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HYDROLOGY OF THE CATCHMENTS DRAINING TO THE PAUATAHANUI INLET

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Hydrology of the catchments draining to the Pauatahanui Inlet

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Wellington

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A study of the hydrology of the catchments draining to the Pauatahanui Inlet was undertaken as part of an interdepartmental environmental study.

Fresh water inflows and sediment yields were evaluated for the six significant inflows to the Inlet by correlating each catchment's instantaneous flows with one continuous streamflow record. Success with this technique is demonstrated, affording significant savings.

Water yields, and sediment concentrations and yields for each catchment were established. How these varied between catchments of differing size (approximately 1 to 40km²), relief, and land use (pastoral to the earthwork phase of urban development) were identified.

Only mean inflows and greater were found to be a significant contribution to the tidal compartment of the Inlet.

Floods were confirmed as the major contributors of sediment and events of various return periods were related to the long term mean annual sediment yield. Variations of an order of magnitude in annual sediment yields are apparent.

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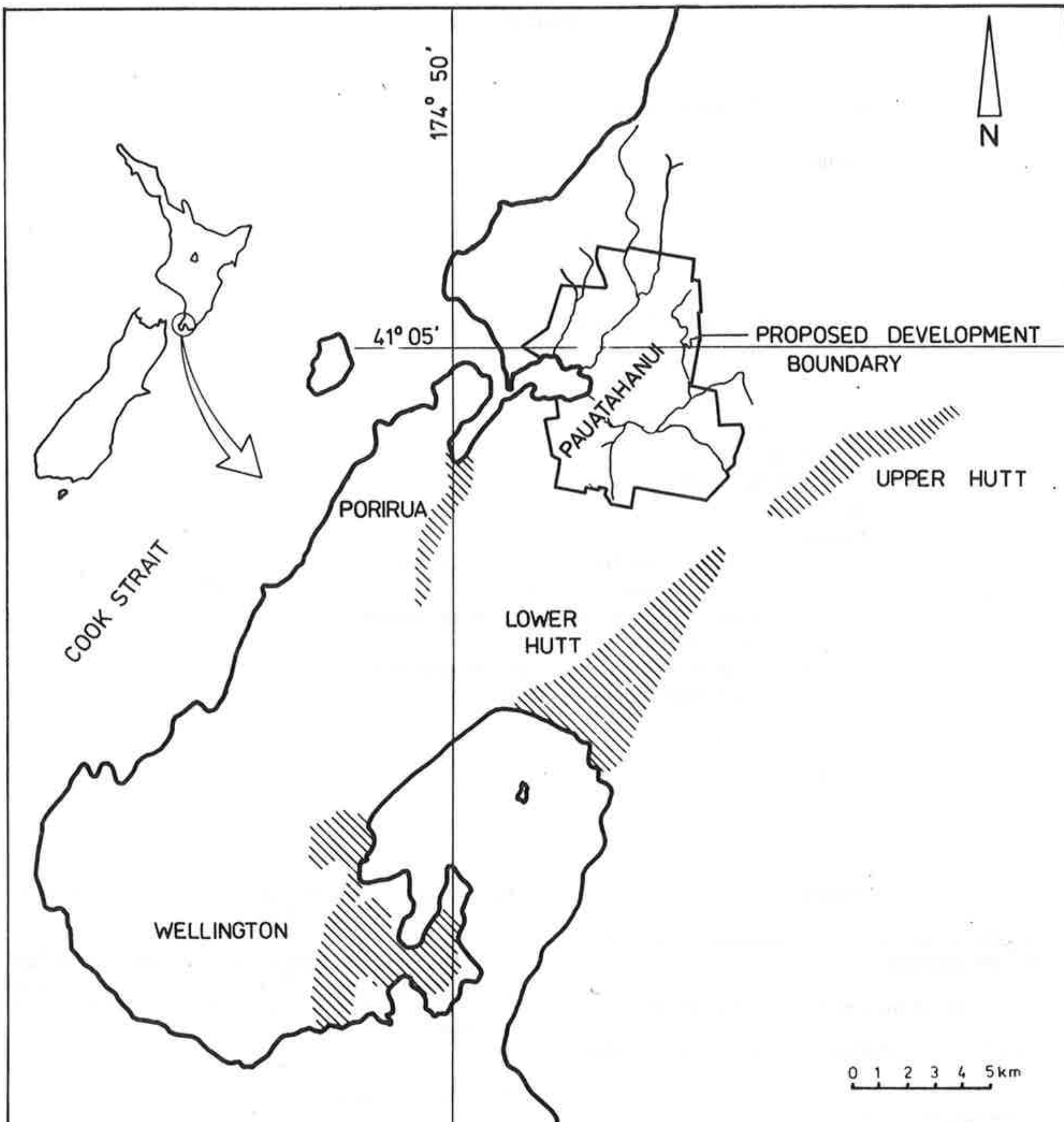


Figure 1 General location of proposed development area of the Pauatahanui Basin.

INTRODUCTION

The Pauatahanui Comprehensive Development Plan (Hutt County Council 1970) outlined a proposed urban development scheme for the Pauatahanui Basin which was to accommodate a projected population of 45,000 by 1986 and 80,000 by the turn of the century. The proposed Pauatahanui Development Area, comprising 71 km^2, drains to the Pauatahanui Inlet, (Fig.1) a shallow arm of the Porirua Harbour. The Pauatahanui Environmental Programme (PEP) was therefore set up to study the effects of such urbanisation on the Inlet and its catchment area with a view to understanding the present environment or ecosystem, to define its sensitive features, to produce data of assistance to planners to enable wise management of this natural resource as a viable entity, and to establish base lines for monitoring changes resulting from development.

In 1975 the Pauatahanui Environmental Research Committee (PERC) prepared a three year research programme. Since the study objectives encompassed wide ranging interests the research required cooperative involvement of a number of Government departments and Victoria University of Wellington.

This paper details that part of the study, dealing with the hydrology of the catchments draining to the Inlet, which was undertaken by the Water and Soil Division, Ministry of Works and Development. It sought to evaluate the spatial and temporal distribution of the stream flows and sediment loads, and their effects on the Inlet.

Consideration was also to be given to the effects of urbanisation on the catchment hydrology based on observations from Browns Stream, a completely developed sub-catchment of the Inlet.

Following the initiation of the research programme it became clear that the 1970 population projections would not be realised due to a general depression in the economic climate. Nevertheless the programme proceeded because sound base line data would be obtained and sensitive features would be identified and understood. This would enable wise management of the Inlet to be implemented regardless of its rate of development.

CATCHMENT CHARACTERISTICS

The total catchment area draining to the Pauatahanui Inlet is 108.6 km^2 of which six main streams, the Pauatahanui, Horokiwi, Duck, Kahao, Ration and Browns drain 105.5 km^2 (97%) of the total area. The remaining 3.1 km^2 comprises several extremely small catchments draining mainly the narrow northern edge of the Inlet between the Kahao Stream and the Inlet's confluence with the Porirua Harbour. The water surface area of the Inlet at high tide is 4.4 km^2. (Fig.2).

Details of the Pauatahanui, Horokiwi, Duck, Kahao, Ration and Browns predominant catchment characteristics are given in Table 1. All the sub-catchments rise gently up to the 100 metre contour and then generally more steeply towards the catchment boundaries which feature as well defined ridges.

The Pauatahanui area is traversed by faults of two separate ages which have influenced landscape development in the catchment (Healy 1980). An older fault system (West Wairarapa and Horokiwi–Belmont) had a northerly trend and initially influenced the drainage system in early Pleistocene times. Later a fault system aligned to the north-east captured much of the major drainage. Movement of the younger faults (Owhariu, Moonshine and Haywards) commenced in the early Pleistocene after the previously active northerly trending faults had ceased to move. These north-easterly trending faults are still active. Buckling associated with these faults produced irregularly distributed hills and hollows modifying the very large west to east uplift surface associated with the West Wairarapa Fault (See Fig.2).

Table 1: Catchment characteristics

Catchment	Catchment Area (km^2)	Altitudinal Range (m)	Main Channel Length (m)	Average Channel Slope (m/m)	Catchment Cover
Pauatahanui	43.4	431	9600	0.023	Pastoral; pockets of scrub and bush
Horokiwi	32.9	530	12900	0.022	Pastoral; pockets of scrub and bush
Duck	10.5	490	7200	0.034	Pastoral to Urban Transition (approx. 20%)
Kahao	11.3	439	6000	0.037	Pastoral; pockets of scrub
Ration	6.13	260	4800	0.027	Pastoral; pockets of scrub
Browns	1.23	157	1200	0.065	Urban development (Earthworks phase)
TOTAL	105.5				

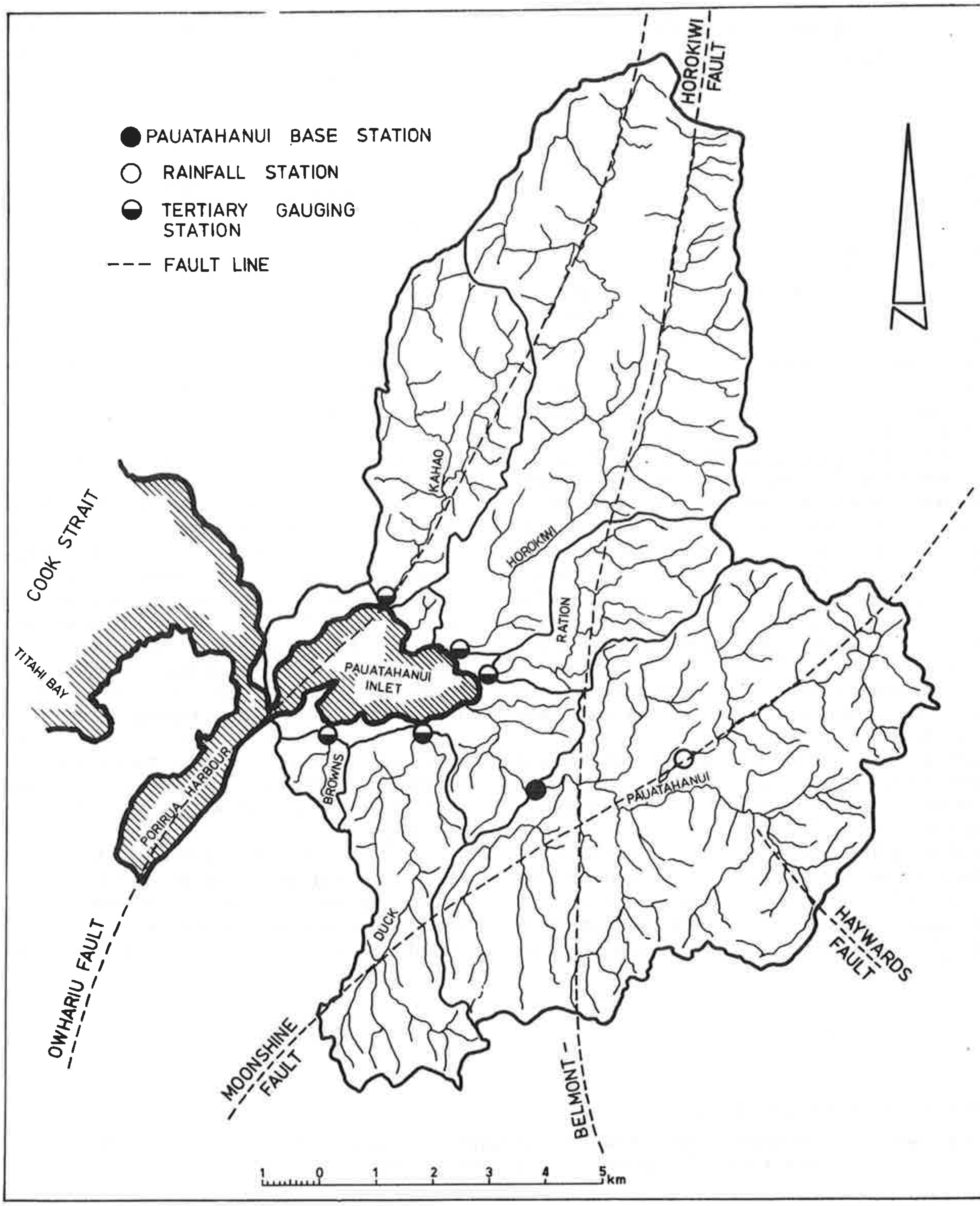


Figure 2 Catchments draining to the Pauatahanui Inlet.

