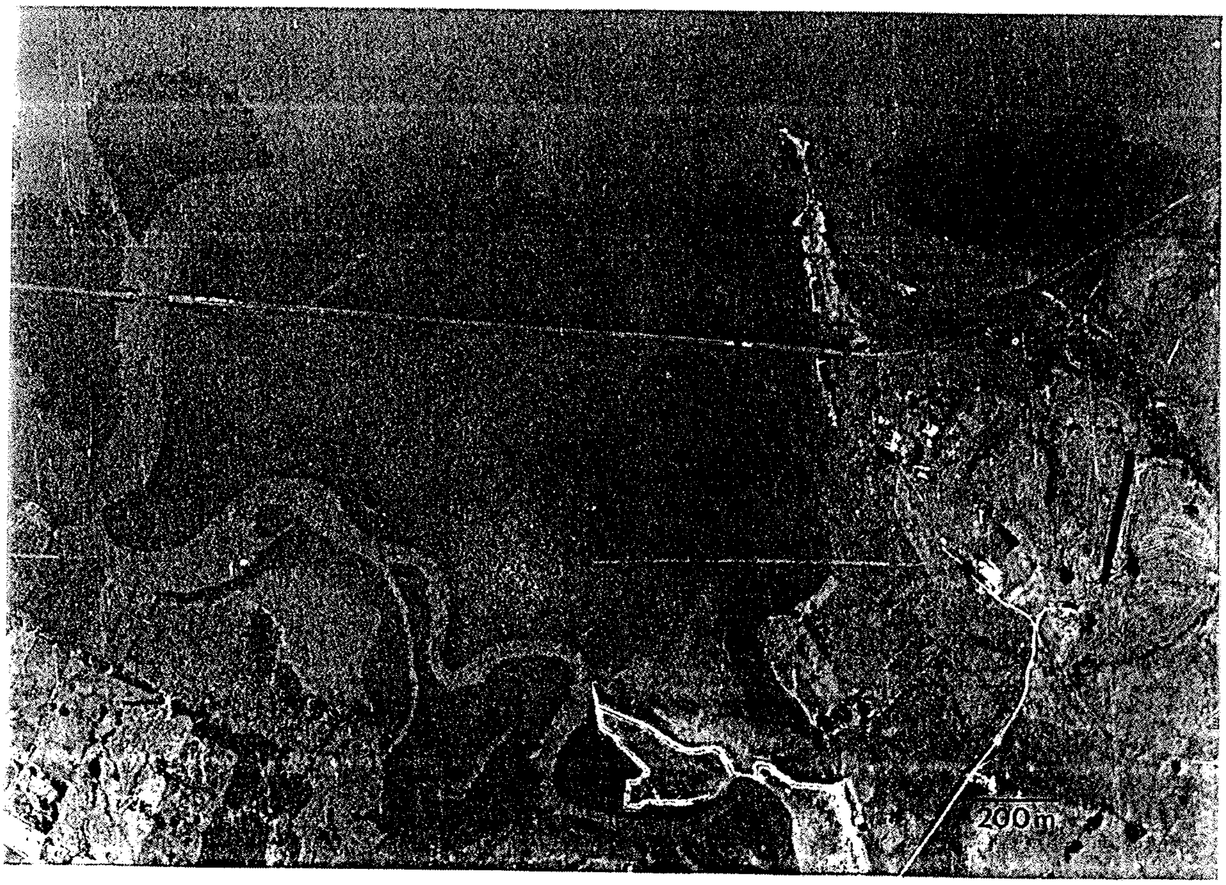


Figure 3.3: The railway causeways at Otaika, Whangarei Harbour, in 1942 (above) and 1982 (below). The only changes associated with this major structure are a slight increase in the density of mangroves, especially along the flanks of the causeway. Drainage channels and overall coverage of mangroves have remained virtually unchanged over this period.



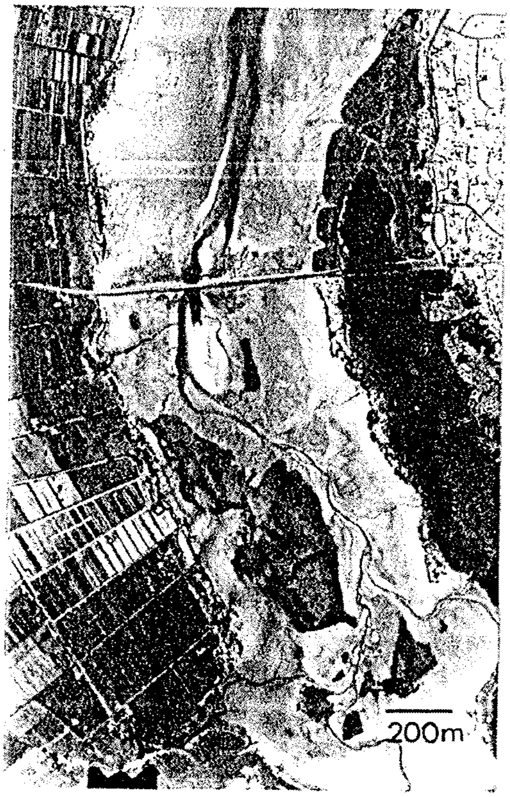


Figure 3.4: The southern arm of Whangateau Harbour in 1953 (above) and 1982 (below) showing the changes resulting from the Broadlands Drive crossing. The position of the main channel has not altered, but scouring has occurred in the immediate vicinity of the bridge. It is possible this scouring and the associated changes in sedimentation have caused the loss of saltmarsh vegetation (SM) either side of the structure.

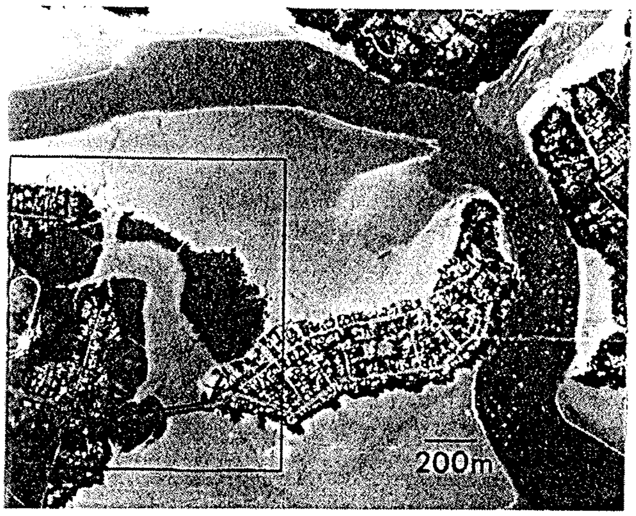


Figure 3.5: Mangroves in the vicinity of Herald Island in 1950 (above) and 1988 (below). Construction of the causeway has caused little overall change. Mangroves in the general area are slightly denser and have grown in narrow bands flanking the causeway. There is no perceivable change in channel morphology or sedimentation.

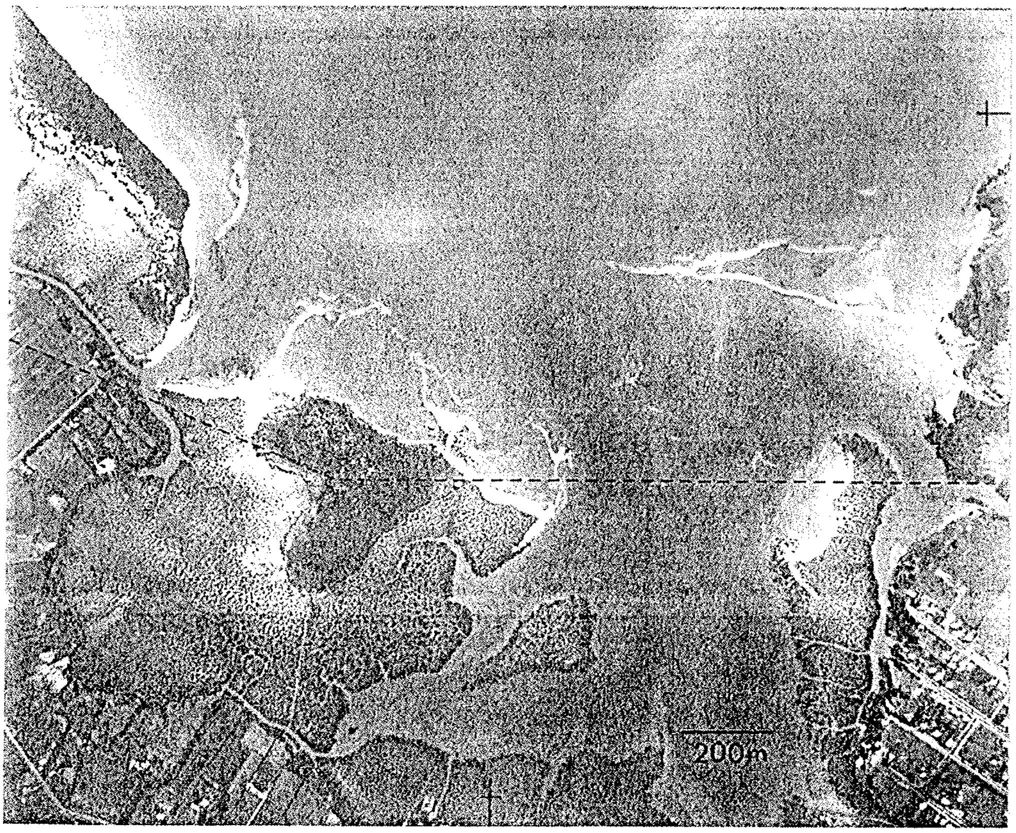
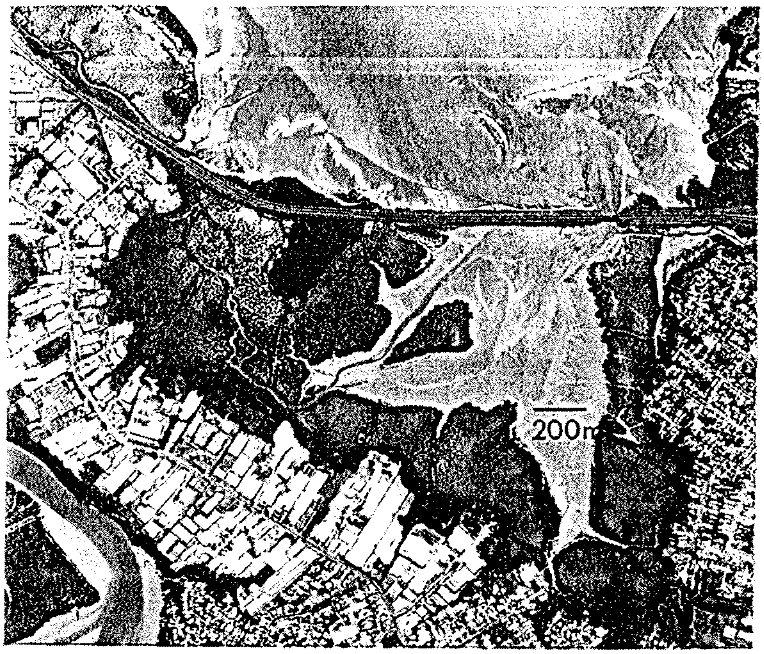


Figure 3.6: Waterview Inlet, Waitemata Harbour, in 1940 (above) and 1988 (below) showing changes associated with construction of a major causeway. There has been little overall impact. Mangroves have spread slightly in parts. There are no major changes in the configuration of shell banks or channels, however, scouring extending some 350 m beyond the causeway has occurred at the bridged opening at the right end of the inlet.



