Journal of Hydrology (NZ) 36(1): 73-95, 1997

Erosion and sediment transport from the market gardening lands at Pukekohe, Auckland, New Zealand

L.R. Basher[1], D.M. Hicks[2], B. Handyside[3], and C.W. Ross[4]

[1] *Manaaki Whenua - Landcare Research, Lincoln and* [4] *Palmerston North*
[2] *National Institute of Water and Atmospheric Research, Christchurch*
[3] *Erosion Management Ltd, Auckland; formerly Auckland Regional Council*

Abstract

Sediment yield from the 1.8 km^2 Whangapouri basin near Pukekohe, used predominantly for market gardening, is compared with erosion from plots of bare soil measured at Bombay Hill. The cause of large differences between the two is inferred from soil physical properties.

The yield of suspended sediment from Whangapouri basin averaged 49 t/km^2/yr over a 3-year measurement period. Bedload was negligible compared with the suspended sediment load. Sediment yields during winter-spring storms were higher than during storms with the same peak runoff in other seasons. Soil loss from plots of continuously bare soil was two orders of magnitude higher than loss from the basin, averaging 5680 t/km^2/yr over a 2.5 year measurement period. Soil loss during individual storm events reached more than 1000 t/km^2. A small proportion (32%) of the storms was responsible for most (87%) of the soil loss, and these storms were concentrated in the winter and spring periods.

The difference in yields between the plots and the catchment suggests large quantities of soil were mobilised within paddocks by storms in the Pukekohe area, but little of this sediment was transported as suspended load in streams. This is a function of both the small proportion of fields that deliver sediment directly into the drainage system, and the strongly aggregated soils. Analysis of aggregate size and stability indicated the soils were resistant to slaking and dispersion into sand, silt, and clay particles that would contribute to suspended load. It is inferred that soil is being moved by runoff during storms, but that it is moving as aggregated material which is deposited within paddocks and drains close to the source.

Both the plot and catchment studies indicate the importance of the winter-spring period for sediment generation. This period is characterised by a

high frequency of storms, poor ground cover and increased sediment concentrations in storm runoff. Attempts to reduce sediment load and soil movement should target this period of the year.

Introduction

The Granular[1] soils of the South Auckland area, derived from volcanic ash, are some of the most intensively used in New Zealand. Approximately 8000 ha of these soils are utilised for large-scale vegetable production. There has long been a perception that the intensive land use and cultivation, combined with frequent high-intensity rain storms, cause severe erosion which is a source of pollution to local streams (Zuur, 1989) and the Manukau Harbour (Kingett Mitchell, 1988).

Accounts of the types and magnitude of erosion in the area are largely anecdotal. Rills on steeper slopes and deposition at the base of slopes are common within paddocks after storms. Many local farmers periodically use scrapers to transport soil back upslope. Sedimentation is commonly observed in drains and on roadways, and clearing of this sediment is a significant cost to Local Authorities (Rod Saunders, Franklin District Council, pers. comm., 1995). The terracetted nature of the landscape, with steps in height at paddock boundaries, is cited as further evidence of soil movement within paddocks. Molloy (1988) suggests from such evidence that up to 1 m depth of soil has been transported downslope in 100 years of intensive market gardening. However, little quantitative information is available on the total amount of soil erosion, its effect on soil properties and the sustainability of land use, or on the significance of market gardening as a source of sediment transported into the Manukau Harbour.

Previous studies in the South Auckland area have investigated the effects of land use on catchment sediment yields and soil physical properties. An analysis of sediment yields from a range of land uses in the Auckland area (Hicks, 1994) concludes that sediment yield from catchments undergoing urban development is an order of magnitude greater (at approximately 1000 t/km^2/yr) than from any other land uses, including market gardening. Zuur (1989) estimates sediment yields for streams in the Pukekohe area ranging from 23 to 88 t/km^2/yr, and suggests the highest yields are associated with market gardening.

Long-term market gardening on the Granular soils, such as Patumahoe clay loam, affects soil structure, organic matter levels, soil biological activity and soil water storage. Under native forest and pasture the

---

[1] Soil classification after Hewitt (1992); formerly classified as Brown Granular Loams

macrostructure of Patumahoe soils is typically strongly developed granular or nut, but after 15 years of market gardening is typically platy to blocky, and after 50 years of market gardening is massive (Barratt, 1971). Under prolonged cultivation the water stability of aggregates decreases and the porosity of the aggregates becomes lower (Gradwell, 1973). However, the aggregates break down to smaller aggregates rather than primary soil particles (Gradwell and Arlidge, 1971). The breakdown of structure and porosity with cultivation is linked to a reduction in macro- and microbiological activity, and loss of organic matter (Dutch, 1967; Stout and Dutch, 1967; Gradwell and Arlidge, 1971). Soil water storage in topsoils of the Patumahoe clay loam is significantly lower under market gardening than pasture (Gradwell, 1987). The implications of these induced changes in soil structure and water storage for runoff generation and erosion have not been assessed.

This paper evaluates results of investigations carried out to assess sediment yield from a small catchment and soil losses from plots, and considers the relationship of these to soil physical properties. Catchment sediment yield and its seasonal distribution were measured in the upper reaches of Whangapouri Creek near Pukekohe (reported in detail by Hicks, 1995). The catchment yield is compared with previously unpublished data on soil loss, collected in the early 1970s by the Ministry of Works, from small (40 m^2) plots. The reason for the difference in yields at the catchment and plot scale are inferred from data on the physical properties of the soils, the nature of the drainage system and crop cover.