The bedrock is indurated siliceous sandstones with beds of indurated mudstone known as the Wellington greywacke argillite. The covering of the valley floors is mainly post-glacial valley till and estuarine beds of silt, gravel and clay varying in depth from 15 to 45 metres overlain by a general loess cover.

The present Inlet is a glacio-eustatically drowned valley of the last glaciation terrace of the Pauatahanui Stream and with changing catchment areas the Inlet has tended to silt up. The valleys have filled with alluvial sediments but the present rivers do not appear to have entered the mature stage of the erosion cycle because they have been periodically rejuvenated by uplift and sea level changes (Hutt County Council 1970).

METHODS

As the stream flows and sediment loads reflect the characteristics and condition of each catchment a programme to monitor continuous water and sediment flows from the six catchments was established. A stable controlled section was located on the Pauatahanui Stream in the gorge at NZMS 1 map reference N 160: 471460 and a permanent water level recording station (Site No. 30802) was installed. Flow recording commenced on 30 May 1975.

Economics and logistics did not allow the establishment of similar installations near the mouths of the other five streams; therefore a concurrent stream flow gauging programme was initiated in order that flow characteristics for each of the five streams could be estimated by correlation with the recorded flow data from the Pauatahanui control station. Depth integrated suspended sediment sampling was undertaken with all stream flow measurements with a view to establishing water versus sediment discharge relationships (i.e. sediment ratings) for the six streams so that their sediment discharges could be estimated. The procedure used was that of Hopkins & Moreton (1959).

The Pauatahanui Stream level records from 1 June 1975 to 31 May 1977 (Fig.6a) were used as this represented two years of record within the three year PEP study period. Flows for the Horokiwi, Duck, Kahao, Ration and Browns Streams were generated at 15 minute intervals from the Pauatahanui flow record using the respective regression equations, thus producing two years of continuous synthetic water and sediment flow data for all five streams.

As flow measurements for all the streams except the Pauatahanui were taken at locations close to the stream mouths (immediately beyond the tidal influence) all the flows represent each stream's total input to the Inlet. The Pauatahanui Stream data was increased by the ratio of the total Pauatahanui Stream catchment area to the catchment area above the recorder station ($43.4 \div 39.2 = 1.107$) to obtain the Pauatahanui Stream contribution to the Inlet.

RESULTS

Stream Flow Correlations

Despite differing storm patterns and catchment characteristics (e.g. catchment areas as small as 3.2% of the Pauatahanui Stream catchment area) excellent correlations were obtained with the Horokiwi, Duck and Kahao Streams while acceptable correlations were obtained with the Ration and Browns Streams (Fig.3). The correlation coefficient generally diminished proportionately by the extent to which the catchment areas were less than that of the Pauatahanui, this probably being due to the faster response times associated with the smaller catchments. All correlations explained a high percentage of the variation (minimum 96.8%) thus justifying the use of the respective regression equations for the generation of continuous synthetic flow data for each of the five streams from the Pauatahanui records.

Suspended Sediment

Suspended sediment samples taken over a range of flows revealed concentrations from 5 to 1500 mgl^{-1}).

The lowest concentrations were recorded in the Ration Stream (5 to 250 mgl^{-1}) and reflect the stable nature of this small low relief pastoral catchment.

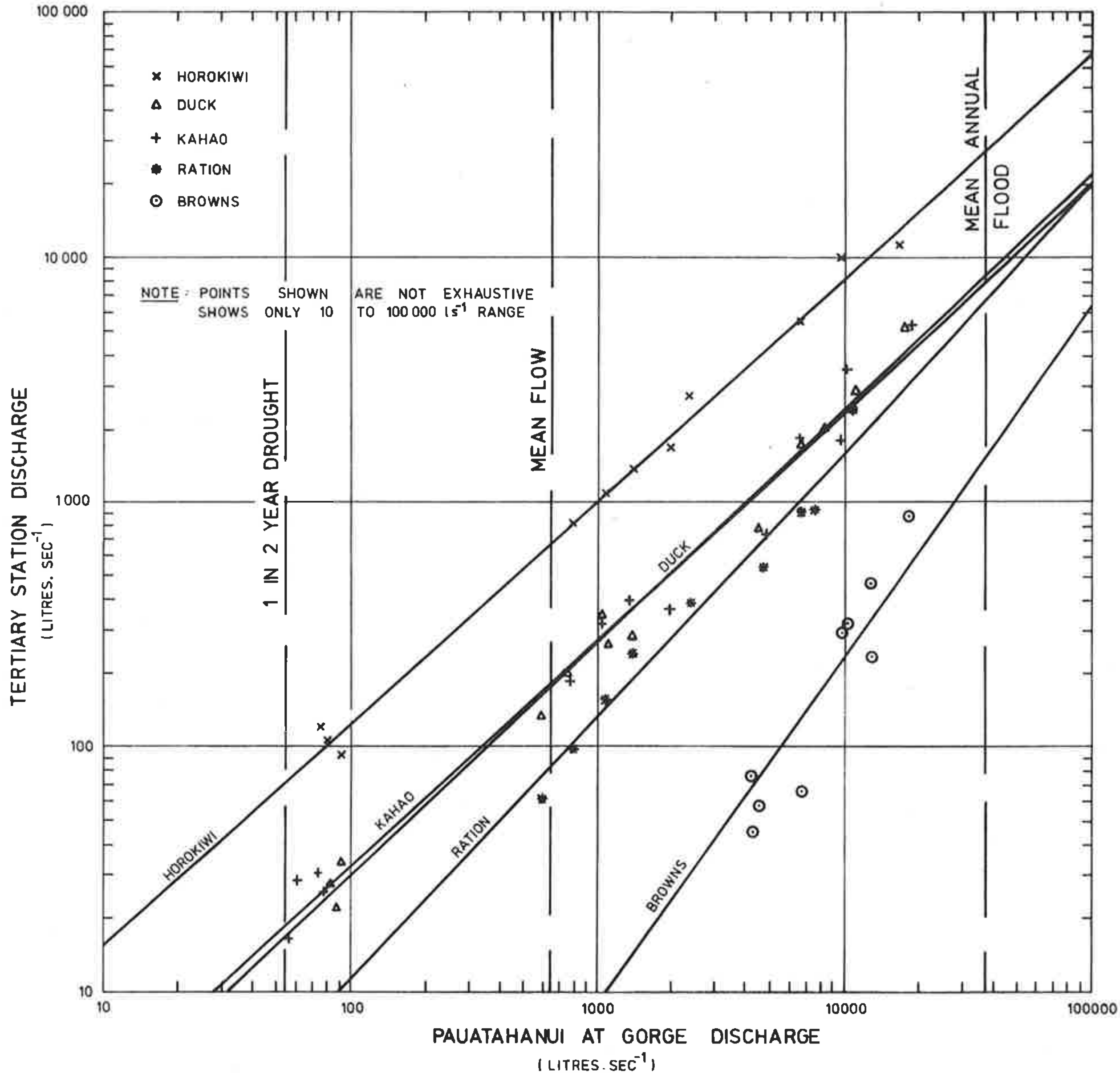
The Pauatahanui, Horokiwi and Kahao Stream sediment concentrations ranged from 5 to 500 mgl^{-1} and were seen to be typical of the relatively stable larger catchments.

Concentrations in the Duck Stream ranged from 7 to 1000 mgl^{-1}, the higher upper limit being due to the earthworks associated with urban development in the upper catchment. The reduction of the lower concentrations to a level similar to those from the natural catchments is attributed to the large detention dams in the catchments, downstream of the development.

As expected, the highest concentrations were measured in the Browns Stream due to major earthwork development throughout its entire catchment area. Concentrations ranged from 25 to 1500 mgl^{-1} downstream of the silt pond. Although the silt pond was effective during most storm events and large amounts of sediments were trapped, higher concentrations were recorded at the outlet of the pond than at the inlet during several very large events (e.g. inlet concentration = 1000 mgl^{-1} and outlet concentration = 1300 mgl^{-1} during flood of 16 July 1976). These results indicate negligible settling of sediments and a stirring up of previously impounded sediments by the incoming waters. This suggests either inadequate pond capacity and/or too infrequent excavation of the pond. From observations, greater attention to energy dissipation of incoming waters prior to their entry into the pond would have reduced the very noticeable 'stirring up' effect.

Suspended sediment discharges were calculated and the water/sediment discharge ratings were established for all six streams (Fig.4). These ratings were assumed to apply to both rising and falling stages.

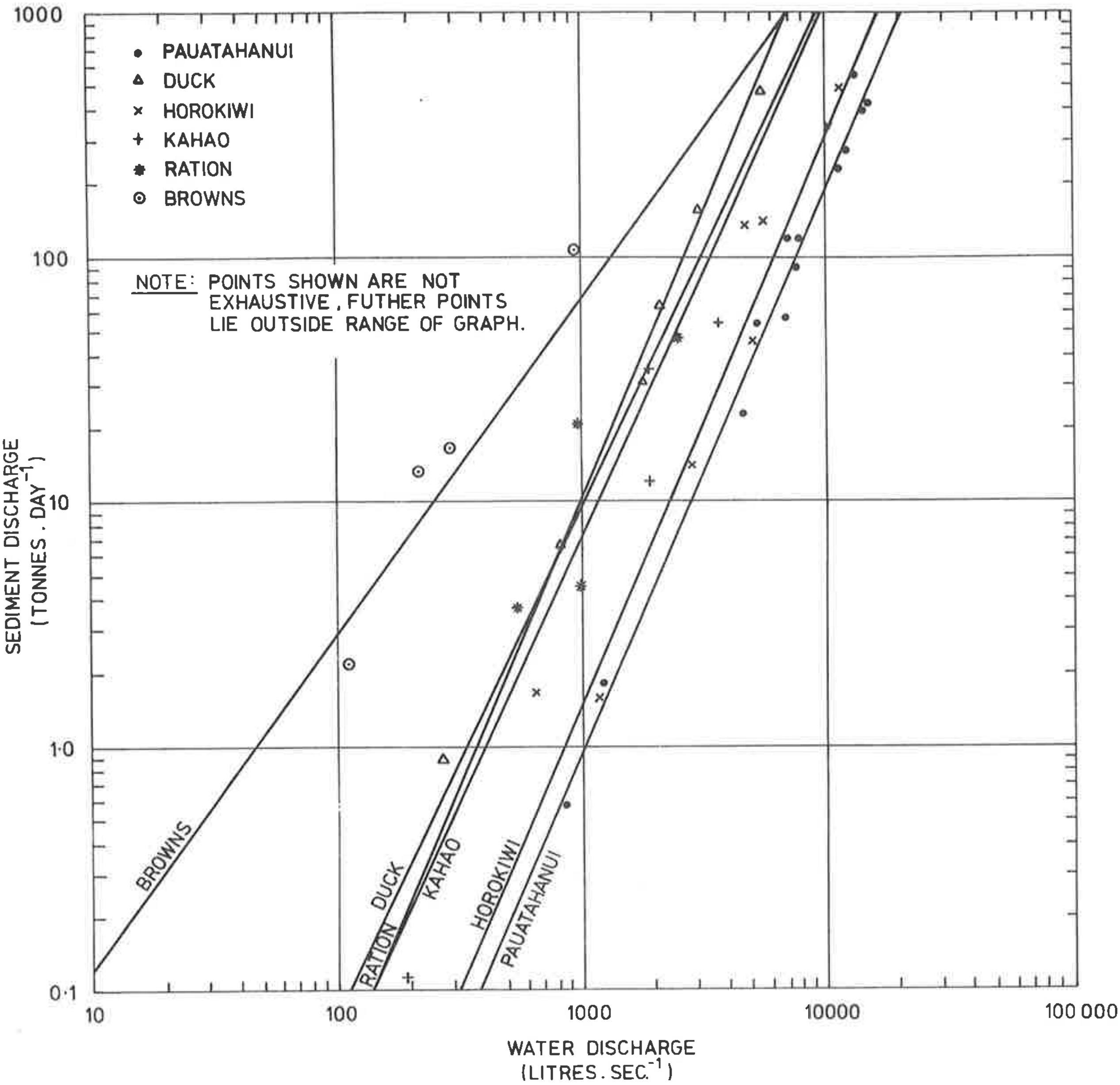
The Browns Stream sediment rating has since changed now that all surfaces in the catchment have either been sealed or vegetated. Although flow behaviour has changed, with quicker rainfall response times, sediment concentrations have returned to levels typical of pastoral use (approximately 10–500 mgl^{-1}).