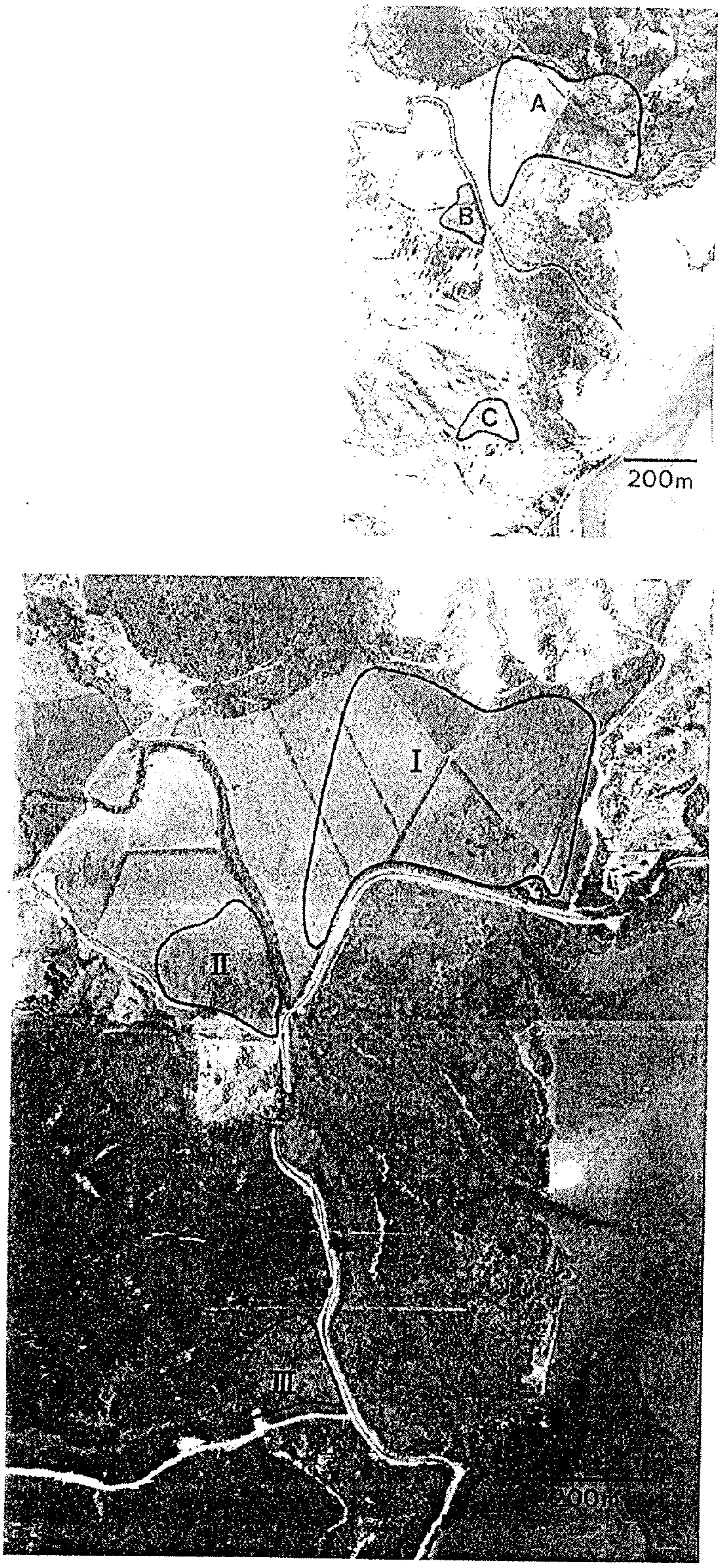


Figure 3.7: The estuary associated with Oturu Stream, Tairua Harbour, in 1944 (above) and 1983 (below). The causeway was constructed through what appeared to have once been wetland. Differences in the vegetation in areas labelled A, B, and C in the 1944 photo suggest these were probably wetland originally. In 1983 wetland vegetation in these same areas (shown as I, II, and III) appears to have virtually disappeared, leaving only the estuarine area to the right of the road. This represents a loss of about 36% of the original wetland area.

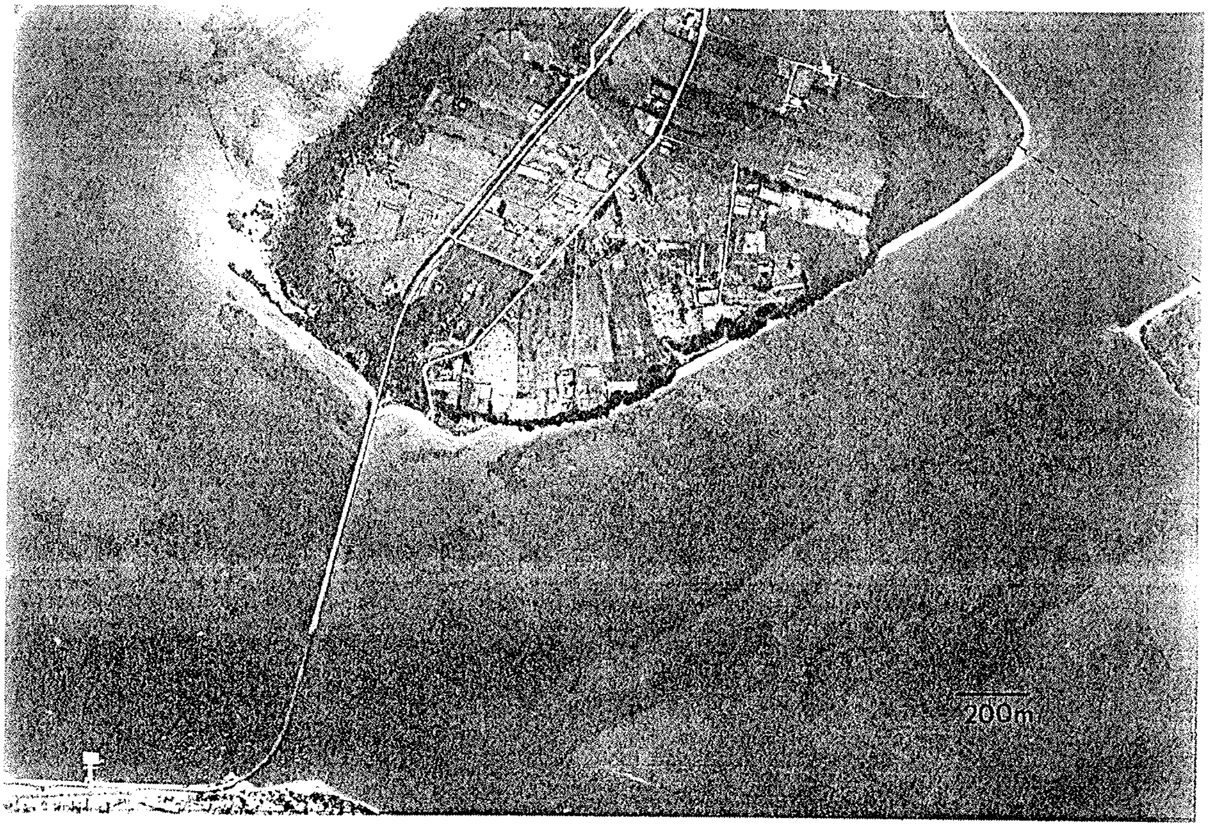


Figure 3.8: Tauranga Harbour in 1948 (above) and 1986 (below) showing the Maheka Point causeway on the left and the Maungatapu causeway on the right. These long causeways (700 & 1100 m) cut across channels and sand flats in the upper harbour. Despite the causeways lengths, the large bridges over the main channel have ensured that there has been no effect on the surrounding estuary. Channels have remained stable and there is no evidence of increased sedimentation.

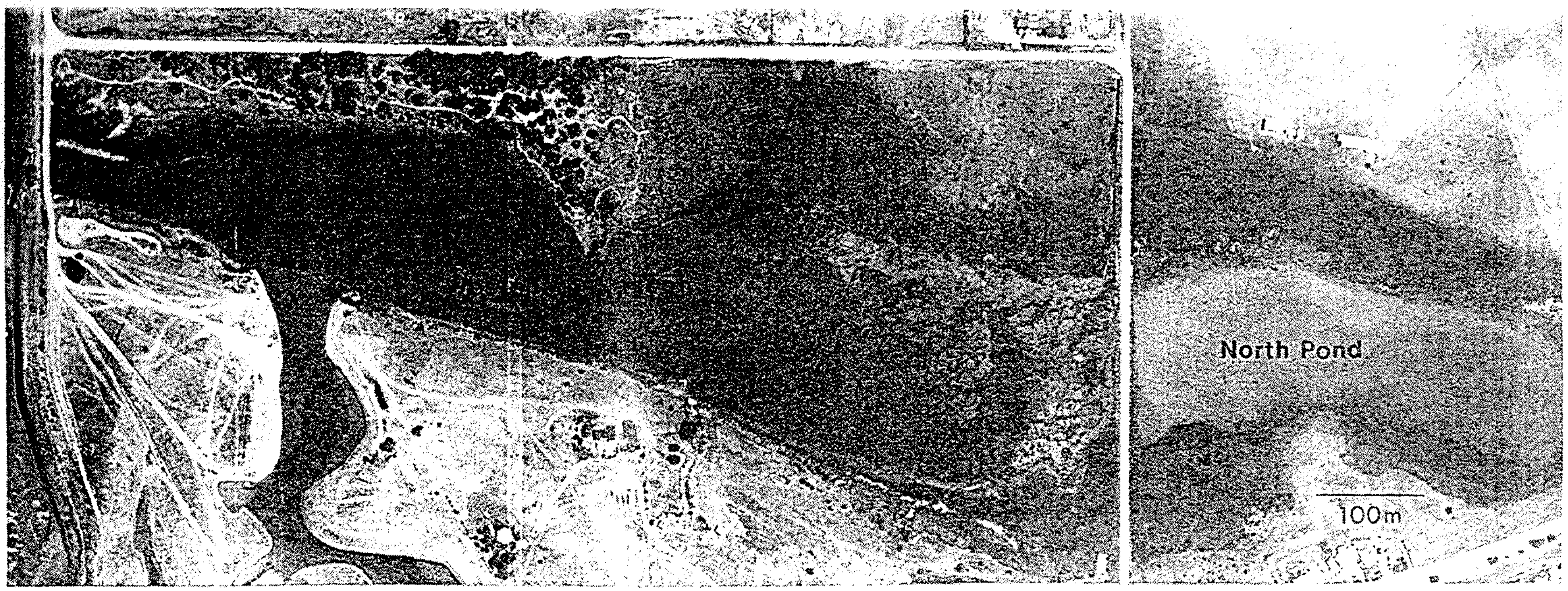


Figure 3.9: In Ahuriri Estuary the Watchman Road causeway divides Westshore Lagoon from North Pond. This 1988 photo shows the changes in habitat that have resulted from the restricted water circulation.