Study area

The 1.8 km^2 Whangapouri basin is situated 2 km south west of Pukekohe (Fig. 1). It drains from the flanks of Pukekohe Hill into Whangapouri Creek and eventually into the Drury Creek inlet of the Manukau Harbour. The drainage system is man-made, with drains at paddock margins and along roadways. Below the site used for monitoring sediment yield the drains feed into a natural channel. Slopes range from 0 to 3° in the lower part of the basin, and from 4 to 10° in the upper part of the basin. Soils are mapped (Orbell, 1977) as predominantly Patumahoe clay loam, with smaller areas of Pukekohe and Whatatiri clay loam complex on the steeper slopes of the flanks of Pukekohe Hill, and Helvetia clay loam in drainage depressions in the lower part of the basin. These are clay-rich Granular soils formed from moderately to strongly weathered Hamilton Ash deposits overlying basalt. These soils generally have excellent physical properties for plant growth and are resilient to the effects of cultivation. Rainfall at

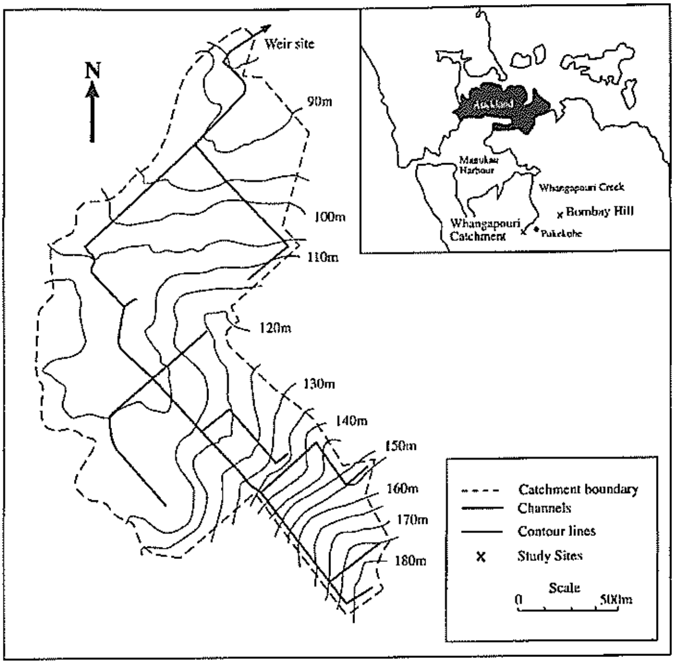

Figure 1 - Topographic map of Whangapouri basin. Inset shows location of Whangapouri basin and Bombay Hill study sites.

Pukekohe is 1400 mm/yr with a slight winter maximum. Measured rainfall intensities for short durations (10 minutes) are as high as 110 mm/hr (Coulter and Hessell, 1980).

Vegetable production is continuous, often with more than one crop grown per year. Cultivation consists of deep ripping following harvesting to break up the wheel tracks, one or two passes with "jumbo buster" tines to bring clods to the surface, rotary hoeing to incorporate trash, a fallow period of 2 to 3 months to allow clods to break up, and rotary hoeing before planting of crops. Crops are generally planted up and down slope to facilitate surface drainage, particularly for early crops. At the time of the sediment yield study, 65% of the catchment was utilised for market gardening with the remainder under pasture or used for flower growing.

The plot study was carried out in a paddock at Bombay Hill, 9 kms to the east of Whangapouri basin (Fig. 1). The soil at this site is Patumahoe clay loam, and the slope of the site is 6 to 8°. Rainfall amounts and characteristics are similar at this site to those in the Whangapouri basin. The site had been in pasture and used for grazing before plot establishment.

Catchment sediment yield study

Data collection

Stream flow was monitored by recording water levels at a "v-notch" weir during the periods December 1988 to January 1990 and August 1991 to July 1993. Rainfall was recorded by an automatic tipping-bucket rain gauge near the weir. To determine suspended sediment concentrations a 24-bottle automatic sampler was used to collect samples of water from near the weir plate during storm flows.

Three different approaches to operating the automatic sampler during storms were used. For the storms sampled before 1991, a simple bulk-sampling procedure was followed. Samples of equal volume were composited at even time intervals to provide the time-averaged concentration over the storm. After August 1991, discrete samples were collected every 7 minutes to produce time-series of suspended sediment concentration through storms. Two auto-samplers were used in series, permitting up to 48 samples to be collected for each storm. In 1993, a flow-proportional compositing system was employed. This provided for each storm a composite sample approximating the flow-weighted concentration over the storm.

Six cross-sections, spaced 0.5 m apart along the weir pond, were surveyed several times in order to check bedload accumulation rates. In addition, in 1992, a bedload trap measuring 1.5 m long (along the flow direction) by 0.3 m wide and 0.3 m deep was placed in the streambed upstream of the weir pond, and was monitored for bedload accumulation. Particle size distribution was determined for three samples of material collected in the bedload trap.

Analysis methods

Determining storm sediment yields

For storms in which discrete samples were collected, the time-series records of suspended sediment concentration and water discharge were integrated to calculate the storm suspended sediment yield. Corrections were applied to the storm yields determined by bulk-sampling. For the storms sampled in 1989, the regular-time-interval compositing approach provides only the time-averaged concentration over the storm, not the flow-weighted average concentration. To correct for this, the bulking procedure was simulated with a computer program for the storms sampled in 1991-92 that did have detailed concentration time-series. This showed that the simple compositing approach consistently underestimated the actual storm sediment yield over a wide range of storm magnitudes. An empirical factor was therefore used to scale-up the yields of storms sampled before August 1991.

A similar procedure was used to empirically correct the yields determined with flow-proportional composite-sampling during 1993, since these still missed the sediment carried at the beginning of the event, before sampling began. Further details of these analysis methods are given in Hicks (1995).

Determining longer-term suspended sediment yields

Long-term average suspended sediment yields were estimated using the storm yield rating method (Hicks 1990, 1994). This involved:

(i) accurately measuring the sediment yield from a sampling of storms,
(ii) determining the relationship between storm sediment yield and storm peak flow from this sample, and
(iii) using this relationship to estimate the yields in unmeasured events over the complete flow record.

When calculating the sediment yield over the period of flow record, storms were distinguished on the basis of discrete quickflow events. The yields from very small events were ignored if the event quickflow was less than 0.1 mm. A quickflow separation slope of 0.000152 l/s/km^2 was used.