STREAM	REGRESSION EQN.	CORRELATION COEF (R)	No OF POINTS
HOROKIWI	$Y = 1{\cdot}86X^{0{\cdot}913}$	0·996	11
DUCK	$Y = 3{\cdot}48\times10^{-1}\,X^{0{\cdot}960}$	0·994	13
KAHAO	$Y = 4{\cdot}51X^{0{\cdot}931}$	0·991	13
RATION	$Y = 7{\cdot}88\times10^{-2}X^{1{\cdot}08}$	0·995	12
BROWNS	$Y = 1{\cdot}02\times10^{-6}X^{2{\cdot}09}$	0·984	9

X = INSTANTANEOUS FLOW OF PAUAHATANUI STREAM
Y = FLOW FOR THE STREAM AT ITS TERTIARY STATION

Figure 3 Flow correlation of streams draining to the Pauatahanui Inlet.



STREAM	RATING EQUATION	CORRELATION COEF (R)	Nº OF POINTS
PAUATAHANUI	$Gs = 1{\cdot}027 \times 10^{-7}\ Qs^{2{\cdot}327}$	0·994	14
HOROKIWI	$Gs = 1{\cdot}4622 \times 10^{-7}\ Qs^{2{\cdot}336}$	0·966	9
DUCK	$Gs = 8{\cdot}606 \times 10^{-7}\ Qs^{2{\cdot}3601}$	0·911	7
KAHAO	$Gs = 1{\cdot}917 \times 10^{-6}\ Qs^{2{\cdot}1907}$	0·947	7
RATION	$Gs = 4{\cdot}218 \times 10^{-6}\ Qs^{2{\cdot}117}$	0·977	6
BROWNS	$Gs = 4{\cdot}76 \times 10^{-3}\ Qs^{1{\cdot}382}$	0·952	5

WHERE, **Qs is the water discharge in litres per second.**
Gs is the suspended sediment discharge in tonnes per day.

Figure 4 Suspended sediment discharge ratings.

Table 2 Summary of water discharges

			DAILY WATER FLOWS FOR PERIOD 1.6.75–1.6.77										ANNUAL WATER YIELDS		
			MINIMUM			MEAN			MAXIMUM						
Catchment	Area km^2	Percent. Total Area	Flow ls^{-1}	Spec flow $ls^{-1}km^{-2}$	% of Tot	Flow ls^{-1}	Spec flow $ls^{-1}km^{-2}$	Ratio to Min	Flow ls^{-1}	Spec flow $ls^{-1}km^{-2}$	% of Tot	Ratio to Mean	Yield $m^3 \times 10^6$	Spec Yield $m^3 \times 10^6$ km^{-2}	% of Annual Yield
Pauatahanui	43.4	41.2	55	1.27	33.9	939	21.6	17.1	25800	594	40.8	27.5	29.61	0.68	39.3
Horokiwi	32.9	31.2	70	2.13	43.2	848	25.8	12.1	19100	580	30.2	22.5	26.73	0.81	35.5
Duck	10.5	9.9	16	1.52	9.9	232	22.1	14.5	5890	561	9.3	25.4	7.31	0.70	9.7
Kahao	11.3	10.7	16	1.42	9.9	234	20.7	14.6	5860	519	9.3	25.0	7.38	0.65	9.8
Ration	6.13	5.8	5	0.82	3.1	126	20.6	25.2	4550	742	7.2	36.1	3.98	0.65	5.3
Browns	1.23	1.2	0.1	0.08	0	9	7.32	90.0	2060	1670	3.2	229	0.29	0.24	0.4
TOTAL	105.5	100	162	–	100	2388	–	–	63260	–	100	–	75.30	–	100

The Duck Stream sediment loads have since increased as more of the upper catchment is affected by urban development.

Water and Sediment Inputs to the Pauatahanui Inlet

Water. Water flows from all six streams, summed to give a total water input hydrograph to the Inlet for the two year period, are given in Fig.6b. Daily discharges are calculated and the minimum, mean and maximum daily discharges for each stream are given in Table 2.

The total average annual low, mean and flood water yields from all the streams during one tidal cycle is 0.009×10^6 m^3, 0.11×10^6 m^3 and 1.12×10^6 m^3, respectively which represents 0.4%, 4.6% and 47% respectively of the Pauatahanui Inlet tidal compartment (2.4×10^6 m^3 as calculated by Heath, 1976). This shows that fresh water inflows to the Inlet are only significant during medium to high floods.

A comparison between the Pauatahanui Stream specific flow duration curve and the derived specific flow duration curves of the other streams (Fig.5) shows differences in the flow characteristics.

Horokiwi Stream The specific discharges are higher than those of the Pauatahanui Stream during low flows, indicating that the Horokiwi catchment has greater natural storage, probably in the form of a shallow groundwater resource in the lower valley gravels. During high flows the Horokiwi Stream specific discharges are lower than those of the Pauatahanui Stream, probably due to the Horokiwi's relatively long, flat lower channel which promotes attenuation of flood hydrographs.

Duck Stream The flow duration curve closely approximates that of the Pauatahanui Stream at low flows but exhibits higher specific discharges than the Pauatahanui for high flows. The latter is probably attributable to the urbanisation in the upper part of the Duck catchment causing faster rainfall/run-off response times.

Kahao Stream The Kahao Stream yields similar discharges per unit area to the Pauatahanui Stream over the full flow range.

Ration Stream The flow duration curve crosses that of the Pauatahanui Stream, producing higher specific discharges during high flows and lower specific discharges during low flows. This is to be expected considering the size of the Ration catchment (15% of the Pauatahanui Stream catchment area) and its associated short runoff response time. The low discharges are lower than those of the Pauatahanui Stream probably because of the more limited storage areas associated with steeper channel gradients in the lower reaches of the Ration Stream.

Browns Stream The flow duration curve demonstrates to an even greater extent the differences between the Ration Stream and the Pauatahanui flows. This is due to the Browns Stream's even smaller catchment area (3% of Pauatahanui Stream). The higher discharges in the higher flow range are a result of extremely fast rainfall/runoff response times brought about by a combination of steep natural channel slopes, piped stormwater and large areas of impermeable surfaces. These steep and large impermeable areas are also responsible for the minimal base flows shown on the Browns Stream flow duration curve. The Browns/Pauatahanui correlation coefficient although good was accordingly the lowest (0.984) also demonstrating the widely differing flow response characteristics of the two catchments.

Overall, apart from Browns Stream, the flow duration curves exhibit a high degree of similarity, indicating homogeneous hydrologic response by the catchments draining into the Pauatahanui Inlet.

Sediment. The sediment ratings were applied to the Pauatahanui and the five generated flow records and the resulting sediment flows (calculated at 15 minute intervals) were summed to give a sediment input hydrograph to the Inlet for the two year period (Fig.6c).

Mean and maximum daily sediment discharges are given in Table 3. As with water flows, the percentage contribution of each stream is also noted for comparison with its respective catchment size.

The minimum suspended sediment input to the Inlet was approximately 1.2 tonnes per day (t day^{-1}), the mean was 36.6 t day^{-1} and the maximum recorded during the two year period was 9090 t day^{-1}.

Table 3 shows the annual sediment yield from each catchment expressed as a percentage of the total sediment yielded to the Inlet. When this is com-

Table 3 Summary of suspended sediment discharges

Catchment	Area km²	Percent. Total Area	DAILY SEDIMENT FLOWS FOR PERIOD 1.6.75–1.6.77 — MEAN: Flow t day^{-1}	MEAN: Spec flow t day^{-1} km^{-2}	MAXIMUM: Flow t day^{-1}	MAXIMUM: Spec flow t day^{-1} km^{-2}	MAXIMUM: % of Total flow	MAXIMUM: Ratio to Mean	ANNUAL SEDIMENT YIELDS: Yield t	ANNUAL SEDIMENT YIELDS: Specific Yields t km^{-2}	ANNUAL SEDIMENT YIELDS: % of Total Yield
Pauatahanui	43.4	41.2	12.8	0.295	3360	77.4	37.0	262	4670	108	35.0
Horokiwi	32.9	31.2	10.9	0.331	1780	54.1	19.6	163	3980	121	29.8
Duck	10.5	9.9	4.52	0.430	924	88.0	10.2	204	1650	157	12.3
Kahao	11.3	10.7	3.15	0.279	727	64.3	8.0	231	1150	102	8.6
Ration	6.13	5.8	1.29	0.210	278	45.4	3.0	215	470	77	3.5
Browns	1.23	1.2	3.94	3.20	2020	1640	22.2	513	1440	1170	10.8
TOTAL	105.5	100	36.6	–	9090	–	100	–	13360	–	100

pared with the catchment area of each catchment expressed as a percentage of the total Inlet catchment area the relative sediment contributions from each stream are apparent.