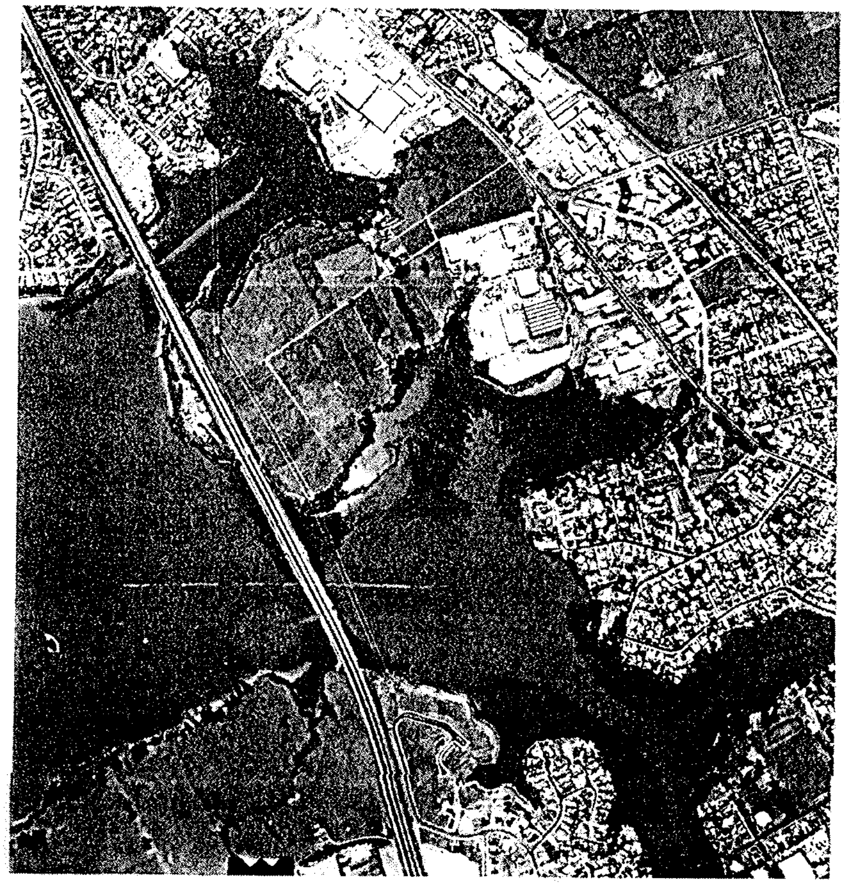


Figure 3.10: Pahurehure Inlet, Manukau Harbour, in 1960 (above) and 1991 (below) showing the two causeways of the southern motorway of SH1. Mangroves in the general area have spread over the past 30 years, however this spread has been dramatically hastened near the causeways. Although the causeways seem to have had a marked effect, there has been considerable land development which could have increased sedimentation and encouraged mangrove colonisation. There do not appear to have been significant changes in channel morphologies.

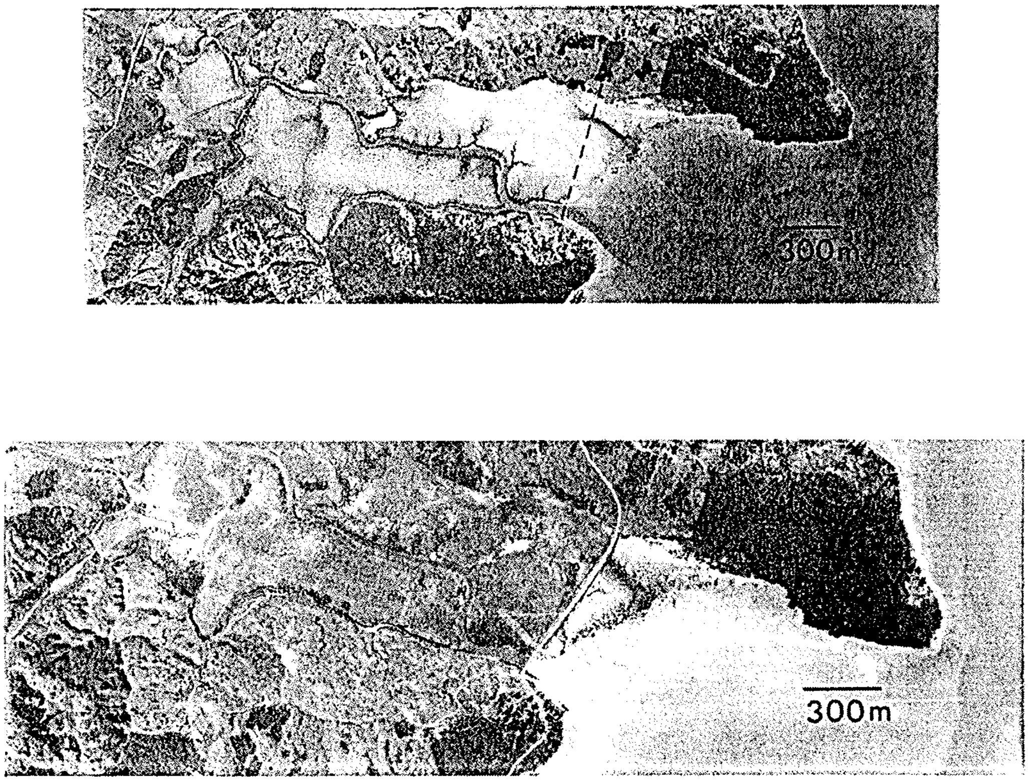


Figure 3.11: Waireia Creek, Hokianga Harbour, in 1960 (above) and 1984 (below) showing the changes which occurred after a causeway was constructed across the entrance. In 1960 the creek contained sparse mangroves, but these have been replaced by what appears to be pasture or rushes. This substantial change in habitat type has probably resulted from flood gates in the causeway impeding tidal flushing.

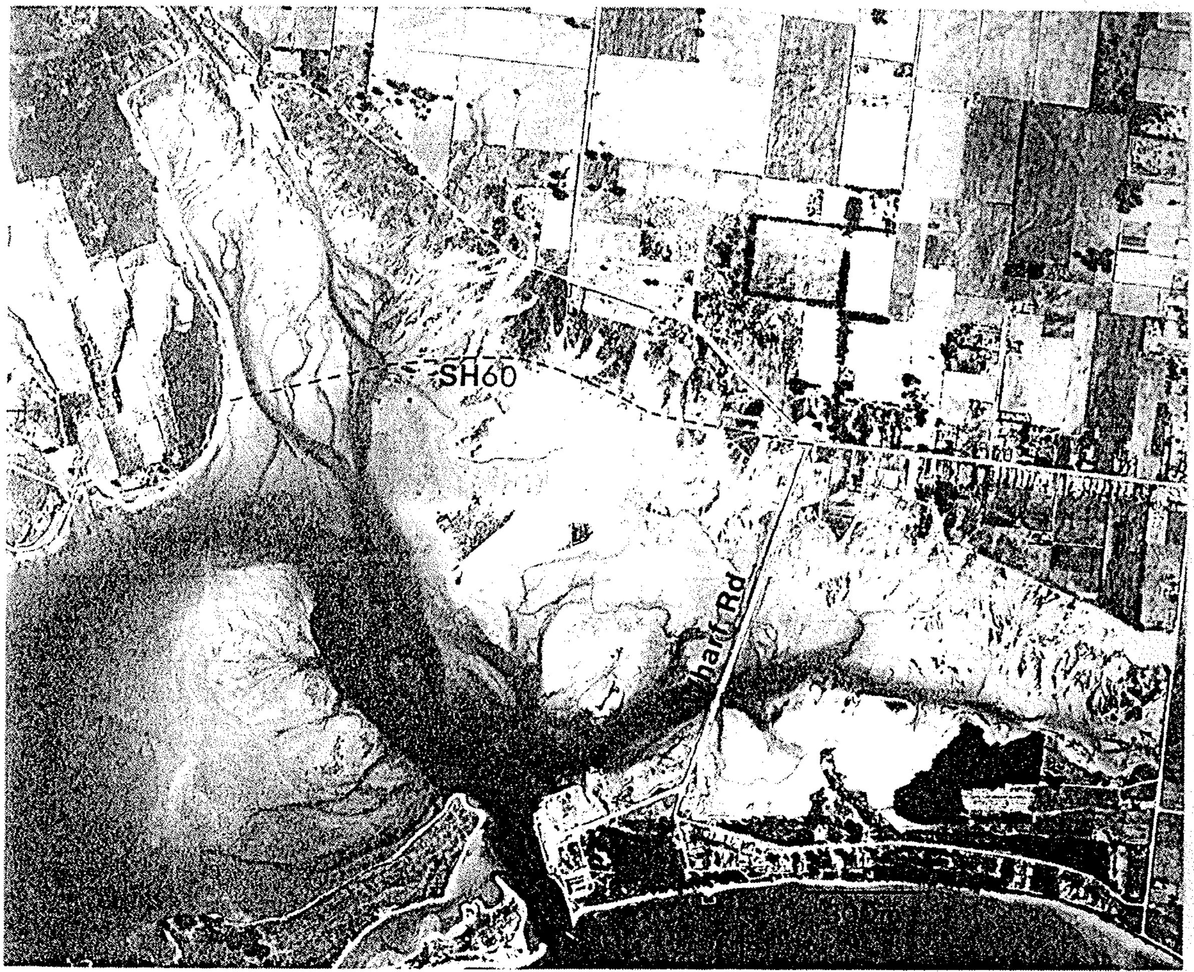
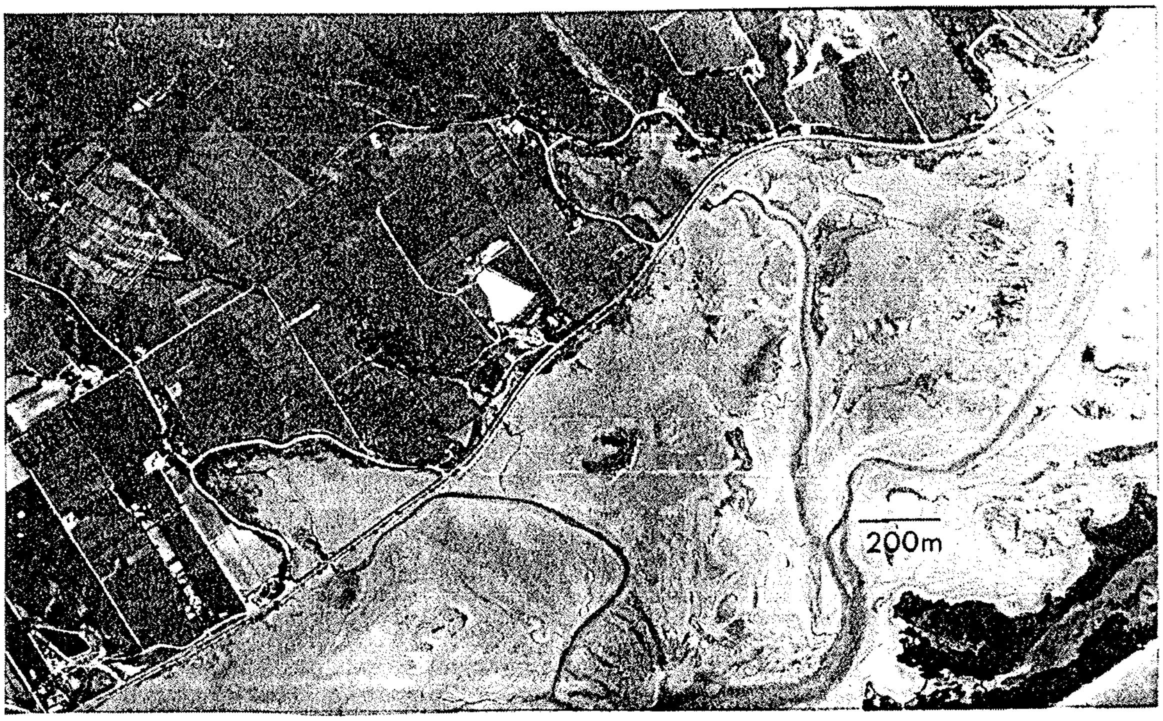