Least-squares regression of log-transformed data was used to model the relationship between storm sediment yield (SSY, in kg/km^2) and peak flow (Q_p, in l/s). The model has the form:

$$SSY = a\, Q_p^{\ b}$$

where the coefficient a incorporates Duan's (1983) non-parametric factor for removing the bias induced by de-transforming the regression results from log to linear values. The percentage standard-error-of-the-estimate (SE) for this model was estimated as:

$$SE = \pm\, 100\,(\exp(s) - 1)$$

where s is the standard error of the estimate in natural log units. The 95% confidence interval on the long-term average yield integrated over all events during the record period was estimated as:

$$\pm\sum_i 100\left(\exp\left[t*s*\sqrt{\left(1/N+(X_i-\bar{X})^2/\sum_j(X_j-\bar{X})^2\right)}\right]-1\right)*Y_i/\sum_i Y_i$$

where t is the Student's t value, N is the number of data pairs in the regression analysis, X_i is the logarithm of the peak flow for the ith storm, $\bar{X}$ is the mean of the logarithms of the peak flows used in the regression, X_j are the logarithms of the individual peak flows used in the regression, and Y_i is the estimated yield for each storm.

Plot soil loss study

Over the period February 1971 to September 1973, soil loss was measured from four 40.5 m^2 plots bounded by wooden borders. The plots were approximately 13.1 m long and 3.1 m wide. The total amount of runoff and soil transported across the sill at the base of the plots was collected in drums during each storm. Rainfall was recorded by a Dines chart recorder from which total rainfall and maximum 15-minute rainfall intensity were determined for each storm. The plots were cultivated with a rotary hoe and levelled immediately before measurements of soil loss began, and were then maintained in a bare fallow condition with regular hand hoeing to keep them weed free to simulate bare cultivated soil conditions. In March 1972 two of the plots were grassed down, to assess the effect of pasture in reducing soil loss.

Data from this study were never published by Ministry of Works. The results reported here were obtained from Ministry of Works files now held in the National Archives, Auckland. As a result only limited data were available for individual storms (soil loss, runoff, rainfall, maximum 15-minute rainfall intensity) and this limited the analysis that was possible. However, the data provided a strong contrast with the catchment sediment yield and provided an estimate of the potential erosion under bare soil conditions.

Soil physical properties

A series of samples were collected to determine the physical properties of the soils in Whangapouri basin, and the sediments accumulating in the drainage system. Some key chemical properties that influence soil structure were also determined. The sample sites included a paddock which had just been ploughed, paddocks in a range of crops (potatoes, onions, lettuces), and three samples of material collected from within the drains.

These samples were analysed for aggregate size distribution and aggregate water stability following the methods of Gradwell and Birrell (1979). Structural units were examined on freeze-dried 2 to 4 mm aggregates using a Cambridge Stereoscan electron microscope. The samples were analysed for total carbon, pyrophosphate, oxalate and dithionite-citrate extractable Fe and Al following the methods of Blakemore *et al.* (1987).

Results

Catchment sediment yield study

Suspended sediment concentrations

In all, suspended sediment concentration data were obtained for 33 storms. Maximum concentrations during storm runoff ranged from less than 100 mg/l to almost 3000 mg/l. Mean storm concentrations ranged from about 30 to 2000 mg/l. The mean and maximum concentrations tended to increase with peak flow magnitude.

Figure 2 shows the relationship between instantaneous suspended sediment concentration and water discharge (i.e. the 'sediment rating'), compiled from all the discrete suspended sediment samples. The relationship is poor, with concentrations varying by a factor of 200 for a given discharge. The poor correlation ($r^2 = 0.21$) shown was the main reason why sediment yields during unsampled storms were not estimated using the traditional sediment rating approach. The scatter relates in part to hysteresis effects, since some storms showed clockwise hysteresis and others showed anti-clockwise hysteresis (Fig. 3). The variable hysteresis effects probably reflect the location and longevity of sediment sources: the clockwise hysteresis suggested riparian sources becoming relatively exhausted during the event, while the anti-clockwise hysteresis suggested sediment arriving with surface runoff after the flood wave had passed the recorder site.

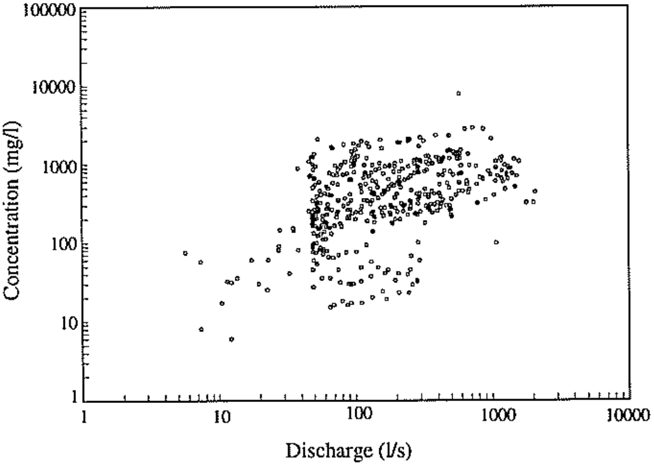

Figure 2 - Instantaneous suspended sediment concentration plotted against water discharge.

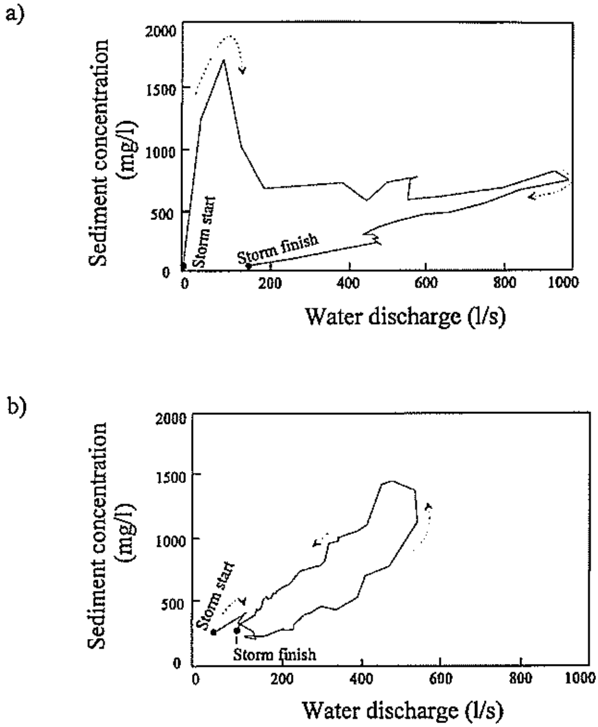

Figure 3 - Relationship between instantaneous suspended sediment concentration and water discharge through storms, showing (a) clockwise (b) anticlockwise hysteresis.