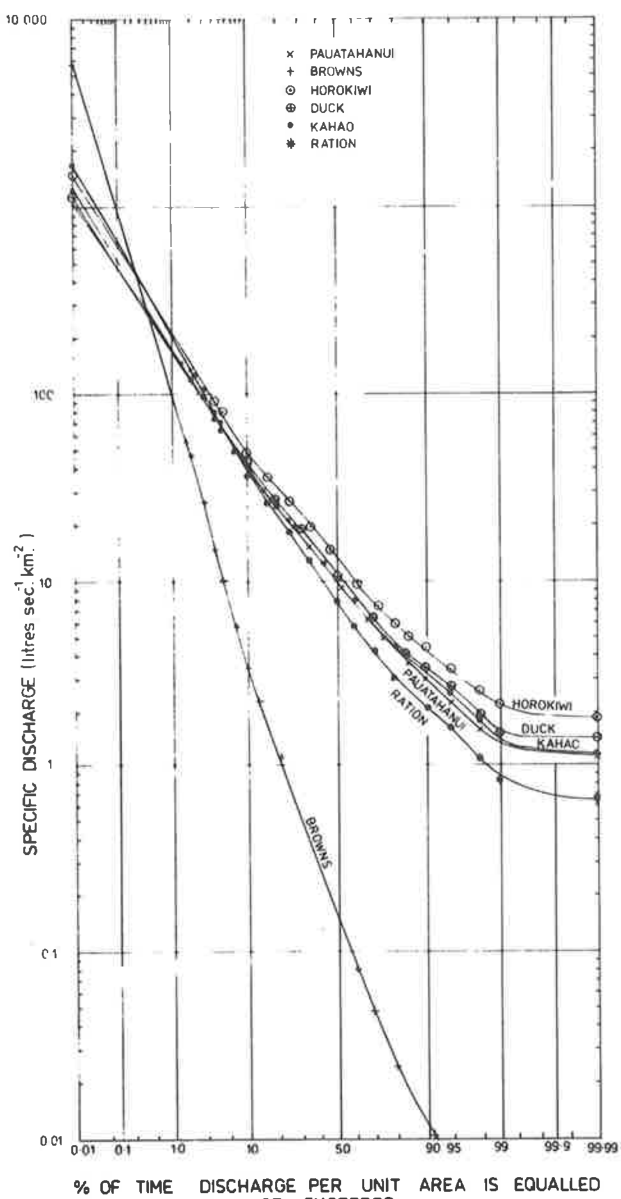


Figure 5 Flow distribution curves for the streams draining to the Pauatahanui Inlet, June 1975–May 1977.

With the exception of Browns Stream the percentage sediment yield contribution from each stream is within ±40% of that which would be expected on a proportionate catchment area basis. For example the Ration Stream sediment contribution is [(3.5 – 5.8) ÷ 5.8] × 100 = –39.6% of that which would be expected on a proportionate catchment area basis. The Browns Stream contribution is 800% higher than would be expected i.e. [(10.8–1.2) ÷ 1.2] × 100 = +800%.

The Kahao, Pauatahanui and Horokiwi are typical of the rural region and produce annual sediment yields of 102, 108 and 121 tonnes km^{-2} (t km^{-2}) respectively. The Ration Stream, draining a relatively stable, low relief pastoral catchment, produces a much lower annual yield of 77 t km^{-2}. The Duck Stream produces an annual yield of 157 t km^{-2}, reflecting the urban development in the upper portion of its catchment.

The Browns Stream demonstrates the contribution of a fully developed catchment in the earthworks phase, producing an annual yield of 1170 t km^{-2}, 15 times greater than that of Ration Stream, the next smallest and most similar of the other five catchments. Furthermore, the maximum mean daily sediment discharge from Browns Stream, during the largest flood in the two year period (16 June 1975), was 1640 t day^{-1} km^{-2}. This was approximately 35 times that of Ration Stream and was 22% of the total sediment input to the Inlet on that day (Browns catchment = 1.2% of total catchment area draining to the Inlet). For the same flood, the maximum instantaneous specific sediment discharge from Browns Stream was 6700 t day^{-1} km^{-2}, approximately a 70-fold increase on the Ration Stream specific sediment discharge. This storm was estimated to have a recurrence interval of 1 in 5 years.

RELATIONSHIP OF STUDY PERIOD MEANS TO LONG TERM MEANS

To determine whether the study period was typical of the long term means, the rainfall, stream flows and sediment yields were compared with the long term statistics.

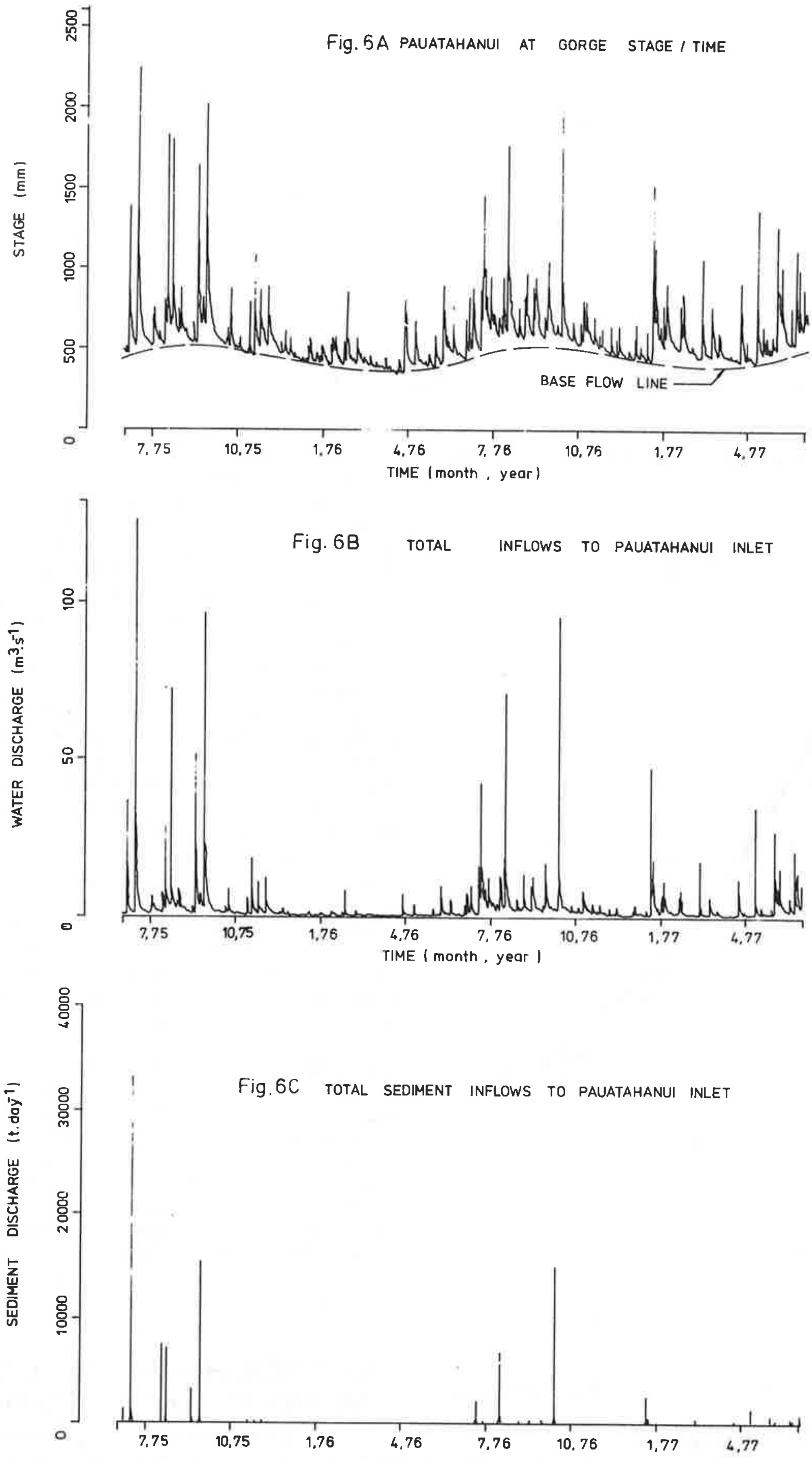


Figure 6 Stage, water and sediment hydrographs, June 1975–May 1977.

Table 4 Summary of study period rainfall, streamflow and sediment yield

Parameter	Period			
	1.6.75 to 1.6.76	1.6.76 to 1.6.77	1.6.75 to 1.6.77	Long Term
Rainfall (mm)	1191 (+ 6%)	1508 (+ 34%)	1350 (+ 20%)	1126
Streamflow (mm)	612 (+ 19%)	920 (+ 78%)	766 (+ 48%)	515
Sediment Yield (t yr^{-1})	5750 (+ 423%)	2690 (+ 198%)	4220 (+ 310%)	1360

(Percentages in brackets signify relationship to long term mean annual yields.)

Rainfall

The 30 year normal rainfalls derived from several rainfall stations in the area were available in New Zealand Meteorological Service (1973) and ranged from 1040 to 1400 mm (mean 1126 mm). Rainfalls for the two study years (1 June 1975 to 1 June 1976 and from 1 June 1976 to 1 June 1977) were respectively 6% and 34% greater than the 30 year normals.

Stream Flow

A long term mean flow of 640 l sec^{-1} (20.2 × 10^6 m^3 or 515 mm depth) for the Pauatahanui Stream was derived from a correlation with the longer term Mill Creek at Papanui (Site No. 30516) records (see Appendix 1).

The Pauatahanui Stream flows for the years 1 June 1975 to 1 June 1976 and 1 June 1976 to 1 June 1977 were higher than the long term mean flow by 19% and 78% respectively.

The stream flow records indicate an unusually high number of storm events within the period. Fortunately this provided greater opportunity to measure flood discharges and allowed a better estimate of a possible upper limit of the annual sediment yields. However, the greater numbers of large events presented some difficulty in establishing the long term sediment yields due to the enormous inputs of sediment during these large floods (discussed later).

Sediment Yields

The long term mean sediment yield of 1360 tonnes per year for the Pauatahanui Stream was derived by a normal storm distribution adjustment method and checked using sediment rated, synthetic flows derived from Mill Creek records (see Appendix 2).

The Pauatahanui Stream recorded sediment yields for the two study years were greater than the derived long term mean annual sediment yield by approximately 400% and 200% in 1975–76 and 1976–77 respectively.

Table 4 shows that the sediment yields for 1975/76 exceed the long term mean annual yield by more than the 1976/77 sediment yield which is in contrast with the rainfall and flow, both of which exceed their long term means by more during 1976/77. This is attributed to the larger incidence of intense floods during the winter of 1975. Although the base flows were generally less during 1975/76 than in 1976/77 the massive inputs of sediment during the 1975/76 floods were responsible for the greater yields for that year.

STORM EVENTS

As the storm events are the major contributors of both water and sediment (Fig.6b and 6c) many field measurements were carried out during these events. The results of two events, which were monitored in detail, are given in Tables 5 and 6 and plots showing the stream flow and sediment contributions from all catchments during the storm of 16–18 July 1976 are shown in Fig.7 and 8 respectively.

The relative sizes of the streamflow hydrographs in Fig.7 are generally proportional to catchment areas. Note that the Duck and Kahao Streams, very similar in size, behave almost identically and appear as one line.

The storm sediment hydrograph rankings (Fig.8) are not so predictably related to catchment size as the Browns Stream hydrograph crosses over and exceeds both the Ration and Kahao hydrographs. The Duck and Kahao hydrographs separate, the former, although the smaller of the two catchments, contributing more sediment during the storm peak.

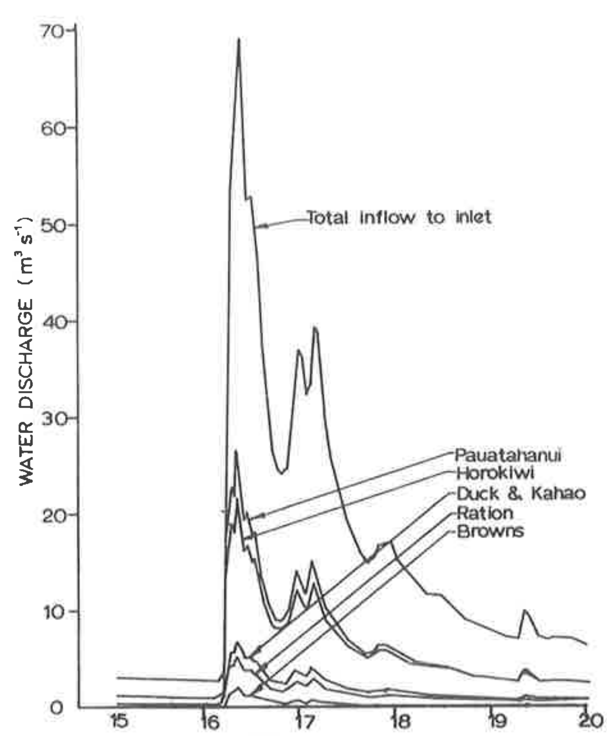


Figure 7 Stream flows for the storm of 16–20 July 1976.