Figure 3.12: Moutere Inlet in 1947 (above) and 1985 (below) showing effects of the Wharf Road and SH60 causeways. The more recent photo shows slight changes in channel morphology downstream of Wharf Road. The SH60 causeway traverses tidal flats at the mouth of Moutere River. By restricting river flows to one channel this causeway has caused major changes in channel configuration, both upstream and downstream, and large shifts in sandbank positions downstream. In addition to any effects of causeway construction, there has been extensive shoreline infilling behind the causeway.

Figure 3.13: Moutere Inlet in 1947 (above) and 1985 (below) showing effects of causeways associated with SH60. These three small causeways appear to have caused only minor changes, with increases in saltmarsh vegetation.



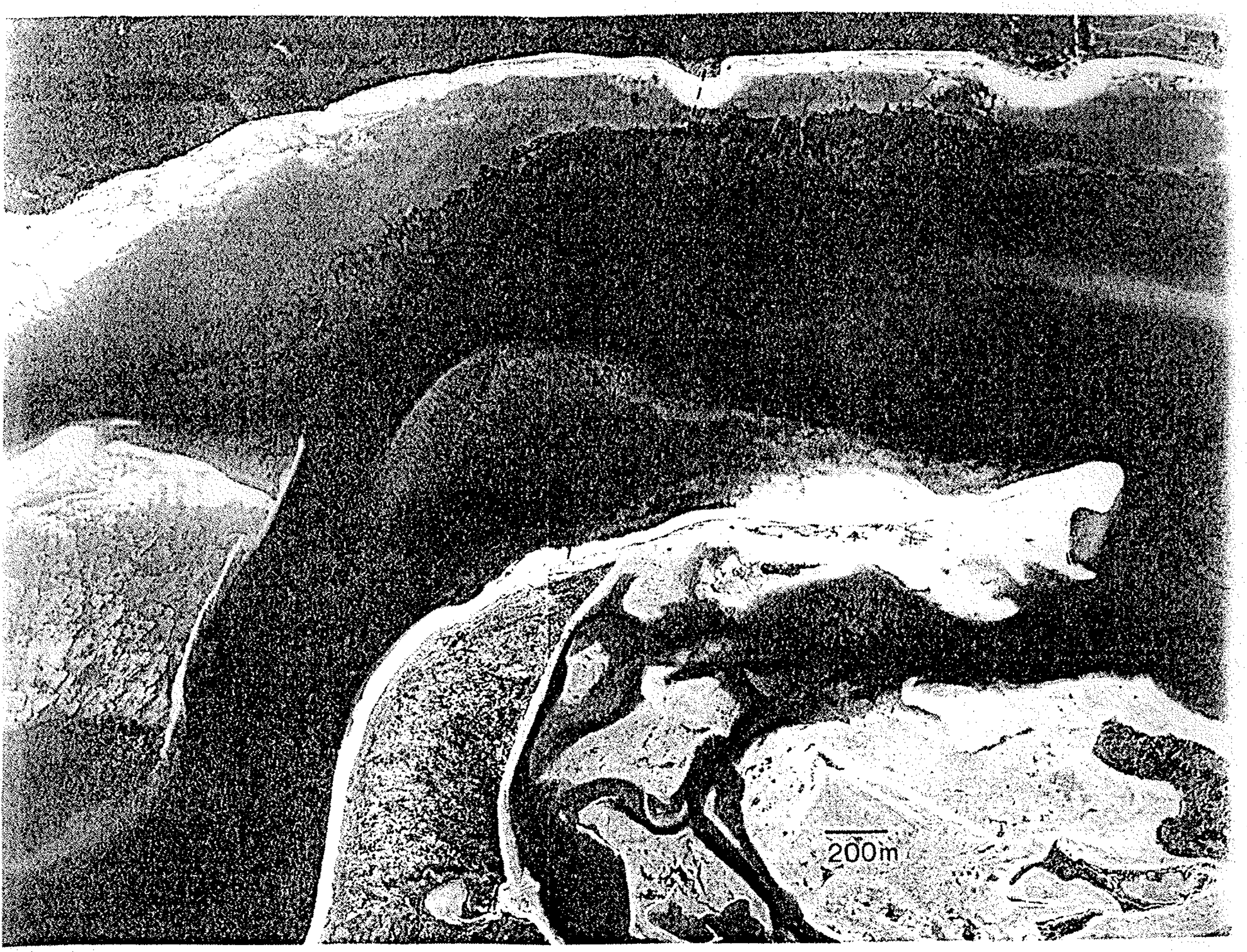
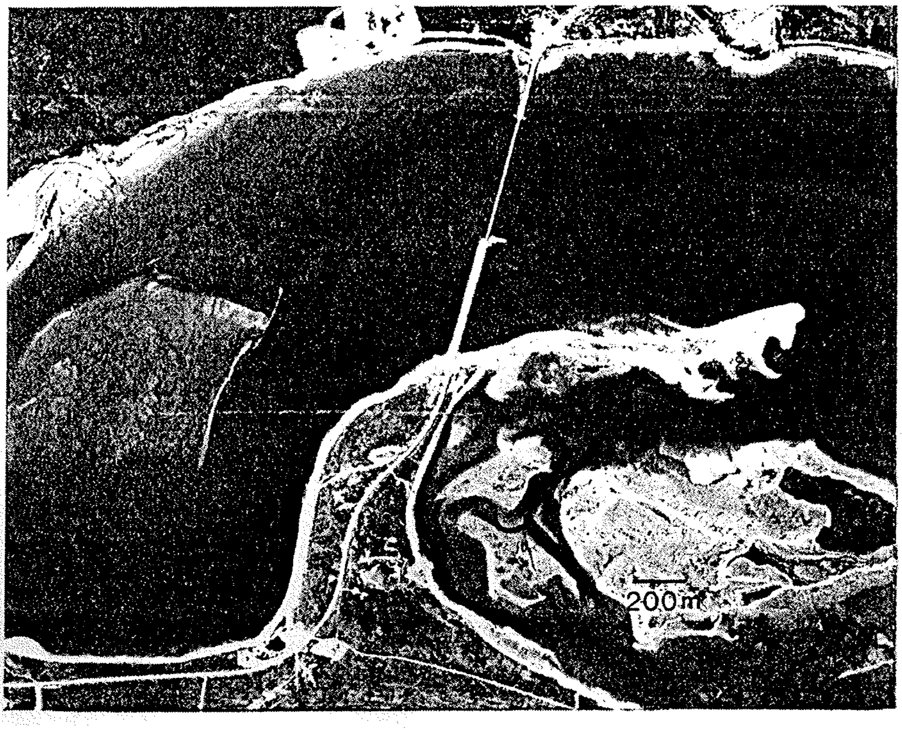


Figure 3.14: Awarua Bay, Southland, in 1951 (above) and 1985 (below) showing the Tiwai Road causeway. This long (1200 m) causeway cuts across the channel and intertidal area of the bay, but has had no obvious effects on channel morphology or sedimentation patterns.



4 PROCEDURES FOR MINIMISING CAUSEWAY IMPACTS

4.1 Introduction

The literature review (Section 1) and aerial photograph analysis (Section 3) identified the range of impacts which can arise from causeways across estuaries. It is mainly the potential for hydrological changes which leads to wider ecological effects. In designing a causeway crossing it is therefore essential that hydrological changes are minimised. Other important considerations are the impact that the causeway may have on estuarine habitats (including flora and fauna), fisheries, birdlife, and water quality.

This section reviews the various hydrological factors which must be considered and describes some computational methods which can be used to assess the potential for modification to water discharges and velocities. Specific concerns regarding habitat, fisheries, birdlife, water quality, and construction activity impacts are then addressed.