Suspended sediment yield

The storm suspended sediment yield *vs.* peak discharge 'rating' is plotted in Figure 4. Separating the data according to season suggested that the winter-spring (May-October) yields for a given peak flow were slightly higher than those in summer (November-January), and a factor-of-ten higher than yields in autumn (February-April). This probably resulted from seasonal changes in the degree of ground cover by crops. Because the autumn regression relationship would be based on only three points, a separate storm rating was not calculated for the autumn data, and the regression relationship based on the total dataset was used to estimate yields during all seasons. While this may lead to an overestimation of yields from autumn storms, this has little effect on the total sediment yield. Few storms occurred, and little sediment was generated, during the autumn

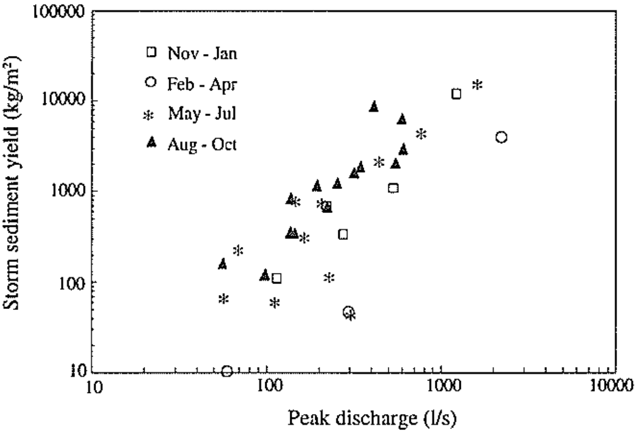

Figure 4 - Relationship between storm suspended sediment yield and storm peak flow. Data separated by season.

period, whereas the winter-spring period was characterised by a high frequency of storms and high sediment yield (Fig. 5).

The regression relationship fitted to the data of Figure 4 was:

$$SSY = 0.289\ Q_p^{\ 1.44} \qquad r^2 = 0.61$$

where *SSY* has units of kg/km² and Q_p is in l/s. The 95% confidence interval of the estimate of *SSY* is ±21%. The mean annual suspended sediment yield for the Whangapouri basin, derived from this storm yield *vs* peak flow relationship applied to the 2.8 years of flow record, was 49±6 t/km²/yr.

Bedload

Bedload transport during storm runoff was estimated from accumulation in the recorder weir pond, and in bedload traps that were installed in 1992. Sediment accumulation in the weir pond was negligible. Repeat surveys on 26 August and 30 September 1991, a period spanning several storms, showed a maximum accumulation of 0.045 m³ (0.054 tonnes, assuming a bulk density of 1.2 t/m³). Over this period, the suspended sediment yield was 24 tonnes, and therefore the bedload was only 0.2% of the total load. The weir pond was cleared by back-hoe on 17 July 1992, with the removal of 0.19 m³ of sediment. Again, this amount is a tiny proportion (also 0.2%) of the suspended sediment yield (approximately 120 tonnes) over the preceding nine months.

The particle-size distributions for samples taken from the bedload trap

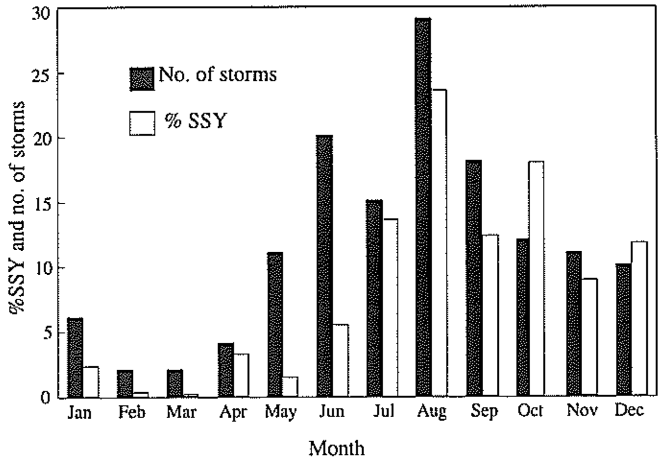

Figure 5 - Monthly distribution of suspended sediment yield (SSY) and storms over the study period. % SSY is the percentage of the total SSY generated in each month.

(Fig. 6) show one-half to three-quarters of the material from the bedload trap was of sand size (0.2-2 mm); the bulk of the remainder was coarser soil aggregates. This material was far coarser than the primary particles of the soil and similar to samples taken from the paddocks and drains. The particle-size distribution for the bedload samples appeared to have a finer tail than the within-paddock and drain samples.

Therefore it is concluded that the Whangapouri Creek carries negligible bedload compared with its suspended load, and that the bedload comprises soil aggregates.

Plot soil loss study

Measurements of soil loss were made from 59 storms that occurred during the 2.5 years of the study. During individual storms, soil losses from the plots often varied by a factor of two, but this averaged out through time and there were no statistically significant differences in average plot yields from bare soil. All four plots had consistently high rates of soil loss while the soil surface was kept bare.

Soil loss from bare soil (Table 1) averaged over the plots for the entire record was 5680 t/km^2/yr. Over the period when all four plots were kept bare, soil loss ranged from 5700 to 6900 t/km^2/yr, with an average of

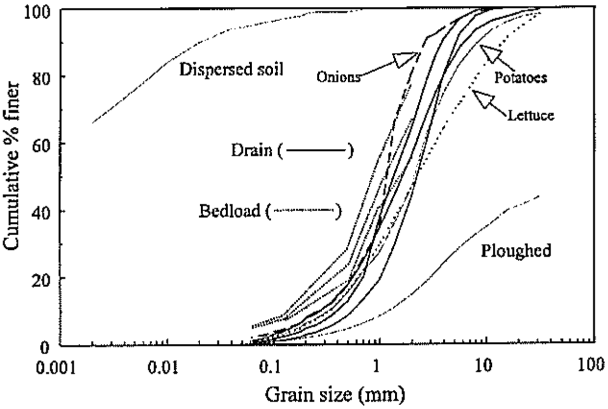

Figure 6 - Size distributions of material from bedload trap, aggregates from paddocks with various crops, drains and dispersed soil material (soil primary particles).