Table 5 Storm inputs for flood of 18–23 June 1976
(Total storm rainfall at Moonshine gauge (141193) = 105 mm; Main burst of rainfall = 73 mm)

		WATER			SEDIMENT		
Stream	% of Total Catchment Area	Yield $m^3 \times 10^3$	Yield mm	% of Total Storm Input	Yield t	Specific Yield t km^{-2}	% of Total Storm Input
Pauatahanui	41.2	1968	45	37.9	256	5.9	29.8
Horokiwi	31.2	1834	56	35.3	350	10.6	40.7
Duck	9.9	522	50	10.0	129	12.3	15.0
Kahao	10.7	523	46	10.1	80	7.1	9.3
Ration	5.8	321	52	6.2	35	5.7	4.1
Browns	1.2	25	20	0.5	10	8.1	1.1
TOTALS	100	5193	—	100	860	—	100

% of long term mean annual water yield $\frac{5193 \times 10^3 \text{ m}^3}{51.4 \times 10^6 \text{ m}^3} = 10.1$

% of long term mean annual sediment yield $\frac{860 \text{ t}}{3900 \text{ t}} = 22.0$

Table 6 Storm inputs for flood of 16–20 July 1976
(Total storm rainfall at Moonshine gauge (141193) = 103 mm; Main burst of rainfall = 91 mm)

		WATER			SEDIMENT		
Stream	% of Total Catchment Area	Yield $m^3 \times 10^3$	Yield mm	% of Total Storm Input	Yield t	Specific Yield t km^{-2}	% of Total Storm Input
Pauatahanui	41.2	2515	60	38.2	857	20	34.8
Horokiwi	31.2	2252	68	34.2	806	24	32.7
Duck	9.9	657	63	10.0	348	33	14.2
Kahao	10.7	657	58	10.0	244	22	9.9
Ration	5.8	432	70	6.6	98	16	4.0
Browns	1.2	67	54	1.0	109	89	4.4
TOTALS	100	6580	—	100	2462	—	100

% of long term mean annual water yield $\frac{6580 \times 10^3 \text{ m}^3}{51.4 \times 10^6 \text{ m}^3} = 12.8$

% of long term mean annual sediment yield $\frac{2462 \text{ t}}{3900 \text{ t}} = 63.1$

The storm event of 18–23 June 1976 contributed 10% of the long term mean annual water input and 22% of the long term mean annual sediment inputs to the Inlet. The 16–20 July 1976 storm event contributed 13% and 63% of the long term mean annual water and sediment inputs respectively. For the increase of 3% in the mean annual water input during the two storm events, an increase of 40% of the mean annual sediment input was realised.

The flood of 16 June 1975, recorded shortly after the start of flow recording, was the highest during the two year study period and was calculated as contributing 10 350 tonnes, approximately 3 times the mean annual sediment input to the Inlet.

Since the end of this two year period, three storms with peak discharges higher than the 16 June 1975 flood (47.7 m^3s^{-1}) have been recorded in the Pauatahanui Stream. On 26 June 1977, 4 July 1977 and 22 November 1977 peak discharges of 69.7, 62.0 and 69.4 m^3s^{-1} respectively were recorded, highlighting the uncertainties of flood frequency estimation with such a short length of record.

However, an attempt to estimate the frequency of occurrence of the floods recorded was undertaken using comparisons with the Mill Stream (see Appendix 1) and other hydrological records in the region. The 16–20 July 1976 flood was estimated as being

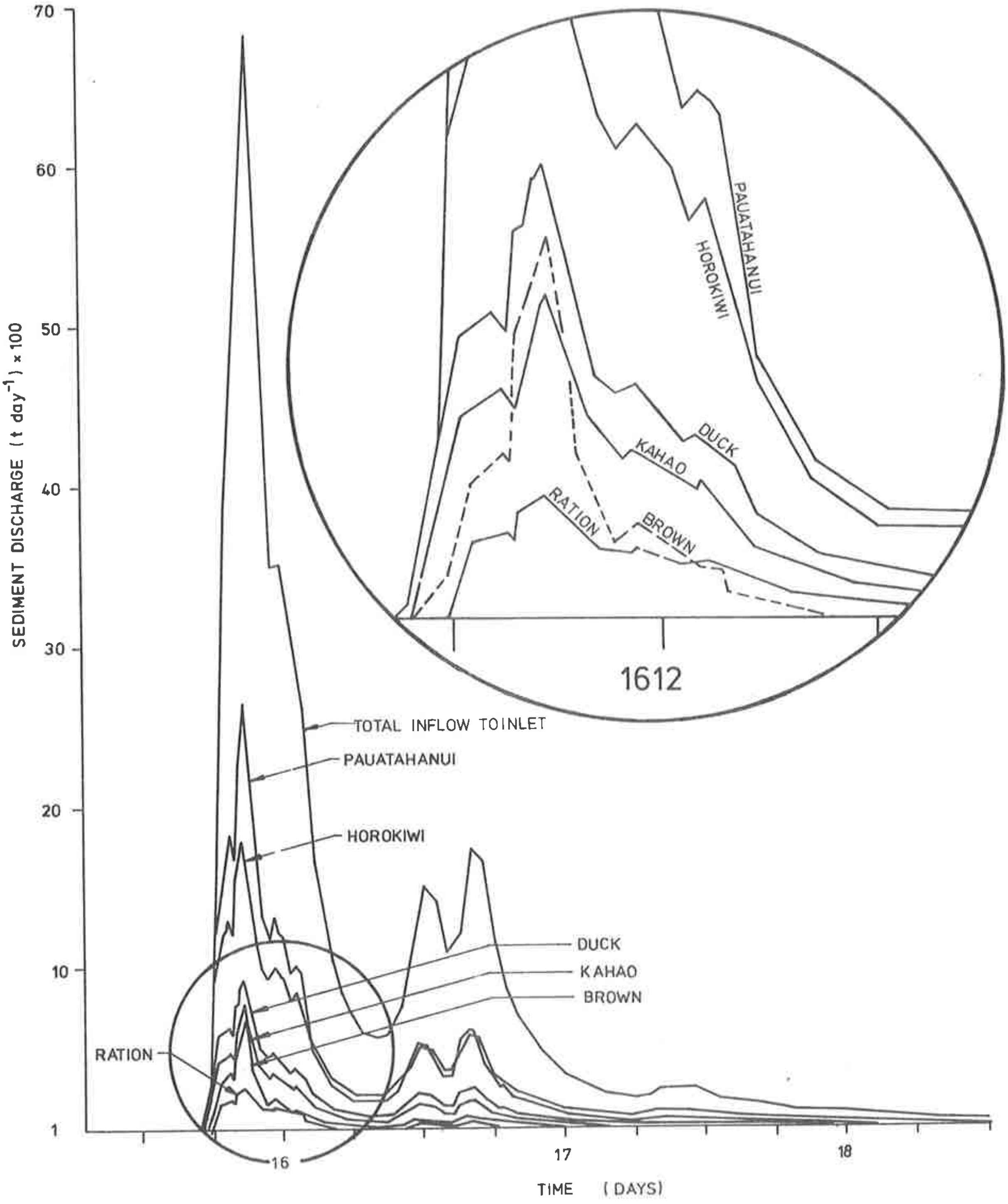


Figure 8 Suspended sediment discharges for the storm of 16–18 July 1976.

approximately equal to the average annual flood (1 in 1 year recurrence interval) in terms of a peak discharge but slightly higher than the average annual flood in terms of total water and sediment inputs due to the attenuated nature of its hydrograph. The 1 in 1 year flood was therefore estimated to contribute approximately 12% of the mean annual water input and 50% of the mean annual sediment input to the Inlet.

The maximum instantaneous discharges at the Pauatahanui recorder station were plotted against total sediment inputs to the Inlet resulting from the respective storm events (Fig.9). Using a dimensionless flood frequency distribution typical of catchments in the region, the 1 in 1, 2.33, 5, 10, 20, 50 and 100 year floods were derived and inserted in Fig.9 to give some indication of the quantities of sediment involved with the high ranking floods.

Assuming stable sediment ratings and typical hydrograph shape the mean annual flood (1 in 2.33 year return period) is seen to produce a sediment input equal to approximately 90% of the long term mean annual input, whilst the 5, 10, 20, 50 and 100 year floods are seen to produce total sediment inputs of approximately 150%, 220%, 300%, 460% and 750% of the long term mean annual sediment input respectively. These estimates are conservative as normally with floods of the magnitude described much land slipping and slumping would occur, thus increasing the sources of supply of sediment to the streams and temporarily altering the sediment ratings.

The extent to which the annual variability of sediment yield is influenced by the occurrence of the larger events is clear and indicates that an upward variation of an order of magnitude in annual sediment yield can occur.

Samples for particle size distribution were taken from all streams during the June 1976 storm and results (Table 7) show that on average 50% of all suspended sediment is clay sized (finer than 0.002 mm). Suspended sediment from the Browns Stream (catchment in earthworks phase) was much finer with 75% of the particles in the clay range. This suggests good suspension. However, comparing the Inlet residence time of 2–5 days (Heath 1976) with laboratory flocculation data which show as little as 25% of fine sediment to be in suspension after 12 hours (Healy 1977) indicates this may not be sufficient to permit adequate flushing of sediments from the Inlet.

Monitoring of suspended sediments at the Inlet entrance during both the June and July 1976 storm events showed concentrations to rise to a peak of 70 mg l^{-1} and then return to the normal range of 10 ± 8 mg l^{-1} three days after the peak river flows. This suggests both rapid settlement of suspended material and efficient tidal flushing of the whole Inlet, the latter particularly as the flushing period corresponds well with the Inlet residence time (Smith & McColl 1978). It is therefore surmized that strong tidal currents coupled with wind action considerably enhance the flushing ability of the Inlet. However, in embayments such as Browns where these actions are not prevalent, problems of sediment accumulation have arisen. This is discussed in Appendix 3 "Hydrological effects of urbanisation on the Pauatahanui Inlet and Catchment".

CONCLUSIONS

1. There were very high correlations (all with Pearsons $R > 0.98$) between the recorded flows in the Pauatahanui Stream and gauged flows in the five other streams draining into the Inlet. Surprisingly this applied to the Browns Stream catchment which is only 3.2% of the Pauatahanui Inlet catchment area. Major savings in establishment, instrumentation, operational and personnel costs can be achieved by utilising flow correlation and generation techniques on projects where stream flow information is required on a number of streams within a climatologically and geologically homogeneous area.
2. Minimum mean and maximum specific flow contributions from each catchment varied significantly, the variations being attributable to individual catchment characteristics.
3. Only the combined mean stream water flows and above are significant inputs to the Inlet when considering their tidal cycle contributions expressed as a percentage of the Inlet tidal compartment.
4. Suspended sediment concentrations were generally within the range of 5 to 500 mg l^{-1}; however concentrations in the fully developed Browns Stream ranged from 25 to 1500 mg l^{-1}.