4.2 Hydrology

The two most important aspects of estuarine hydrology which can be altered by a causeway are circulation and flows. Circulation refers to the overall pattern of water movement around the estuary as the tide ebbs and floods. Disruption to established circulation patterns arise when culverts or bridges are inappropriately placed, and can result in changes to sedimentation patterns and movement of sandbanks and shoals, with associated habitat and ecological impacts. Flow refers to the quantity of water moving passed a fixed point per unit time. Apart from when channel positions change, flows are most likely to be altered when the channel cross section (i.e., the open area) of an estuary is constricted by a causeway and water is forced through the reduced open area provided by a bridge or culvert. In this situation the bed becomes unstable and scours, increasing channel cross-sectional area. The impacts of causeways can be minimised by ensuring that channel positions are maintained and circulation patterns are therefore unaltered, and by providing an adequate waterway area to allow tidal and flood-water flows to pass without undue restriction. There are several approaches for determining the most suitable placement of bridge and culvert openings and the appropriate total open area. The methods discussed range from qualitative analysis of the channel morphology, through to sophisticated numerical models. The method(s) adopted will depend upon the site characteristics, the scale of the perceived impact, the resources at risk, and cost.

4.2.1 Channel morphology

A prerequisite for any project is a morphological analysis of channel stability based on a field inspection at low tide, and an examination of air photos and bathymetric charts. Analysis of historical air photos will show if channels are stable or have meandered in the past. If channels are stable then bridges or culverts can be placed in the major flow paths with some certainty that there will be minimal disruption to flows and sediment transport in future. Examination of the locations of subsidiary channels provides a guide as to the best location for additional culverts to facilitate good tidal exchange. In general, flow should be maintained in existing channels. In situations where channels have shifted in the past, it is likely that this will continue. In this case consideration should be given to siting the causeway elsewhere, or making allowance for possible changes in channel location.

4.2.2 Empirical calculations

There are empirical formulae that can be used for a first approximation of the waterway area required to minimise the impacts on tidal flow regime, bed scour and sediment transport patterns. Empirical formulae can be used to calculate stable channel cross-sectional area and scour depth. Maximum scour depth is applicable where the existing channel width is being reduced by a causeway and the opening is spanned by a bridge. It provides an estimate of the depth to which the channel under the bridge will scour. There are several empirical formulae available (see Appendix 3), but the following are recommended for New Zealand estuaries.

Stable channel area can be estimated from:

$$A_{mtl} = 7.39 \times 10^{-6}.\Omega_s^{1.164}$$

where A_{mtl} is the channel cross-sectional area at mid tide (m^2) coinciding with peak flow, and Ω_s is the spring tide prism (m^3), or the volume of water flowing into the estuary on the incoming tide (Hume 1991). The parameter Ω_s can be obtained from the literature, measured off hydrographic charts, or calculated from field data. If the data for calculating Ω_s are not readily available it may be derived using relationships such as those below, which use parameters that are simpler and less expensive to determine. For instance, Ω_s can be calculated from the surface area (m^2) of the estuary at high tide, E, which can be measured from topographic charts, or Ω_s can be calculated from the peak discharge ($m^3\ s^{-1}$) through the waterway, Q_p, which is determined by current meter measurements at the time of peak flow. So that:

$$\Omega_s = 1.261 \times 10^{-1}.E^{1.172}$$

or,

$$\Omega_s = 5.572 \times 10^3.\ Q_p^{1.105}$$

Maximum scour depth (D_s in m) can be calculated by:

$$D_s = 0.365\ \frac{D_o}{D_{mo}} \cdot \frac{Q^{0.784}}{B^{0.784}\ .\ d_{50}^{0.157}}$$

where D_o is the peak discharge water depth (m) at the lowest point in the cross section, D_{mo} is the peak discharge water depth (m) to the mean bed level, Q is the peak discharge ($m^3\ s^{-1}$) in the tidal cycle, B is the channel width at peak discharge (m), and d_{50} the sediment mean grain size (m). The formula is applicable to a straight reach, in beds formed of sand and gravel, and is accurate to about ±10%.

The derivation and use of these formulae are described in Appendix 3 and (Hume 1991).

Interpretation of the results from the empirical calculations should always be made in conjunction with the results of the morphological analysis. The empirical formulae are best used for making initial estimates, in hydraulically simple situations (e.g., where there is minimal freshwater inflow), and may help in deciding whether more sophisticated calculations are necessary.

The advantage of empirical calculations is that they are often quick, simple and inexpensive to perform. The disadvantage is that they do not have the accuracy or provide the detailed information obtainable from hydraulic analysis or numerical modelling.

4.2.3 Hydraulic analysis

Compared to using empirical formulae, hydraulic analysis provides a more precise method for sizing causeway openings and gives additional information on tidal flows, which can be useful for both causeway design and impact assessment.

In hydraulic analysis a series of repetitive calculations is made to establish the desired outflow characteristics from, for instance, a culvert through a causeway, under prescribed inflow conditions. The calculations are done in an iterative manner, with various culvert sizes being substituted in the calculation until the desired outflow characteristics (i.e., mean velocity, discharge and water level over a tidal cycle) are achieved. Details of the theory and method of hydraulic analysis are given in Appendix 3. Computer programs can be developed to perform the series of repetitive calculations. To set up the inflow conditions for the calculations, field measurements have to be made to establish existing hydrological characteristics. This usually involves carrying out a tidal gauging (i.e., measuring the tide levels and currents at the site of the proposed causeway over a half or full tidal cycle. This enables the tidal discharge to be computed. Where river flows dominate, discharges are obtained from river flow records or estimated from catchment yield data. Full details on carrying out tidal gaugings are provided in Hume and Bell (1993).

Using hydraulic analysis, various outflow scenarios and different bridge/culvert options can be tested. Hydraulic analysis can also be used to predict the velocity regime at the causeway opening over the tidal cycle. This is of use in calculating bed scour and also in assessing how the altered velocity regime may affect the ability of fish to swim through the culvert. Also, the predicted upstream and downstream water level regimes can be examined to assess possible habitat impacts. This level of hydraulic analysis will be adequate for many situations.

4.2.4 Numerical modelling

Numerical modelling allows predictions to be made of very detailed hydrological conditions (e.g., current velocity and direction) at the causeway opening and at some distance away, and can be used to provide quantitative information on tidal flushing. Numerical modelling was used in the design of a causeway and bridge in Tauranga Harbour (Barnett 1985) to test the effect of different designs and configurations on:

- tidal flushing
- current speeds at key parts of the harbour, which would affect boating
- flow patterns over sand banks and in channels, which may have affected shellfish beds
- resistance of bridge piers, an important engineering consideration
- sediment scour and deposition at the causeway and around the harbour

The particular value of numerical modelling lies in its predictive capability for assessing impacts on hydrology and sedimentology, and testing various causeway design options. However, this level of computation requires detailed bathymetric and hydrological field data, making it an expensive exercise, and generally appropriate only in situations where high capital costs are involved.

4.3 Habitat

Estuarine habitat can be affected by a causeway through direct smothering of habitat in its path or modification resulting from changes in hydrology. These hydrological changes may include modification of water depths, velocities and circulation patterns, ponding of floodwaters, or changes in salinity. They may also extend to scouring of the estuary bed and altered sedimentation patterns.

To assess the potential for habitat impact and the possible ecological consequences of this it is necessary to know what different habitat types are present. This requires, at least, a qualitative survey of the estuary and surrounding wetlands. Physical habitat characteristics need to be considered, including bathymetry, tidal ranges, velocities, current patterns, channel positions, salinity, and sediment types. Where wetlands are involved, special attention may need to be given to ground water levels and salinities, and flows. In addition to this physical information, distributions of algae, wetland plants and animals need to be established.

With any causeway it is inevitable that there will be some impact, even if it just limited to loss of that habitat under the causeway itself. To help make an assessment of the consequences and acceptability of impact the relative proportion of the various estuarine habitats affected can be calculated. Ultimately however, unless the functioning of the estuarine ecosystem is particularly well understood, it is usually a value judgement as to whether or not loss or modification of habitat is acceptable.

4.4 Fisheries

Estuaries play an important role for many fish species. They act as spawning areas for some species, several coastal fishes utilise estuarine nursery areas, fish migrate through estuaries on their way out to sea or into rivers, and there can be large resident estuarine fish populations. Causeways may affect fish either through destruction of habitat (e.g., used for feeding or spawning), or by impeding or prohibiting passage as a result of high water velocities through culverts.

Destruction of habitat has been dealt with above. With respect to fish it is necessary to consider that habitat utilised by fish. By considering the size of the area affected relative to that habitat type remaining it is possible to gauge the likelihood of adverse impacts.

There is no information available on the swimming ability of New Zealand marine fish, however, Mitchell (1989) has studied the swimming ability of some native freshwater fishes, some of which will occur in estuaries. Making observations of five diadromous fishes (*Anguilla australis, Galaxias maculatus, G. fasciatus, Retropinna retropinna, Gobiomorphus cotidianus*) in a flume allow estimates of critical velocities for fish passage. Mitchell (loc. cit.) concluded that for juvenile fish (30-80 mm long) velocities below 0.3 m s^{-1} should allow unrestricted passage through obstacles (e.g., culverts) less than 15 m long. For obstacles over 15 m long velocities below 0.25 m s^{-1} may be necessary. For the grey mullet (*Mugil cephalus*) it is possible that velocities below 0.15 m s^{-1} would allow its passage through obstacles less than 5 m long, however over greater distances than this velocities as low as 0.05 m s^{-1} may be required (unless resting areas are provided).

When considering the potential impact of an estuarine causeway on fish passage the figures provided by Mitchell (1989) provide a basis for assessment. Using hydrological modelling techniques (as described above) water velocities which will occur as water passes through the bridges or culverts in a causeway can be calculated and compared with the velocities without a causeway present. It is also necessary to consider the distribution of velocities across the estuary channels and the variation in velocity during the tidal cycle. It is possible, for example, that velocities may be significantly weaker in the shallow water at the sides of main channels or in subsidiary channels, and that the critical velocities provided by Mitchell (1989) are only exceeded for a small part of the tidal cycle.

4.5 Birdlife

Many different bird species may be found in the various habitats available in an estuary. Some species will be present in estuaries year-round, possibly breeding there. Others will breed elsewhere in New Zealand and move into estuaries to feed over winter, while in some estuaries migrants will come from the northern hemisphere to spend spring - autumn there. Birds may be affected through loss of habitat (e.g., used for feeding, roosting, or breeding) or disturbance associated with motor traffic.

Loss of habitat has been considered above. With respect to birdlife it is necessary to identify those habitats important to the estuarine bird fauna, and the size of the area affected relative to that habitat type remaining. There appears to be no published information available on the problem of bird disturbance. It is clear that many species adapt to human activity and will continue to live nearby airports and roads. The risk of disturbance and possible loss of local bird populations has to be weighed against the size of populations elsewhere and rarity of those birds affected, and the amount of undisturbed habitat remaining.