Table 1 - Plot soil losses. Plots 2 and 3 were converted to grass in March 1972.

	Soil loss (t/km^2/yr)			
Period	Plot 1	Plot 2	Plot 3	Plot 4
26/2/71 - 14/3/72	6944	6679	5723	5878
15/3/72 - 11/9/73	4820	48	27	4062
26/2/71 - 11/9/73	5690			4806

6310 t/km^2/yr. The coefficient of variation for mean yield of the plots was less than 10%. When plots 2 and 3 were grassed down, soil loss on these plots reduced to an average of 37.5 t/km^2/yr, while on the bare soil plots it remained at 4100 to 4800 t/km^2/yr. Soil loss from the bare plots was lower during this second period of measurement (4440 cf. 6310 t/km^2/yr), but remained two orders of magnitude higher than soil loss from pasture. These figures illustrate the enormous potential for soil loss from bare soil, and the mitigating effect of vegetation. Soil loss from the grassed plots was similar to that measured in the catchment study.

Soil loss during individual storms (averaged across all plots) reached extremely high values, with losses during 19 of the 59 storms exceeding 100 t/km^2 and 4 storms exceeding 1000 t/km^2. The 32% of storms in which soil loss exceeded 100 t/km^2 were responsible for 87 % of the measured soil loss and the nine largest storms (15%) resulted in 65% of the soil loss,

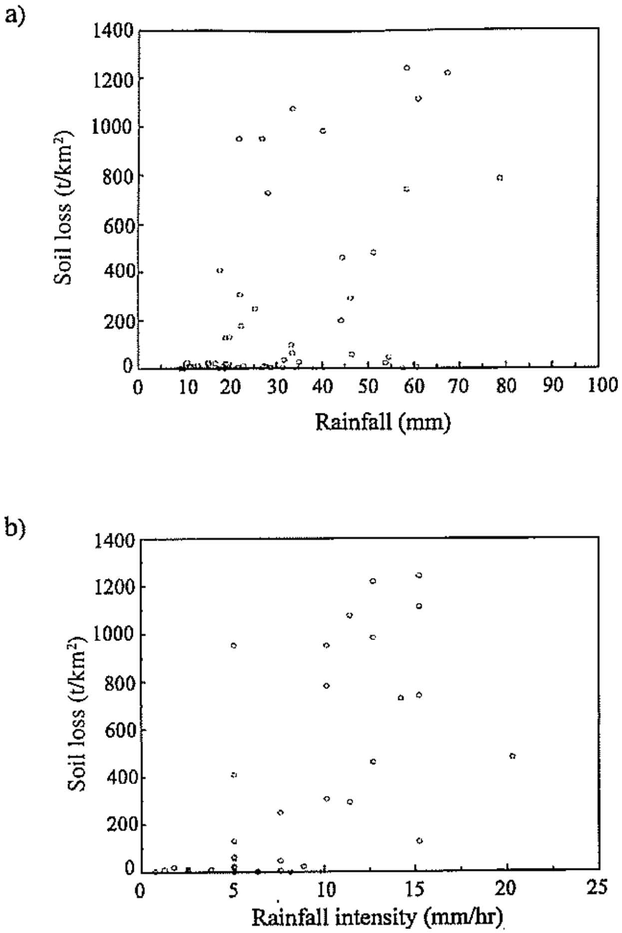

Figure 7 - Relationship between plot soil loss during storms and (a) storm rainfall (b) maximum 15-minute rainfall intensity.

illustrating the importance of the larger rainfall events in causing erosion. Recurrence intervals cannot be calculated for these events as their duration is unknown. On the plots that were grassed down, soil loss only once exceeded 20 t/km^2 and progressively declined with time, presumably as the grass cover and root mass developed. Storms which produced up to 300 t/km^2 on the bare soil plots produced no soil loss on the grassed plots.

Limited data were available to assess the relationship between soil loss and storm parameters because the original data on time-series storm rainfall were not available. There was a poor relationship (linear, logarithmic or exponential) between total storm rainfall and soil loss ($r^2<0.25$). Although there was a trend for increasing soil loss with higher rainfall, there were a large number of storm rainfalls in excess of 20 mm that produced very little soil loss (Fig. 7a). Rainfall totals during the major soil loss events ranged from 17 to 67 mm. There was a stronger, but still poor, relationship (linear, logarithmic or exponential) between peak 15-minute rainfall intensity and soil loss ($r^2<0.46$), with much variation in the yields at both low and high rainfall intensities (Fig. 7b). Measured peak 15-minute rainfall intensities were relatively low, with a maximum value of 20 mm/hr. By comparison, the two year return period, ten-minute duration rainfall intensity at Pukekohe is 60 mm/hr (Coulter and Hessell, 1980).

Soil loss was strongly related to total storm runoff (Fig. 8). A log-log relationship explained more of the variation ($r^2=0.72$) in soil loss than a simple linear relationship ($r^2=0.65$). There was no evidence of seasonal effects on the soil loss-runoff relationship. There was a poor relationship between runoff and both total rainfall ($r^2=0.36$) and rainfall intensity ($r^2=0.27$). Only a very small proportion of storm rainfall was returned as runoff, generally less than 10%, although it reached as much as 50% in some storms. The proportion of rainfall leaving as runoff tended to increase as the total amount of runoff increased.

During the plot study, the frequency of storms varied with the season. Most storms (47 out of 59) occurred in the winter and spring months (May to September), with fewer in the summer and autumn (Fig. 9). Most of the large events that produced large soil losses also occurred in the winter and spring months. The relatively high proportion of soil loss occurring in March and November (in relation to the small number of storms) resulted from the very large soil losses (700 to 1000 t/km^2) in individual storms in these months. The plot data did not show the same seasonal effect as the catchment sediment yield data, with no evidence of seasonal differences in soil loss for similar peak 15-minute rainfall intensities, or similar amounts of runoff, indicating that the seasonal effect is most likely related to variation in ground cover rather than soil properties.