Table 7 Particle size distribution of stream sediments sampled during storm of 20–21 June 1976

	Percent of Particles Finer Than			
Stream	0.002 mm	0.006 mm	0.02 mm	0.06 mm
Pauatahanui	44	67	87	100
Horokiwi	55	77	92	100
Kahao	43	65	78	100
Duck	44	59	81	100
Ration	40	57	81	100
Browns	75	91	99	100
MEAN	50	69	86	100

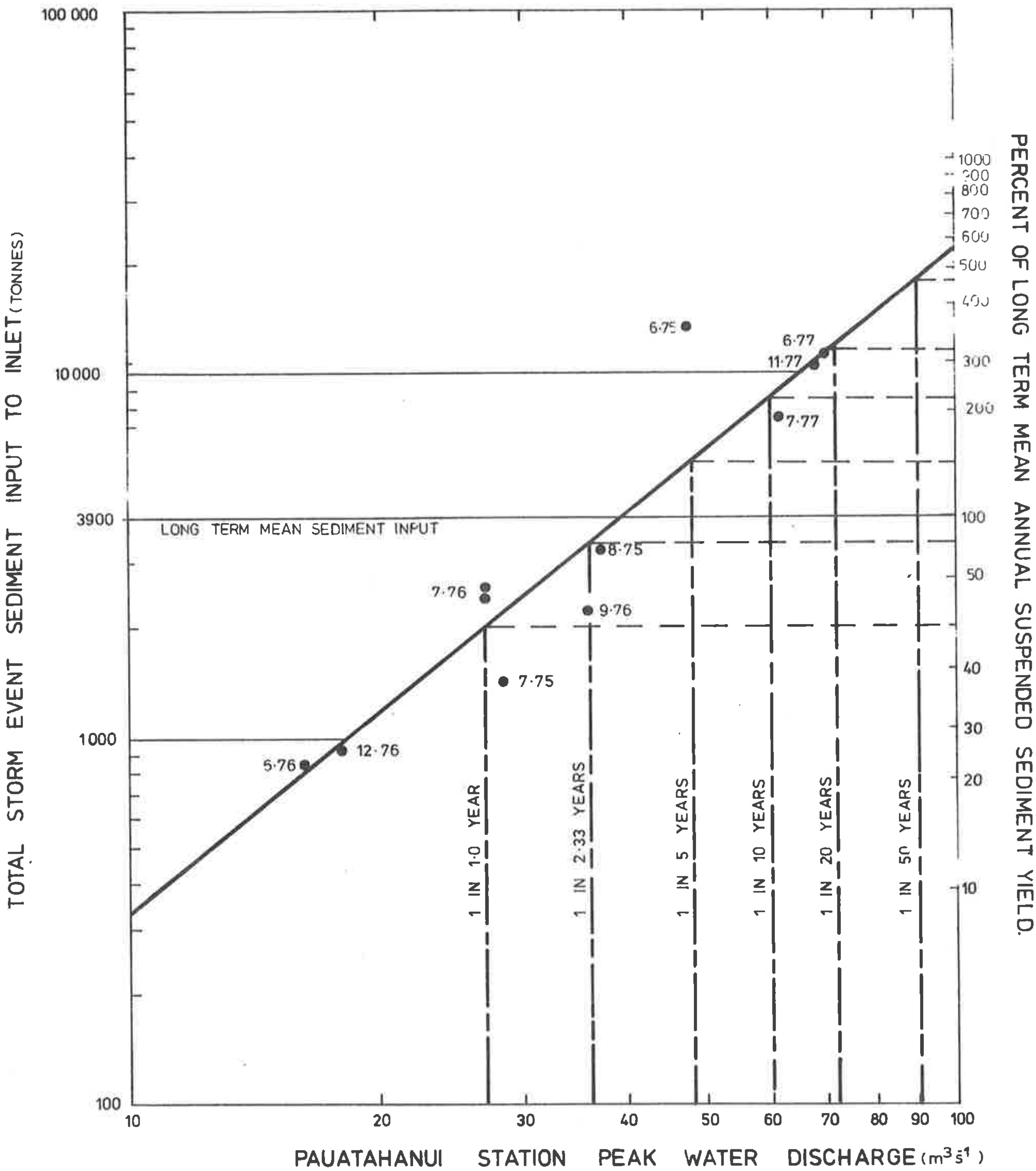


Figure 9 Relationship between peak Pauatahanui Stream water discharge frequencies and the long term mean annual sediment input to the Pauatahanui Inlet.

5 The minimum, mean and maximum daily sediment inputs to the Inlet during the two year study period were approximately 1.2 t day^{-1} (0.01 t day^{-1} km^{-2}), 37.0 t day^{-1} (0.35 t day^{-1} km^{-2}) and 9000 t day^{-1} (85 t day^{-1} km^{-2}) respectively.

6 Annual sediment yields for the two year study period ranged from approximately 75 t km^{-2} for a low altitude pastoral catchment, through to a median of 110 t km^{-2} for three similar catchments, to approximately 160 t km^{-2} for a partially urbanised catchment. The fully developed Browns Stream Catchment produced approximately 1200 t km^{-2}, in excess of 15 times greater than its pastoral counterpart. (Long term mean annual yields would be approximately 0.3 of these recorded yields).

7 The maximum recorded mean daily sediment discharge from the Browns Stream was approximately 1640 t day^{-1} km^{-2}, about 35 times greater than its pastoral counterpart and 22% of the total sediment input to the Inlet on that day (Browns catchment area is 1.2% of the Inlet catchment area). For a 1 in 5 year recurrence interval flood Browns Stream produced a maximum instantaneous sediment discharge of approximately 6700 t day^{-1} km^{-2}, about 75 times that of its pastoral counterpart.

8 A long term mean annual water yield and sediment yield of 4.87×10^5 m^3 km^{-2} and 37.0 t km^{-2} respectively were calculated with a reasonable degree of confidence despite the two year study period recording rainfall, streamflow and sediment yields of approximately +20%, +50% and +300% of their respective 30 year normals.

9 The average annual flood (approximately 1 in 1 year recurrence interval) is estimated to contribute 12% of the long term mean annual water yield and 50% of the long term mean annual sediment yield.

10 The mean annual flood (1 in 2.33 year recurrence interval) is estimated to contribute 90% of the long term mean annual sediment yield whilst the 1 in 5, 10, 20, 50 and 100 year floods are estimated to produce approximately 150%, 200%, 300%, 400% and 750% of the long term mean annual sediment yield.

11 All particles of suspended matter were silt-sized or smaller (<0.06 mm) and, with the exception of Browns Stream, an average of 50% were clay sized (<0.002 mm). Suspended sediment from the developed Browns catchment was finer with more than 75% in the clay range and when allowed to discharge into Browns Bay with its low energy currents, flocculation and settlement occurred before the tidal flushing action could remove the suspended particles from the Bay. Whilst tidal flushing of the Inlet is generally thorough, care must be taken to minimise erosion during urban development particularly in catchments draining into embayments and quiescent areas.

12 Monitoring of suspended sediment concentration both upstream and downstream of the Browns Bay silt trap showed sediment concentrations to be up to 30% higher downstream than upstream during particularly large events. This suggests inadequate pond capacity and/or too infrequent clearing of the pond. Greater attention to energy dissipation of incoming waters is important to reduce the amount of 'stirring up' in the pond.

13 The Pauatahanui Stream flow recording station with its stable bedrock control (a rare feature in the region) has proved a most efficient and reliable indicator for all the streams flowing into the Pauatahanui Inlet. Although the projected developments around the Inlet have been deferred, the Pauatahanui Stream record with its now known relationship to all the significant inputs to the Inlet, remains a valuable tool for the prediction and monitoring of changes resulting from any future urban development.

ACKNOWLEDGEMENTS

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APPENDIX 1

Estimation of Long Term Mean Flow for the Pauatahanui Stream

In order to establish long term mean water flow for the Pauatahanui Stream, water discharge measurements were carried out on the Pauatahanui Stream and the Mill Creek (a tributary of the Makara Stream) over a wide range of flows. The simultaneous flows from each stream were correlated with a resulting correlation coefficient of 0.96. From the Mill Creek records, the mean daily flow for the years 1970–1976 is 154 l s^{-1}. The Mill Creek mean annual rainfall for these years closely approximates its long term normal; thus its mean catchment rainfall for the same period was used to check the results. Using the Mill Creek mean catchment rainfall of 1240 mm and allowing an average evapotranspiration rate of 700 mm a runoff of 540 mm was obtained which equates to 160 l s^{-1} (17.1 l s^{-1} km^{-2}) from the 9.35 km^2 catchment area. This agrees well with recorded flows.

Using the Pauatahanui–Mill Creek regression ($y = 3.67 \times +0.075$), 154 l s^{-1} corresponds to a long term mean daily discharge of 640 l s^{-1} (16.3 l s^{-1} km^{-2}) or an annual yield of 20.2×10^6 m^3 for the Pauatahanui Stream. Table 2 shows the Pauatahanui Stream's contribution to be 39.3% of the total water input to the Inlet and so, assuming this relation holds, the long term average annual water yield from all streams to the Inlet is 51.4×10^6 m^3.

APPENDIX 2

Estimation of the Long Term Mean Annual Sediment Yield

Two methods were used for calculating the long term mean annual sediment yield. The first method used the flow correlation between the Pauatahanui Stream and the Mill Creek in order to extend the Pauatahanui records back to establish the long term mean. The Pauatahanui Stream sediment discharge rating was then applied to the synthesized flows and the long term annual sediment yield was generated. The second method was one of establishing a 'number of storms/rainfall depth' distribution initially for the long term mean year and comparing this with that obtained for the two year period of record. An average relationship was then established between individual storm event rainfalls and the resulting storm event sediment inputs to the Inlet from all the streams. This relationship allowed a correction of the recorded sediment yield, on the basis of the number of storms outside the numbers occurring in a 'normal' year, and hence enabled the establishment of the long term average annual sediment yield.

For the flow correlation generation method, a time series correlation of hourly water flows for the two years of common record was used, this giving a highest correlation coefficient of 0.85 at zero hours time lag. This correlation was lower than that obtained for the instantaneous flow correlation probably because its analysis included all storms, some with differing spatial and temporal rainfall patterns. All measurements relating to the higher correlation coefficient of 0.96 were taken on the receding portion of flood hydrograph, hence giving better results. Using the time regression, mean daily flows were generated from the Mill Creek data for the period 1970–1976.

Although annual rainfall and flow data for the period 1970–1976 approximated the long term mean data, much variation was seen within the individual years. Rainfall and flow data for 1970 was seen to differ from the long term data by only −3% and −7% respectively and so the generated Pauatahanui Stream sediment data yield for 1970 was taken as representative of the long term annual sediment yield. The mean daily sediment discharge generated for 1970 was 3330 kg day^{-1} or an annual sediment yield of 1200 tonnes. This was then multiplied by the ratio of the total Pauatahanui Stream catchment area upon the catchment area monitored by the Pauatahanui recorder (1.107) giving a total sediment contribution from the Pauatahanui Stream of 1330 tonnes.

From Table 3 the total Pauatahanui Stream catchment was seen to contribute 35.0% of the total annual sediment input to the Inlet and so, assuming that this relation holds, the long term average annual sediment yield from all streams to the Inlet is 3820 tonnes.

For method 2 the Pauatahanui rainfall data (Met. No. E14194) from 1959 to 1976 was used but because the particular years that approximated the annual long term mean contained extremely wide variations within the months, the year with the monthly rainfall depth that most closely approximated the 30 year normal depth for that month was selected. This then produced an 'average year' made up of a combination of months from various years and enabled the 'normal' number of storms/rainfall depth distribution to be computed (Fig.10a). Similarly a distribution was derived for the years 1 June 1975 to 1 June 1976 (Fig.10b) and 1 June 1976 to 1 June 1977 (Fig.10c) and compared with the normal distribution (Fig.10a).