4.6 Water quality

Roads are the source of a variety of contaminants from motor vehicles, including polynuclear aromatic hydrocarbons (PAHs), lead, zinc, copper, and 'oil and grease'. These contaminants may enter water bodies either through the air or as rainfall runoff. At high concentrations these contaminants are toxic to aquatic life and may pose a human health risk.

Knowing traffic flows and the length of roading associated with a causeway it is possible to calculate likely contaminant loadings to an estuary. To assess the impact of contamination from a causeway compared with contamination from urban runoff and catchment erosion an input budget can be prepared. This will show the relative importance of that contamination coming from the causeway and the likely effect that this will have on general water quality. Williamson (1993) is a valuable source of guidance and information for assessing runoff impacts.

While it is difficult to control airborne contaminants runoff can be controlled by routing it through the drainage system and away from the estuary. This can also be used to prevent accidental road spillages from entering the water. There is also the possibility of using vegetated roadway margins for filtering runoff.

4.7 Construction impacts

Construction activity has the potential to increase suspended sediment levels in the water and possibly disturb birdlife. The severity of water quality impacts arising from construction are difficult to predict as they will depend on many different factors, including:

- the type of sediments in the estuary and those used for construction
- activity of heavy machinery in the estuary
- rainfall during the construction phase
- tidal flushing and currents in the estuary
- background turbidity levels in the estuary
- the duration of construction

However, as most estuaries have periodically high suspended sediment levels, estuarine organisms are generally resistant to adverse effects. Impacts can also be avoided by careful site management during the construction phase. Geo-textile barriers can be used in some situations to contain suspended solids. It may be possible to minimise disturbance to birdlife or disruption of fish spawning or migratory activity by timing construction to a period of the year when important species are absent.

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[1] Many of the reports cited in the references were not available in New Zealand and therefore abstracts obtained from 'Aquatic Sciences and Fisheries Abstracts' had to be relied upon.

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Appendix 1: Estuary causeways in the North and South Islands[1]. Sites are in geographical order, starting at the north of each island and proceeding eastward.

Name	Location	Reference	Structure[2] (bridge length)	Use	Total length (m)	Upstream estuary distance (m)[3]	Figure no.	Causeway type[4]		
								Emb.	Chan.	Is
North Island										
Kaimaumau Rd (1)	Rangaunu Hr	O04/343975	e/c	road	100	100		•		
Kaimaumau Rd (2)	Rangaunu Hr	O04/356992	e/c	road	200	200		•		
Kaimaumau Rd (3)	Rangaunu Hr	O04/321964	e/c	road	100	100		•		
Poko Pohaia Rd	Rangaunu Hr	O04/333883	e/c	road	150	150		•		
Omaia Is	Rangaunu Hr	O04/351886	e/c	road	600	1300				•
SH10	Taipa	O04/535893	e/b (100m)	road	350	3500			•	
Ryder Rd	Taipa	O04/534888	e/b (20m)	road	200	1600	Fig. 3.1		•	
Oruru Rd	Taipa	O04/533878	e/c	road	300	100		•		
SH10	Mangonui Hr	O04/606876	e/b (70m)	road	450	800	Fig. 3.2			•
Kohumaru Rd (1)	Mangonui Hr	O04/611874	e/b (70m)	road	500	1200				•
Kohumaru Rd (2)	Mangonui Hr	O04/618857	e/b (70m)	road	200	150		•		
Totara Nth Rd (1)	Whangaroa Hr	P04/760842	e/c	road	200	200		•		
Totara Nth Rd (2)	Whangaroa Hr	P04/750831	e/c	road	200	400		•		
Totara Nth Rd (3)	Whangaroa Hr	P04738820	e/b (100m)	road	400	900		•		
Whangaroa Rd	Whangaroa Hr	P04/788824	e/c	road	300	200		•		
Rangihoua Rd	Te Puna In	P04/083720	e/c	road	250	300		•		
Kerikeri In Rd	Kerikeri In	P05/005643	e/b (50m)	road	150	1200		•		
Puketona Rd	Waitangi	P05/077568	e/b (100m)	road	200	800		•		
Opua (1)	Kawakawa R	Q05/125532	e/c	rail	400	150		•		
Opua (2)	Kawakawa R	Q05/121527	e/c	rail	100	200		•		
Whangae Br	Kawakawa R	Q05/113520	e/b (100m)	rail	400	1600		•		
Kawakawa (1)	Kawakawa R	Q05/111506	e/b (50m)	rail	300	350		•		
Kawakawa (2)	Kawakawa R	Q05/117487	e/c	rail	500	200		•		
Waikare Rd (1)	Karetu R	Q05/127476	e/b (100m)	road	700	600		•		
Waikare Rd (2)	Waikare In	Q05/228511	e/b (70m)	road	200	300		•		
Russell Rd (1)	Waikare In	Q05/208556	e/c	road	200	350		•		
Russell Rd (2)	Waikare In	Q05/192551	e/b (100m)	road	250	600		•		
Russell Rd (3)	Waikare In	Q05/175549	e/c	road	150	150		•		

Appendix 1: Cont.

Name	Location	Reference	Structure^2 (bridge length)	Use	Total length (m)	Upstream estuary distance (m)^3	Figure no.	Causeway type^4 Emb.	Chan.	Is
Russell Rd (4)	Pomare Bay	Q05/145579	e/c	road	100	200		•		
Waipiro Bay	Waipiro Bay	Q05/222599	e/c	road	100	100		•		
Webb Rd	Helena Bay	Q06/348390	e/c	road	50	100		•		
Matapouri Rd	Matapouri Bay	Q06/473248	e/c	road	150	800			•	
Ngunguru Rd (1)	Ngunguru Est	Q06/463172	e/b (100m)	road	200	200		•		
Ngunguru Rd (2)	Ngunguru Est	Q06/448185	e/b (150m)	road	700	900		•		
Pataua Nth Rd (1)	Horahora Est	Q06/451138	e/c	road	100	100		•		
Pataua Nth Rd (2)	Horahora Est	Q06/450134	e/c	road	200	200		•		
Pataua Nth Rd (3)	Horahora Est	Q06/453131	e/c	road	100	250		•		
Riverside Dr	Whangarei Hr	Q07/334061	e/b (100m)	road	550	1200		•		
Otaika (1)	Whangarei Hr	Q07/306025	e/b (150&150m)	rail	1100	1200	Fig. 3.3	•		
Otaika (2)	Whangarei Hr	Q07/308010	e/c	rail	400	200	Fig. 3.3	•		
Oakleigh	Whangarei Hr	Q07/296962	e/c	rail	200	400		•		
SH1 (1)	Whangarei Hr	Q07/296955	e/b (50m)	road	100	1200		•		
SH1 (2)	Whangarei Hr	Q07/300953	e/b (150m)	road	400	1200		•		
SH1 (3)	Whangarei Hr	Q07/315947	e/b (100m)	road	400	1300		•		
SH1 (4)	Whangarei Hr	Q07/320945	e/c	road	400	1300		•		
Totara Rd	Whangarei Hr	Q07/315943	e/b (100m)	path	400	700		•		
Causeway Rd	Mangawhai Hr	R08/522636	e/c	road	100	400		•		
Insley St	Mangawhai Hr	R08/527622	e/b (70m)	road	500	1500		•		
Warkworth-Leigh Rd	Whangateau Hr	R09/683417	e/b (50m)	road	300	350		•		
Sadler Rd	Whangateau Hr	R09/682419	e/c	road	150	100		•		
Broadlands Dr	Whangateau Hr	R09/690385	e/b (100m)	road	800	2500	Fig. 3.4		•	
SH1	Puhoi R	R10/606179	e/c	road	250	450		•		
Esmonde Rd	Waitemata Hr	R11/681879	e/c	road	70	600		•		
Tuff Crater	Waitemata Hr	R11/673868	e/c	road	350	900		•		
Herald Is	Waitemata Hr	R11/575898	e/c	road	350	1000	Fig. 3.5			•
Upper Harbour Br	Waitemata Hr	R11/590894	e/c/b (600m)	road	1150	100		•		
Whau River	Waitemata Hr	R11/582811	e/b (100m)	road	500	5000			•	
Waterview In (1)	Waitemata Hr	R11/597799	e/c	road	200	800	Fig. 3.6	•		
Waterview In (2)	Waitemata Hr	R11/610798	e/c/b (100m)	road	1400	1800	Fig. 3.6		•	

Appendix 1: Cont.

Name	Location	Reference	Structure[2] (bridge length)	Use	Total length (m)	Upstream estuary distance (m)[3]	Figure no.	Causeway type[4] Emb.	Chan.	Is
Judges Bay	Waitemata Hr	R11/700822	e/c	rd/rl	550	200		•		
Tamaki Dr	Waitemata Hr	R11/708816	e/b (50m)	road	1400	3000			•	
Main trunk Rly (1)	Hobson Bay	R11/710813	e/c	rail	2100	1400		•		
Main trunk Rly (2)	Orakei Basin	R11/723803	e/c	rail	700	700		•		
SH1	Tamaki R	R11/758709	e/b (100m)	road	200	2000			•	
Great Sth Rd	Tamaki R	R11/751702	e/c	road	100	1100		•		
Causeway Rd	Waiheke Is	S11/923873	e/c	road	300	800		•		
O'Brien Rd	Waiheke Is	S11/943866	e/b (50m)	road	200	700		•		
Orapiu Rd	Waiheke Is	S11/012841	e/c	road	150	500		•		
Whangapoua Rd	Whangapoua Hr	T10/437925	e/b (50m)	road	600	250		•		
Grahams Stm	Tairua Hr	T11/647633	e/b (100m)	road	200	400		•		
Oturu Stm	Tairua Hr	T12/622595	e/b (20+20m)	road	1000	-	Fig. 3.7	•		
Opoutere Rd	Wharekawa Hr	T12/648499	e/b (100m)	road	250	300		•		
SH25	Whangamata Hr	T12/633435	e/c	road	100	200		•		
Wentworth R	Whangamata Hr	T12/645408	e/b (100m)	road	300	1800			•	
Mangawhai Bay	Tauranga Hr	U14/782892	e/b (100m)	rail	400	1700		•		
Otumoetai	Tauranga Hr	U14/854866	e/c	rail	100	300		•		
Waikareao Est	Tauranga Hr	U14/891875	e/b (150m)	road	300	3000			•	
Whareroa Marae	Tauranga Hr	U14/905869	e/b (400+100m?)	road	1400	8000			•	
Waimapu Est	Tauranga Hr	U14/892825	e/b (150m)	road	700	1500			•	
Maungatapu	Tauranga Hr	U14/914833	e/b (300m)	road	700	4300			•	
Maheka Pt	Tauranga Hr	U14/905855	e/b (400m)	rail	1100	6700			•	
Wainui Rd (1)	Ohiwa Hr	W15/669495	e/c	road	200	300		•		
Wainui Rd (2)	Ohiwa Hr	W15/663485	e/b (100m)	road	300	200		•		
Wainui Rd (3)	Ohiwa Hr	W15/667470	e/c	road	100	50		•		
Ohiwa Loop Rd	Ohiwa Hr	W15/740460	e/c	road	600	150		•		
Reeves Rd	Ohiwa Hr	W15/749463	e/c	road	100	400		•		
Lowlevel Crossing	Ahuriri Est	V21/419481	e/b (50m)	road	200	7000			•	
Watchman Rd	Ahuriri Est	V21/433850	e/c	road	150	300	Fig. 3.9	•		
Road/rail Br	Ahuriri Est	V21/435837	e/b (400m)	rd/rl	450	8500			•	
SH2	Ahuriri Est	V21/445840	e/b (100m)	road	350	9400			•	

Appendix 1: Cont.