Soil physical properties

Physically, the soils were characterised by high clay (kaolinite, halloysite) and allophane content, strong macro- and micro-aggregation, and structural stability. All samples had strong aggregate water stability and micro-aggregation features. Particle size and mineralogical analyses of Patumahoe and Pukekohe soils indicated that clay contents in surface horizons were in excess of 60%, and that up to 10% of the clay fraction was allophane.

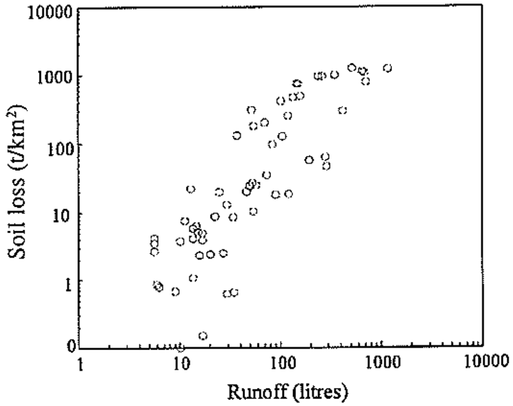

Figure 8 - Relationship between storm runoff and soil loss from plots.

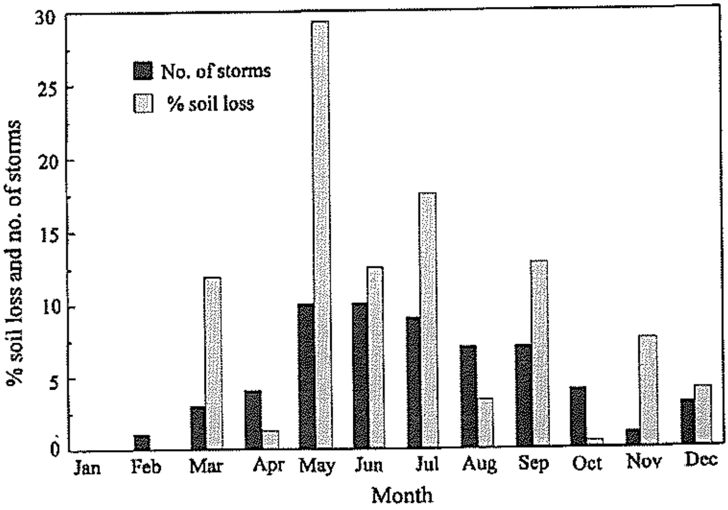

Figure 9 - Monthly distribution of the plot soil loss and storms over the study period. % soil loss is the percentage of the total soil loss generated in each month.

Mean weight diameters of the aggregates of all samples taken from Whangapouri basin were in the 1 to 2.5 mm range, except for soil from the ploughed paddock, where over half the sample was coarser than 31.5 mm (Table 2). This paddock had recently been ploughed and was left with a very rough surface and very large aggregates. Aggregate size distributions (Fig. 6) were well graded with aggregates across the spectrum of sizes, except for the ploughed paddock. In general, the samples showed a small proportion of very fine aggregates (<1 mm) and primary particles, and were typical of strongly aggregated volcanic ash soils. Figure 6 illustrates the large difference between the size distribution of the primary soil particles and the soil aggregates, and the differences associated with crop type and cultivation. The samples taken from paddocks in lettuces and potatoes had a similar aggregate size distribution. The paddock in onions showed a considerably finer aggregate size distribution that was more like the samples taken from the drainage system and bedload trap. Following storms rills were more common in onion paddocks than in paddocks with other crop types.

All samples were moderately to strongly water stable, with between 72.9 and 90.5% of the sample remaining on the 0.5 - 2 mm sieves (Fig. 10). The samples from the drains had a higher cumulative net percentage retained (87.1 - 90.5%) than the samples from the paddocks (72.9 - 80.8%). The drain samples also tended to have a higher proportion of coarser water stable aggregates (retained on the 2 mm sieve) than samples from the paddocks. These trends probably reflected loss of a small proportion of

Table 2 - Soil aggregate mean weight diameters and aggregate water stabilities.

* Mean weight diameter (sum of the % of soil remaining on each sieve multiplied by the mean diameter of adjacent sieves)

\# cumulative % retained on 0.5, 1, and 2 mm sieves after wet sieving

Sample	Aggregate size MWD (mm)*	Aggregate stability Cumulative net % #
Drain	1.39	90.5
Drain	1.51	89.7
Drain	2.03	87.1
Potatoes	1.85	80.8
Lettuce	2.27	72.9
Onions	1.06	77.7
Ploughed	>31.5	79.9

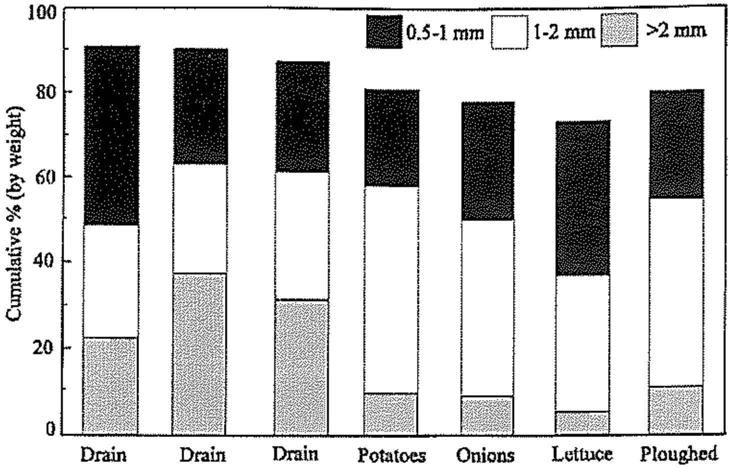

Figure 10 - Aggregate stability analysis showing percentage of aggregates remaining on 2, 1 and 0.5 mm sieves after wet sieving.

unstable soil aggregates by abrasion and dispersion during bedload transport in the drainage system. The results indicated that the soils are relatively strongly aggregated and resistant to slaking and dispersion into the primary sand, silt, and clay particles that would be transported as suspended load.