As the mean monthly selection process did not include a storm of annual flood status (60–80 mm in Fig.10a) the normal distribution was extended to include one of these storms. This also gave a smoother distribution at the upper rainfall depth end.

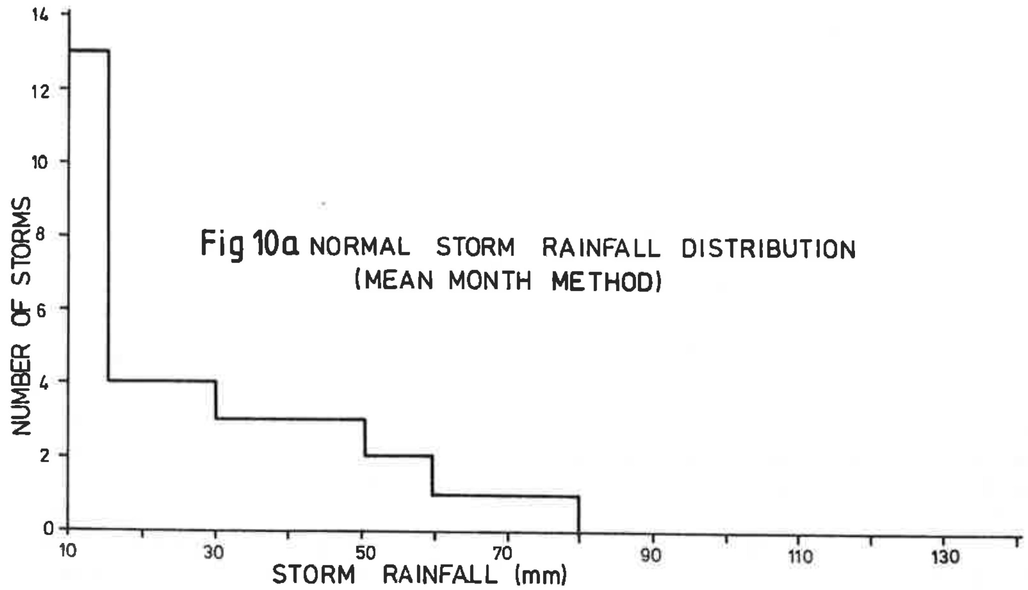
The storm rainfall totals during the period of Pauatahanui flow records were plotted against their resulting sediment input to the Inlet and an average relationship established (Fig.11).

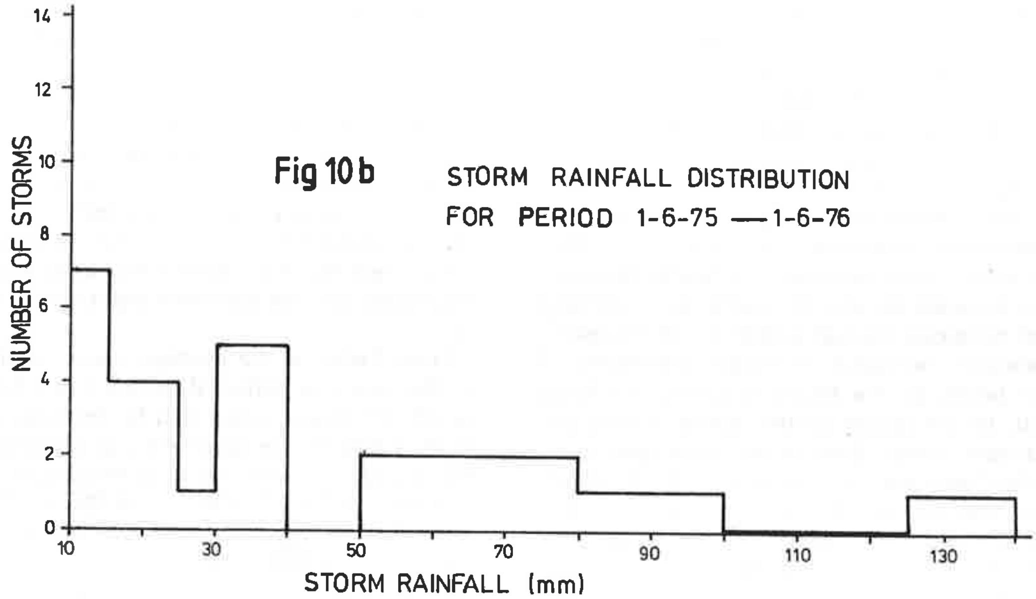
The number of storms during the two year period outside the normal distribution (Fig.10a) were tallied and using the averaged mean sediment input/storm rainfall relationship (Fig.11) the necessary corrections were made to the record thus producing the long term average sediment input to the Inlet (Table 8).

From Table 3, the average annual sediment yield for the two year period of record was 13360 tonnes, or 26720 tonnes total yield for the two year period. From Table 8, the sediment input corrections total 18760 tonnes and so a long term mean two-yearly sediment yield of 26720 − 18760 = 7960 tonnes was calculated giving a long term mean annual sediment yield of 3980 tonnes.

Comparing the two methods then, good agreement was obtained with results of 3820 tonnes long term annual sediment yield by the correlation generation method and 3980 tonnes by the number of storms/rainfall depth distribution method. A long term mean annual suspended sediment yield of (3980 + 3820) ÷ 2 = 3900 tonnes was therefore adopted.

Visual inspections of the stream outlets revealed little change in the delta profiles over the two year period and so it was assumed that negligible amounts of bed load were being transported, an assumption also supported by Irwin (1976). The total long term average annual sediment yield from the catchments draining to the Pauatahanui Inlet can therefore be interpreted as being the same as the suspended sediment yield i.e. 3900 tonnes or 37.0 t km^{-2}.





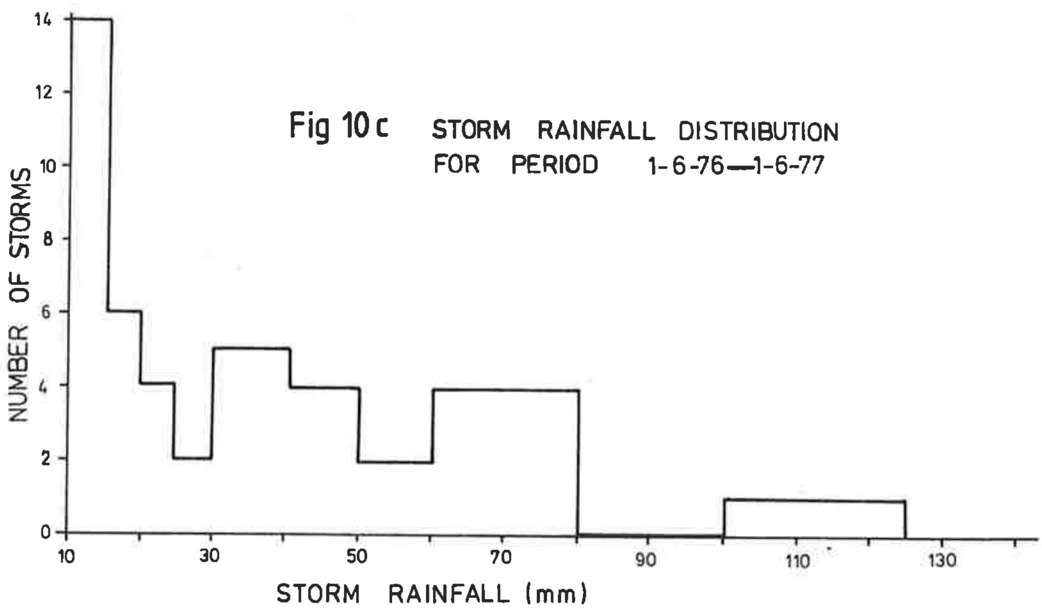


Figure 10 Pauatahanui storm rainfall distributions.

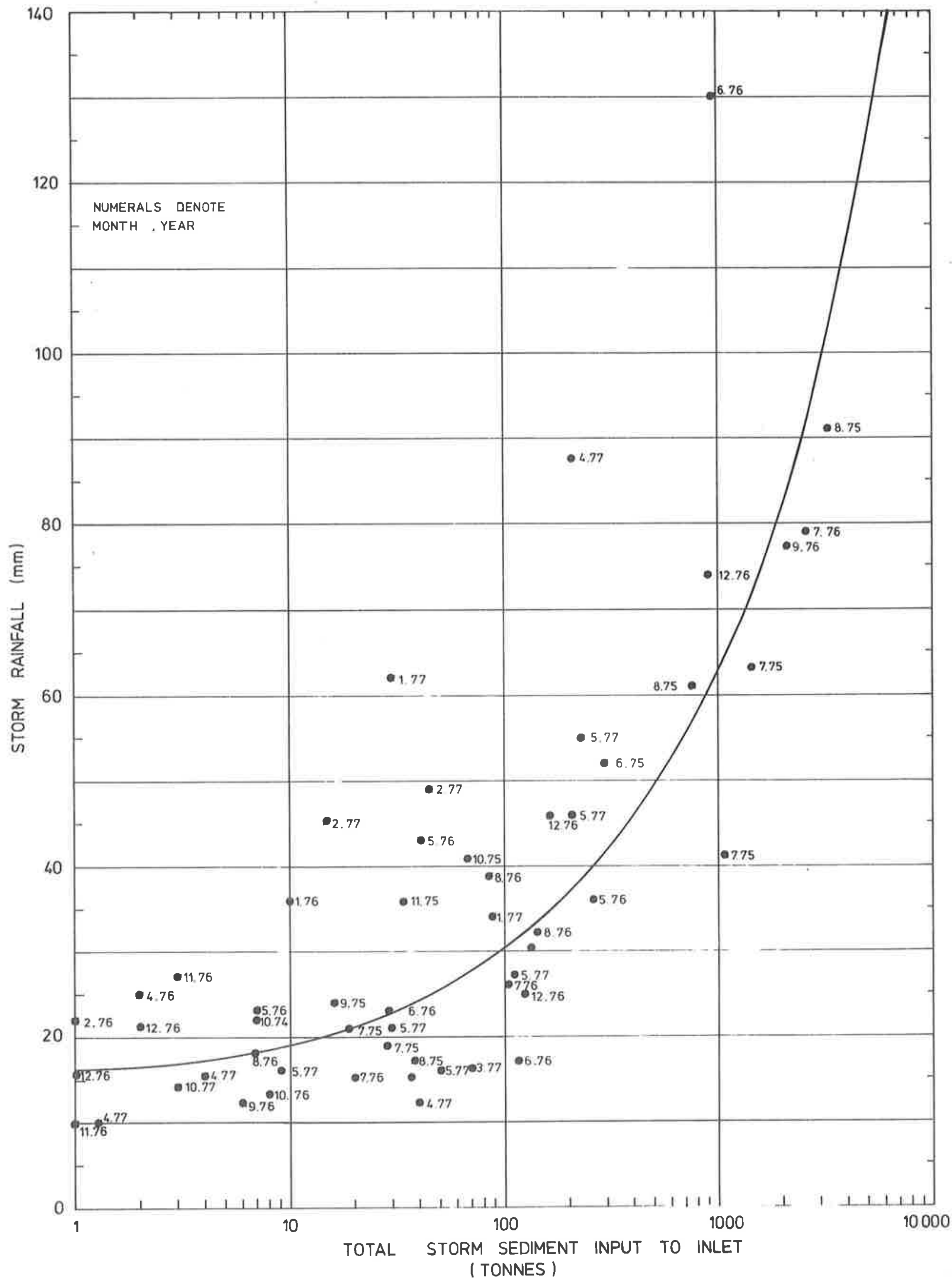


Figure 11 Relationship between storm event rainfall and total storm event sediment input to the Pauatahanui Inlet.