Name	Location	Reference	Structure[2] (bridge length)	Use	Total length (m)	Upstream estuary distance (m)[3]	Figure no.	Causeway type[4]		
								Emb.	Chan.	Is
Pauatahanui	Porirua Hr	R27/670098	e/b (200m)	rd/rl	300	3600			•	
Kawhia Hr Rd	Kawhia Hr	R16/723400	e/b (70m)	road	150	3000			•	
SH31 (1)	Kawhia Hr	R15/731485	e/b (100m)	road	250	1200		•		
SH31 (2)	Kawhia Hr	R15/717497	e/b (50m)	road	200	200		•		
Joy's Pt	Raglan Hr	R14/743751	e/b (70m)	road	150	1300		•		
Pararekau Is (1)	Manukau Hr	R12/803577	e/c	road	100	-				•
Pararekau Is (2)	Manukau Hr	R12/799579	e/c	road	100	-				•
SH1 (1)	Manukau Hr	R12/813583	e/c	road	400	1300	Fig. 3.10	•		
SH1 (2)	Manukau Hr	R12/809593	e/b (80m)	road	100	500	Fig. 3.10		•	
Pukaki Ck	Manukau Hr	R11/713647	e/b (70m)	road	350	3000				•
Wiroa Is	Manukau Hr	R11/708639	e/c	road	200	-				•
Old Mangere Br	Manukau Hr	R11/695726	e/b (300m)	road	600	3900			•	
New Mangere Br	Manukau Hr	R11/697727	e/b (400m)	road	700	3800			•	
Harania Ck	Manukau Hr	R11/723709	e/b (100m)	road	250	600		•		
South Head Rd (1)	Kaipara Hr	Q10/307086	e/c	road	200	100		•		
South Head Rd (2)	Kaipara Hr	Q10/314077	e/c	road	100	100		•		
South Head Rd (3)	Kaipara Hr	Q10/316077	e/c	road	100	150		•		
South Head Rd (4)	Kaipara Hr	Q10/325063	e/c	road	550	500		•		
South Head Rd (5)	Kaipara Hr	Q10/348059	e/c	road	50	350		•		
Fordyce Rd	Kaipara Hr	Q09/395349	e/c	road	500	-				•
Kellys Bay Rd	Kaipara Hr	P08/078512	e/b (50m)	road	600	1100		•		
Wairere R	Hokianga Hr	O05/637489	e/b (50m)	road	400	1500		•		
Kohukohu Rd	Hokianga Hr	O05/592528	e/b (50m)	road	300	1300		•		
Tapuwae	Hokianga Hr	O05/508487	e/b (50m)	road	200	1000		•		
Otengi Rd	Hokianga Hr	O05/460452	e/b (50m)	road	350	900		•		
Whakarapa R	Hokianga Hr	O05/452451	e/c	road	200	200		•		
Rangi Pt Rd	Hokianga Hr	O06/458400	e/c	road	400	800	Fig. 3.11	•		
Kauhanga Rd	Whangape Hr	O05/313523	e/b (30m)	road	300	600		•		

Appendix 1: Cont.

Name	Location	Reference	Structure[2] (bridge length)	Use	Total length (m)	Upstream estuary distance (m)[3]	Figure no.	Causeway type[4]		
								Emb.	Chan.	Is
South Island										
SH60	Parapara In	M25/833527	e/c	road	600	400		•		
Waitapu	Golden Bay	N25/936423	e/c	road	400	1300				•
Otuwhero In	Tasman Bay	N26/093213	e/b (50+50m)	road	300	100		•		
Wharf Rd	Moutere In	N27/115080	e/c	road	900	1100	Fig. 3.12		•	
SH60 (1)	Moutere In	N27/117070	e/b (100m)	road	700	500	Fig. 3.12		•	
SH60 (2)	Moutere In	N27/112063	e/c	road	200	100		•		
SH60 (3)	Moutere In	N27/113061	e/c	road	100	200	Fig. 3.13	•		
SH60 (4)	Moutere In	N27/115053	e/c	road	250	300	Fig. 3.13	•		
SH60 (5)	Moutere In	N27/124045	e/c	road	400	300	Fig. 3.13	•		
SH60 (6)	Moutere In	N27/130037	e/c	road	250	250		•		
SH60 (7)	Moutere In	N27/134033	e/c	road	100	100		•		
SH60 (8)	Moutere In	N27/135032	e/c	road	100	100		•		
SH60 (9)	Moutere In	N27/138029	e/c	road	100	100		•		
Rabbit Is	Waimea In	N27/218919	e/c	road	150	800		•		
Bests Is	Waimea In	N27/227900	e/c	road	400	2100				•
Bells Is	Waimea In	N27/235905	e/c	road	250	2500				•
SH6	Nelson Haven	O27/367969	e/c	road	400	150		•		
McCormacks Bay	Avon-Heathcote Est	N36/879390	e/c	road	600	400		•		
Main Sth Railway (1)	Otago Hr	I44/227833	e/c	rail	1000	200		•		
Main Sth Railway (2)	Otago Hr	I44/219819	e/c	rail	300	100		•		
Main Sth Railway (3)	Otago Hr	I44/216810	e/c	rail	500	200		•		
Main Sth Railway (4)	Otago Hr	I44/213803	e/c	rail	500	200		•		
Main Sth Railway (5)	Otago Hr	I44/204797	e/c	rail	100	50		•		
SH88 (1)	Otago Hr	I44/225835	e/c	rail	200	100		•		
SH88 (2)	Otago Hr	I44/219820	e/c	rail	100	100		•		
Andersons Bay	Otago Hr	I44/174765	e/b (100m)	road	350	500		•		
Allans Bch Rd	Hoopers Inlet	I44/288812	e/c	road	200	400		•		
Tiwai Rd	Awarua Bay	E47/586948	e/b (500m)	road	1200	9000	Fig. 3.14		•	
Disused Rail Br	Jacobs R Est	D46/257169	e/b (150+150m)	rail	800	5000			•	

Appendix 1: Cont.

Name	Location	Reference	Structure[2] (bridge length)	Use	Total length (m)	Upstream estuary distance (m)[3]	Figure no.	Causeway type[4]		
								Emb.	Chan.	Is
SH67	Westport	K29/957385	e/b (200m)	road	350	1100			•	
Dry Rd (1)	Whanganui In	M25/689641	e/b (100m)	road	200	1300		•		
Dry Rd (2)	Whanganui In	M25/694645	e/c	road	150	400		•		
Dry Rd (3)	Whanganui In	M25/701647	e/b (100m)	road	300	900		•		
Dry Rd (4)	Whanganui In	M25/707653	e/b (100m)	road	300	700		•		
Dry Rd (5)	Whanganui In	M25/708650	e/c	road	100	100		•		
Dry Rd (6)	Whanganui In	M25/710650	e/c	road	100	300		•		
Dry Rd (7)	Whanganui In	M25/729659	e/b (70m)	road	20	1100		•		
Dry Rd (8)	Whanganui In	M25/731659	e/c	road	100	100		•		
Dry Rd (9)	Whanganui In	M25/739660	e/c	road	100	400		•		
Dry Rd (10)	Whanganui In	M25/742662	e/b (50m)	road	300	1700		•		
Dry Rd (11)	Whanganui In	M25/776686	e/b (100m)	road	200	1900		•		
Dry Rd (12)	Whanganui In	M25/786689	e/c	road	100	100		•		
Dry Rd (13)	Whanganui In	M25/787690	e/c	road	250	400		•		
Dry Rd (14)	Whanganui In	M25/787694	e/c	road	100	100		•		
Kaihoka Rd (1)	Whanganui In	M24/790702	e/c	road	100	200		•		
Kaihoka Rd (2)	Whanganui In	M24/788721	e/c	road	100	100		•		

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[1] Data source is NZMS 260 1:50,000 topographic maps.

[2] Causeway structure defined as embankment (e) with culverts (c) and/or bridge (b), and the length of bridging. Estuary crossings which are entirely bridged, with no causeway, are not included.

[3] The length of estuary upstream of the causeway, via main flow path.

[4] Whether the causeway cuts off a small tidal embayment or creek (Emb), crosses the main channel or an important flow (Cha), or runs between the shore and an island (Is).

Appendix 2: Aerial photographs used in analysis of impacts of causeways on estuaries. Source of photographs is New Zealand Aerial Mapping, Hastings.