Scanning electron micrographs of topsoil aggregates from the study sites at Pukekohe (Fig. 11) showed strong soil aggregation and inter-particle bonding at the microstructural level. This strong microstructural development was consistent with the aggregate stability results that indicated a high degree of water stability. The topsoil aggregate surfaces exhibited a "glued" appearance caused by surface coatings of organic matter and aggregated surface "skins" of oriented clay particles. This type of surface microstructure formed a protective barrier against the disaggregating forces of water and mechanical breakdown. The internal microstructures of topsoil aggregates from the Pukekohe study area also exhibited strong inter-particle bonding and microstructural development. This helps to explain why volcanic soils at Pukekohe do not disaggregate easily into primary particles during rainstorms or as a result of the mechanical effects of cultivation. Rather, the soil aggregates tend to break into smaller aggregates which are either redistributed downslope within fields or contribute to the bedload of the drains. Dispersion into primary soil particles, which would contribute to suspended sediment in waterways,

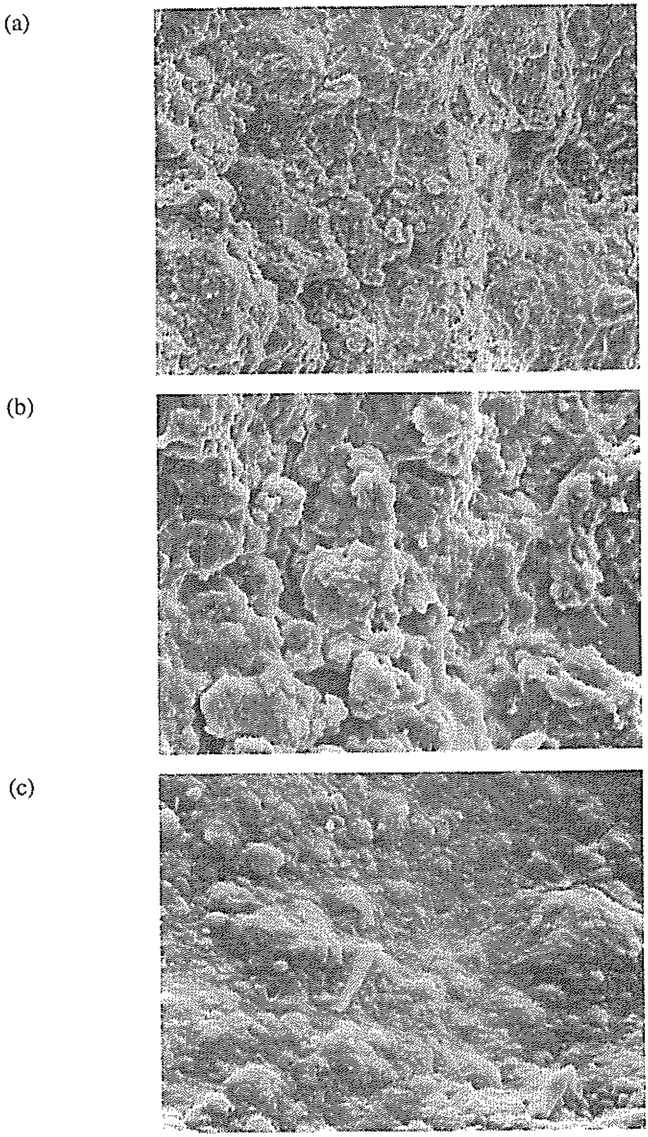

Figure 11 - Scanning electron micrographs showing strongly aggregated microstructures of the surface of the Patumahoe soil. The "glued", strongly aggregated surface coating are shown at (a) 500, (b) 1250 and (c) 2500 times magnification.

is minimal because of the strong micro- and macrostructure.

The results of soil chemical analysis (Table 3) suggested that the strong aggregation was largely a function of the presence of high levels of Fe and Al minerals rather than organic matter. Total C was low to very low in all samples, with a tendency for slightly higher levels in the paddock samples (average 2.1%) than in the drain samples (1.7%). Low levels of pyrophosphate-extractable Fe and Al also suggested little organically complexed Fe and Al. Medium levels of oxalate-extractable Fe, Al and Si indicated a moderate content of short-range order minerals that have an aggregation function. The key features were the high to very high levels of dithionite-citrate extractable Fe, and medium to high levels of dithionite-citrate extractable Al. These indicated a high content of short-range order, secondary crystalline Fe and Al minerals which conferred strong soil aggregation. There was little difference between the paddock and the drain samples in extractable Fe and Al.

Discussion

Sediment export from the Whangapouri basin was very low, both in absolute terms and by comparison with basins undergoing urban development in the Auckland area. The measured sediment yield was comparable with the yields of 23 to 88 t/km^2/yr estimated by Zuur (1989) for other catchments in the Pukekohe area. The uncertainty in how representative the measured yield of 49 t/km^2/yr is of the true 'long-term' average annual yield is larger than the 12% estimated for the measurement period. This uncertainty is caused by the considerable annual variability in sediment yields in the Auckland region. Analysis by Hicks (1994) of

Table 3 - Selected chemical properties of soils.

Sample	Pyrophosphate (%)			Oxalate (%)			Ditionite- citrate (%)	
	C(%)	Fe	Al	Fe	Al	Si	Fe	Al
Drain	1.2	0.11	0.09	0.46	0.64	0.17	6.4	1.2
Drain	1.8	0.27	0.18	0.57	0.78	0.20	5.3	1.1
Drain	2.1	0.13	0.12	0.66	0.66	0.14	3.5	0.75
Potatoes	2.2	0.17	0.15	0.74	0.61	0.09	4.5	1.0
Lettuce	1.9	0.14	0.10	0.60	0.51	0.12	6.9	1.2
Onions	1.9	0.09	0.12	0.76	0.62	0.05	4.5	1.0
Ploughed	2.4	0.15	.012	0.62	0.58	0.13	6.7	1.3

the 17-year record of runoff at the Manukau basin showed that the standard deviation of annual sediment yields there equated to a factor of two. Assuming the same degree of annual variability in sediment yields at Whangapouri basin, these figures suggest a 95% confidence interval of a factor of 2.2 for the estimated long-term average annual yield estimated from the 2.8 year record (i.e. we can be 95% confident the long-term average annual sediment yield lies between 22 and 108 t/km^2/yr).