Table 8 Number of storms during 1 June 1975 to 1 June 1977 outside the number of storms with various rainfall depths occurring during a 'normal' year.

Total storm rainfall depth range (mm)	Number of storms outside those occurring during a 'Normal Year'			Mean sediment input for average rainfall range (t)	Correction (t)
	75/76	76/77	Sum		
10– 15	−6	+1	−5	0	0
15– 20	0	+2	+2	3	− 6
20– 25	0	0	0	24	0
25– 30	−3	−2	−5	86	+ 430
30– 40	+2	+2	+4	170	− 680
40– 50	−3	+1	−2	450	+ 900
50– 60	0	0	0	710	0
60– 80	+1	+3	+4	1600	− 6400
80–100	+1	0	+1	2800	− 2800
100–125	0	+1	+1	4000	− 4000
125–150	+1	0	+1	6200	− 6200
Total					− 18756

APPENDIX 3

Hydrological Effects of Urbanisation on the Pauatahanui Inlet and Catchment

Water

According to the synthetic flood frequency distribution six floods of greater magnitude than the mean annual flood (1 in 2.33 year) occurred during the period June 1975 to December 1977, three of which lie between the 10-year and 20-year return period.

On most of these occasions survey personnel were on location and so visual records of the extent of the flooding are available.

Slips and channel erosion occurred in the upper reaches of the Pauatahanui and Horokiwi catchments causing blockages and washouts to both the Paekakariki Hill and Moonshine Roads. Moderate flood plain flows were reported in the Pauatahanui Valley through the Judgeford Basin and Duck Stream through the golf course, but the most severe flooding was through the lower reaches of the Horokiwi Valley. In this area flood waters topped the Pauatahanui–Plimmerton roadway west of the Horokiwi Bridge by up to 1 metre and other sections of the road to a lesser extent on several occasions. The extent of flooding is largely dependent on the coincidence of the tidal and stream flow hydrographs, the worst case being peak stream flows on a spring high tide. The whole lower Horokiwi Valley floor is extremely prone to flooding indicating the need for extensive stopbanking if the proposed industrial employment areas as noted in the Pauatahanui Comprehensive Development Plan 1970 (Fig.12) were to proceed. This is even without the existence of the proposed low density residential and open space network areas which would of course increase both the magnitude and frequency of occurrence of the various floods. Sizeable waterway areas would be re-

Figure 12 Pauatahanui Development Plan Test Scheme B (from Hutt County Council 1970).

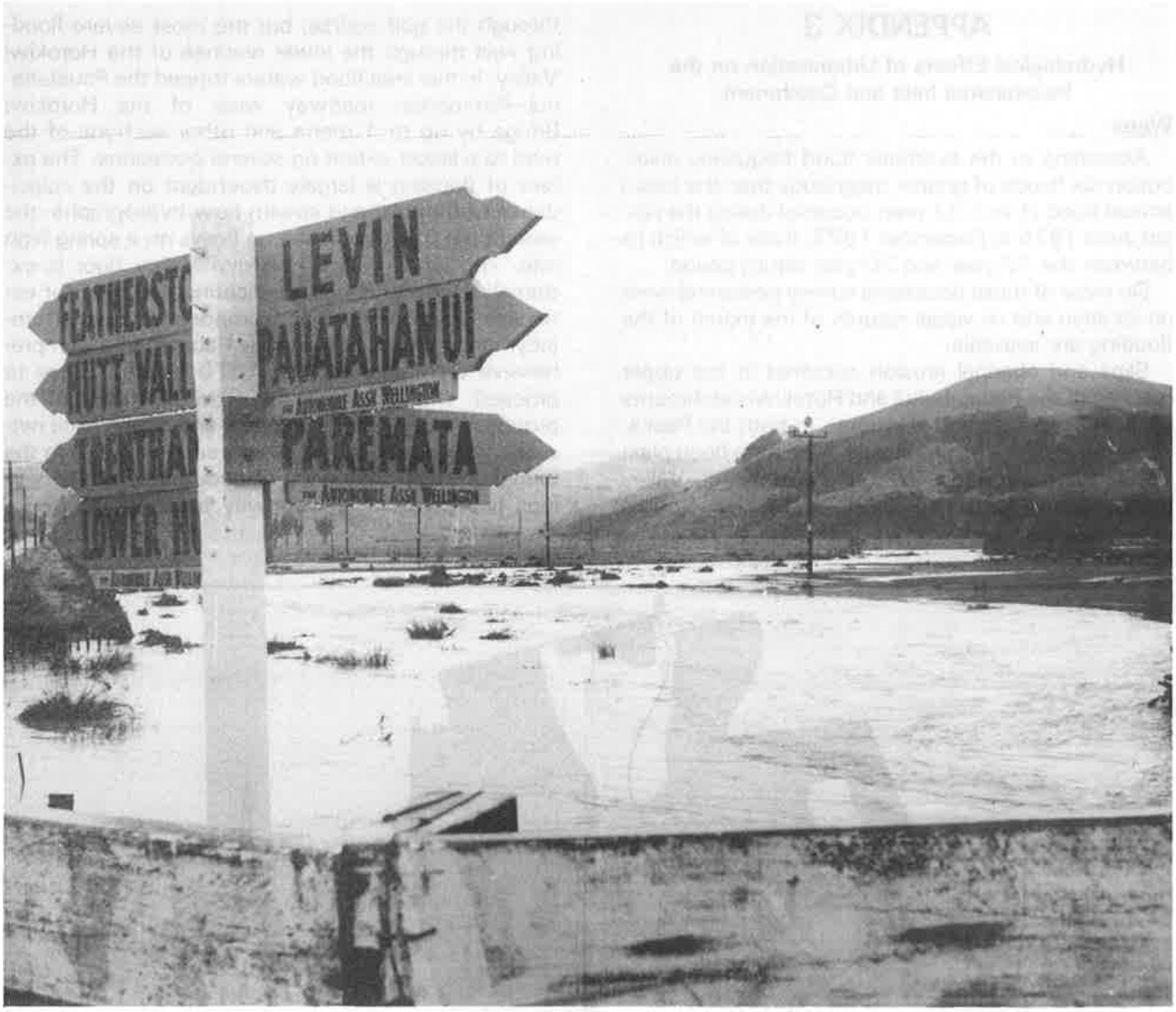


Figure 13 Extent of flooding through proposed site of Town Centre during a flood of 18–19 September 1959. Note the extremely flat berms that would be inundated in a larger event (> 1 in 5 years).

quired to contain floods within such a low gradient channel in these lower reaches. This needs to be taken into account in planning the development of this area.

If urbanisation proceeds, another area requiring stopbanking would be the Pauatahanui Stream through the Judgeford Basin (SH 58–Moonshine Road intersection downstream to the lower gorge) and through to the Inlet where the town centre is proposed. With the flood waterway restricted by stopbanks a larger waterway area would be required for the bridge at NZMS 1 Map reference N 160: 485424 and the highway would need to be raised through the lower flood plain section west of this bridge.

Fortunately all State Highway bridges are designed for the 1 in 100-year flood and urbanisation is not reported to greatly effect floods of this magnitude, however, with the considerable reduction in flood plain storage as a result of the required stopbanking through the Judgeford Basin, some increase in the peak discharge must be expected. Consequently, to ensure a flood free carriageway, the raising of SH 58 through the Pauatahanui Gorge, immediately downstream of the Belmont confluence, would be necessary as the 1 in 20-year flood has been seen to rise almost to road level at this point within the catchment which, of course, is still in its undeveloped state. Possibly a closed channel would be required through the proposed town centre in order to maximise the area available for the town centre complex. However, with careful design it is considered that the channel would be better developed as an aesthetic amenity of the centre. Figure 13 shows the extent of flooding experienced in the vicinity of the proposed town centre during a flood on 18–19 September 1959. The total storm rainfall was 132 mm over the two days and the resultant flood was estimated to have a return period of approximately 1 in 5 years. However, the relationship betweeen the time the photograph was taken and the stage of the stream and tidal hydrographs is not known.

Table 9 Hypothetical sediment yields based on fully developed catchments (in earthworks phase).

Catchment	†Proposed urban areas (ha)	†Percent of catchment	Sediment yield factor for stripped condition (% × 15)	Sediment Yield: Long term mean annual Rural (t)	Long term mean annual Stripped (t)	Study period annual yield (t)
Pauatahanui	1210	28.6	4.29	1360	5830	4670
Horokiwi	461	17.6	2.64	1160	3060	3980
Duck	384	35.3	5.28	480	2530	1650
Kahao	162	13.5	2.02	340	690	1150
Ration	405	58.0	8.70	140	1220	470
Browns	123*	100	*	NA	420	1440
TOTAL	2745	26.0	—	—	13750	13360

* Already developed
† Figures according to Hutt County Council 1970

Sediment

In order to test the effects of urbanisation on the sediment yields of the streams draining into the Pauatahanui Inlet, the data collected from the Browns Stream during the earthworks phase of urban development was compared with those from the Ration Stream, the next smallest monitored rural catchment draining into the Inlet.

The mean daily sediment discharge per unit area for the Browns Stream was recorded as a 15-fold increase on the rural catchment while for the flood of 16 June 1975, (the largest in the two year period of record) the maximum daily sediment input was recorded as a 36-fold increase on the rural catchment. The maximum instantaneous discharge from the Browns Stream for the same flood (estimated 1 in 5 year flood) was 6700 t day^{-1} km^{-2}, a 74-fold increase on the rural catchment.

The Pauatahanui Comprehensive Development Plan proposed that a total of 27.4 km^2 (26% of the Inlet catchment area, according to Hutt County Council 1970) be designated suitable for urban development and so various sediment yields can be calculated depending on the area in the earthworks phase of urbanisation at any one time. For example, if the whole 461 hectares in the Horokiwi catchment was developed concurrently, an annual input of 3060 tonnes, approximately 75% of the mean annual yield from all of the catchments, would be produced (Table 9). The extent to which this stripped condition influences sediment input to the Inlet is dependent on the occurrence of major events and, as these are unpredictable, every effort to both restrict development to manageable areas each construction season and to ensure that these are adequately grassed and drained prior to the onset of winter, should be considered in the development plan. Silt traps should be suitably sited and designed to achieve settling of most of the finer sediments. It is desirable that entry structures and retention times be such that flushing during the larger events, as was observed at the Browns Stream trap, is avoided. These measures would be necessary to minimise significant changes to stream channel morphology and sedimentation of the Inlet embayments.

The ability of the Inlet to receive the extra sediment loads produced by urban development and to remain in its present 'healthy' state is largely dependent on the flushing action of the tides. The fact that the post-storm event flushing time of the Inlet coincides with the Inlet residence time (Smith & McColl 1978) indicates generally good flushing, as does the fact that the two year study period which produced, with no overall ill effects, an average annual yield 97% of that which would have been produced with 26% of the Inlet developed during a mean annual year (Table 9). However, some local effects were observed in the central Inlet/Browns Bay area where as a result of intensive urban development, accumulation of sediments with a high silt content and less than 10% sand were recorded. The Browns Bay bed showed a slight increase in clay content with the coarser grains towards the Inlet shoreline (McDougall 1976) indicating that the particle size of the sediments from a developed catchment with eroding subsoil (75% clay <0.002 mm) may not be as easily flushed due to flocculation and settlement. A further explanation could be the lack of circulating currents in the Browns embayment allowing the settling of sediments in that Bay.

Where catchments undergoing urban development are discharging into embayments with low tidal flushing, particular care is necessary to ensure adequate erosion prevention measures are adopted.

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