Site	Survey #	Run #	Date
NORTH ISLAND			
SH10, Taipa	-	45829(counter #)	9/4/48
	350	1861/2	12/10/50
	5006	F/1	11/12/76
	5932	C/15	28/10/81
	8431	C/1	19/12/84
Kohumaru Rd, Mangonui Hr	350	1861/9	9/4/48
	5006	F/1	11/12/76
	5932	C/18	28/10/81
Russell Rd, Whangaruru Hr	5932	11/45	3/10/81
Otaika, Whangarei Hr	212 (Film 189)	409/32	28/5/42
	5091	I35	10/1/79
	8048	F1/3,4,6	8/2/82
	8328	F10	20/2/84
Broadlands Dr, Whangateau Hr	577	1940/55	24/10/53
	8104	J/32	2/9/82
Herald Is, Waitemata Hr	562	B/76809	14/10/50
	8772	G/11	20/9/88
Waterview In., Waitemata Hr	147	95/22 & 23	14/4/40
	583	1918/42 & 44	9/9/55
	8772	L/13	20/3/88
Whau In., Waitemata Hr	147	95/21	14/4/40
	8772	L/11	20/3/88
Railway & Tamaki, Hobson Bay	146	B/14	22/4/40
	8772	K/5	12/11/87
Oturu, Tairua Hr	8163	0/14	10/1/83
	292 (Film 292)	975 & 976	?
Tauranga Hr	229 (Film 231)	500/48	9/2/48
	8626	H/10	19/3/86
Ohiwa Hr	256 (Film 347)	680/52	26/9/44
	8240	D/8	23/9/83
Ahuriri Es.	563	D/74201, 15, 18, 20	28/9/50
	8993	C/4	9/12/88
Pukaki Ck, Manukau Hr	583	1925/1975	19/8/60
			7/3/85
Pahurehure In., Manukau Hr	583	1928/2333	20/8/60
			7/3/85
	8825	B/3	14/4/91
Kelly's Bay Rd, Kaipara Hr	212 (Film 806)	430/9	24/10/53
	2892	B/5	7/12/75
	8745	A/4	6/4/87
Rangi Pt Rd, Hokianga Hr	1223	2586/13	2/5/60
	2896	D/8 & D/9	8/12/75
	5006	B/24	11/12/76
	5932	N7	3/10/81
	8328	B/1	21/2/84

Appendix 2: Cont.

Site	Survey #	Run #	Date
SOUTH ISLAND			
Wharf Rd & SH1-9, Moutere In.	379	1197/31753	27/3/47
		1196/31799	27/3/47
		1195/31804	27/3/47
	8531	A/11 & B/12	13/9/85
Rough, Rabbit, Bests	379	1202/43 & 45	6/12/46
& Bells Is's, Waimea In.	379	1203/42 & 44	6/12/46
	8531	E/16	13/9/85
McCormacks By, Avon Heathcote	559	H/26	13/9/50
	2860	I/1	17/9/75
	8389	H/18	28/9/84
Andersons & Railway, Otago Hr	399 (Film 476)	Q/33068	29/3/47
	399 (Film 476)	L/33629	16/4/47
	9087	J/11	17/3/90
Tiwai Rd, Awarua Bay	537	1626/12 & 13	15/3/51
	8452	D/9	17/10/85

Appendix 3:

Empirical calculations

Empirical formulae provide a means for doing simple calculations to size causeway openings, thereby minimising the impacts on tidal flow regime and sediment transport patterns. The formulae are derived from field surveys and laboratory experiments and are used extensively in engineering for making preliminary estimates, and to assess whether more sophisticated computational approaches are necessary. They can be used to calculate stable channel cross-sectional area and scour depth (Hume 1991). Parameters derived from field studies, charts or the literature are substituted in the formulae and the calculations made on a pocket calculator. Recommended formulae were given in Section 4.2, however, the range of formulae which can be applied are presented below.

Stable channel cross-sectional area

(1) The Lacey (1929-58) formula allows a river channel cross-sectional area A (m^2), stable at peak discharge, to be calculated by:

$$A = \frac{1.26\,(1.81)\,Q^{5/6}}{f^{1/3}}$$

where Q is the maximum (or peak) discharge (m^3/s) and the coefficient f is a silt factor (which accounts for the cohesion associated with fine sediment) expressed as:

$$f = 1.59\,\sqrt{d_{50}}$$

where d_{50} is the mean grain size (millimetres).

(2) The Simons & Albertson (1960) formula predicts a wetted area A (m^2) of a stable river channel as:

$$A = 1.995.(K_1.Q^{0.5})(K_2.Q^{0.36})$$

where Q is the peak discharge (m^3/s), and K_1 and K_2 are coefficients to account for the types of channel bed and banks and can be obtained from Table 10.3 in Henderson (1966).

Hume (1991) tested the Lacey and the Simons & Albertson formulae using field data from Auckland estuaries and found that in the estuarine cases the formulae tend to underestimate throat area and should only be used in small tidal channels dredged (and maintained) to regular cross section. Furthermore, because they tend to underestimate the throat cross section the bed will scour and tidal exchange may be reduced.

(3) The Bruun (1978) formula is widely used for making a first approximation of tidal inlet throat cross-section area for design purposes as:

$$A = \frac{c.\Omega.\pi}{V_{mm}.T}$$

where A is the throat area at mid tide (m^2) coinciding with peak flow, Ω is the spring tide prism or volume of water entering the estuary on the incoming tide (m^3), V_{mm} is the mean maximum (spring tide) velocity (m/s) over the cross section, T is the measured tidal period (sec) and c is a coefficient (dimensionless) which accounts for the non-sinusoidal nature of the current in the inlet. Keulegan and Hall (1950) observed that $c = 0.86$ gave good agreement with most measurements, and Bruun (1978) suggested 0.8-1.0 for inlets on sandy open coasts.

Hume (1991) calculated c for Auckland tidal waterways as being 1.15 to 1.59 (averaging 1.34), and recommended that for best results that c in the Bruun formula be scaled according to the size of the tidal prism using the equation:

$$c = 3.571 - 0.331 \log \Omega$$

(4) Hume (1991) using data for tidal waterways in the Auckland area derived an empirical formula that described the stable channel area as:

$$A_{mtl} = 7.39 \times 10^{-6}.\Omega_s^{1.164}$$

where A_{mtl} is the channel area at mid tide (m^2) coinciding with peak flow, and Ω_s is the spring tide prism (m^3).

This is probably the best formula to use for estimating stable channel area in estuaries which are similar to those of Auckland i.e., shallow estuaries with extensive intertidal areas containing fine sands/muds

Scour depth

The Maza and Echavarria (1973) formula estimates maximum scour depth in river beds formed of sand and gravel. In a straight reach the maximum depth from design water level to scoured bed level, D_s (m) is given by:

$$D_s = 0.365 \frac{D_o}{D_{mo}} \cdot \frac{Q^{0.784}}{B^{0.784} \cdot d_{50}^{0.157}}$$

where D_o is the depth from design water level (WL = water level at peak discharge, m) to the lowest point in cross section, D_{mo} is the depth from WL to mean bed level (m), Q is the peak discharge (m^3/s) in the tidal cycle, B is the channel width at peak discharge (m), and d_{50} the sediment mean grain size (m). In New Zealand the method is recommended for use in estimating scour depth for bridge and causeway waterway design (Ministry of Works and Development 1979).

Hume (1991) found that the Maza and Echavarria (1973) formula estimates maximum scour depth with an accuracy of about ±10% in estuaries.

Hydraulic analysis

The objective of hydraulic analysis is to determine the discharge through a causeway opening or culvert, for a specified pair of headwater and tailwater levels. This is approached by firstly computing the energy losses for a specified headwater level and a trial discharge, and then examining the computed tailwater level to derive an adjustment to apply to the discharge to improve the match between the computed and specified tailwater levels. This iterative method is known as the 'direct step' method (Ven Te Chow, 1959).

The method follows directly from the basic energy equations for open channel flow. The total energy (E) at any section is given by:

$$E = y + \frac{V^2}{2g} \qquad (1)$$

where y is the hydraulic head (m), V the mean cross-section velocity (m s^{-1}), and g the gravitational acceleration (m s^{-2}). The energy losses at the entrance (h_e) are normally expressed in terms of an entrance loss coefficient (k_e) and the mean cross-sectional velocity at the culvert entrance, viz:

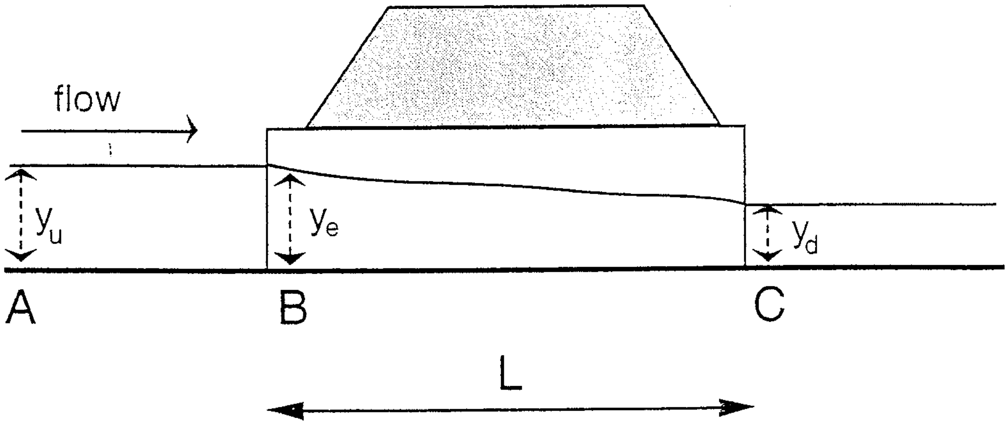
$$h_e = k_e \frac{V_e^2}{2g} \qquad (2)$$

The hydraulic drag loss in the pipe (h_f) is calculated as:

$$h_f = L\left(\frac{nQ}{AR^{2/3}}\right)^2 \qquad (3)$$

where Q is the discharge (m^3 s^{-1}), L is the pipe length (m), A is the cross-sectional area of the flow (m^2), R the hydraulic radius (m), and n is the Manning friction coefficient for the culvert material. The hydraulic radius (R) is the flow area (A) divided by the wetted perimeter (P), i.e., $R = A/P$.

Given the following hypothetical culvert (or a similar bridge configuration):



The total energy at sections A and B (in the above figure) can be equated to determine the water level immediately inside the culvert entrance:

$$E_A = E_B + h_e$$

The velocity in the channel upstream of the culvert (v_u) is negligible.

i.e., $$y_u = \left(y_e + \frac{V_e^2}{2g}\right) + k_e \frac{V_e^2}{2g}$$

or $$y_e = y_u - (1 + k_e)\frac{V_e^2}{2g} \qquad (4)$$

Thus given a trial discharge Q^*, and initially using y_u, rather than y_e which is not known at this stage, for the water level at the culvert entrance, the velocity head can be calculated to give an approximate value for y_e. Using this value of y_e a more accurate value for the velocity head leads to a better estimate of y_e.

In the direct step method the balance of the hydraulic head available ($y_e - y_d$) to drive the flow through the culvert is subdivided into a number of discrete distance increments along the culvert. The energy equations are rearranged to calculate the corresponding length of a culvert section required to generate the head loss for a specified trial discharge, Q^*. A systematic trial and error procedure can therefore be employed to determine the precise flow Q to generate the overall hydraulic head (energy) loss ($y_u - y_d$).

This procedure can be applied to determine the optimum combination of bridges and/or culverts in a causeway to maintain the tidal prism volume and shape of the discharge-time curve at a site.