Field observations, the experience of vegetable growers and Local Authorities, and plot data all suggested large quantities of soil were mobilised during storms in the Pukekohe area. However, the results of the sediment yield study suggested that little of this sediment was transported through the fluvial system and into the Manukau Harbour. This conclusion agreed with that of Kingett-Mitchell (1988), that the market gardening lands are not a major source of sediment for the Manukau Harbour.

The measured sediment yields at the plot and catchment scale differed by two orders of magnitude, and suggested that a much greater amount of sediment is mobilised within the catchment than leaves it. However, the precise comparison of yields is complicated by three factors.

1) The two data sets were collected at different time periods (separated by 20 years) and in different locations and this may have directly influenced results, particularly if climatic conditions affecting sediment mobilisation and delivery differed during the two periods of measurement.
2) At the catchment scale, sediment availability is reduced by farmer and Local Authority drain clearing operations. Much of the sediment transported to the drainage system by overland flow is cleared and therefore not available to be flushed through the channel system by large flow events. This may affect the supply of sediment, particularly in large runoff events.
3) Results of the plot study apply to bare soil conditions rather than those typical of market gardens where soil losses will be lower due to the effects of crop cover.

Although the plot study did not provide an estimate of soil movement under market gardening management practices, it indicated the potential for erosion from bare soil. The high soil losses measured on the plots were similar to those estimated by Hicks (1994) for bare soil in a catchment undergoing urban development in the Auckland area (6600 t/km^2/yr). For most crops that are grown in the Pukekohe area there are considerable periods of time when the land surface has limited ground cover and would be vulnerable to erosion. Post-storm sediment clearing operations by Local Authorities, vegetable grower practice of redistributing soil within paddocks, and the terracetted nature of the landscape also suggest considerable within-paddock movement of soil.

Both the plot and catchment studies indicated the importance of the winter-spring period for sediment generation. This period is characterised by a high frequency of storms, poor ground cover, and increased sediment concentrations in storm runoff. Attempts to reduce erosion should target this period of the year.

The strong aggregation of the volcanic soils results in little slaking and dispersion into primary sand, silt and clay particles that could be transported by the flows within the drainage system in Whangapouri basin. It is inferred that soil is being moved by runoff during storms, but it is moving as aggregated material that is deposited within paddocks and drains close to the source, where runoff velocities decrease. Aggregate size analyses of material from the paddocks, drains and bedload trap showed that all these materials are dominated by soil aggregates ranging from 0.5 to 4 mm in size. This contrasted strongly with the primary particles of the soils which are dominantly less than 0.02 mm in size. Aggregate stability analysis suggested that soil aggregates are strongly resistant to dispersion and slaking into sand-sized and smaller particles that would contribute to suspended load. This analysis also suggests that crop types affect soil erodibility, since soil aggregates from onion paddocks had a finer size distribution than those from lettuce or potato paddocks, and ploughed paddocks yielded very coarse aggregates.

In Whangapouri basin only a small proportion (<10%) of paddocks discharge sediment directly into drains. This also acts to limit sediment supply to the drainage system. Within paddocks slope gradient often diminishes downslope, reducing runoff velocity and sediment transport capacity, resulting in deposition of entrained sediment. Within-paddock soil redistribution is indicated by variation in topsoil depth. Topsoil depths in upper parts of paddocks are typically similar to the plough depth (about 20 cm), whereas the lower parts of paddocks commonly have very deep (>50 cm) topsoils. This within-paddock sediment redistribution is currently being quantified using the radionuclide tracer ^{137}Cs.

Conclusions

Large quantities of soil are mobilised within paddocks by storms in the Pukekohe area. However, little of this sediment is transported by streams into the Manukau Harbour. The mean annual suspended sediment yield for Whangapouri basin of 49 t/km^2/yr was very low in absolute terms, and in comparison with sediment yields from land used for other purposes in the Auckland area. Whangapouri Creek carries negligible bedload compared with its suspended load, and the bedload comprises soil aggregates. Measured soil losses from bare soil plots were two orders of magnitude higher than the Whangapouri basin sediment yield and illustrated the potential for erosion of bare soil. Both the plot and catchment studies indicated the importance of the winter-spring period for sediment generation. This period is characterised by high frequency of storms, poor ground cover and increased sediment concentrations in storm runoff. Attempts to reduce erosion should target this period of the year.

Analysis of aggregate size and stability indicated the soils are strongly aggregated and resistant to slaking and dispersion into primary sand, silt, and clay particles that would contribute to suspended load. Physically the soils are characterised by high clay and allophane contents, strong macro- and micro-aggregation, and structural stability. The strong aggregation is largely a function of the high levels of Fe and Al minerals, rather than organic matter. It is inferred that soil is being moved by runoff during storms, but that it is moving as aggregated material, which is deposited within paddocks and drains where runoff velocities decrease.

Acknowledgements

We are grateful to the Foundation for Research, Science and Technology (Contract CO9402), Auckland Regional Council, and Environment Waikato for funding this study. The Auckland staff of NIWA were responsible for collecting the data for the sediment yield study. Analysis staff of the former DSIR Land Resources carried out the soil chemical analyses (G.P. Lilley, J.W. Ross, C.D. Morgan, and K. Giddens). Amos Glass and Peter Lykles of Water and Soil Division, Ministry of Works were responsible for collecting the plot data. Rick Jackson, Stephen Burgham and Ong Su-wuen reviewed earlier drafts of this paper.

References

Barratt, B.C. 1971: A micromorphological investigation of structural changes in the topsoil of Patumahoe clay loam used for market gardening. *New Zealand Journal of Science 14*: 580-98.

Blakemore, L.C.; Searle, P.L.; Daly, B.K. 1987: Methods for chemical analysis of soils. *NZ Soil Bureau Scientific Report 80*, Department of Scientific and Industrial Research, Wellington.

Coulter, J.D.; Hessell, J.W.D. 1980: The frequency of high intensity rainfalls in New Zealand. Part II Point estimates. *New Zealand Meteorological Service Miscellaneous Publication 162*, New Zealand Meteorological Service, Wellington.

Duan, N. 1983: Smearing estimate: a non-parametric retransformation method. *Journal of the American Statistical Association 78(383):* 605-610.

Dutch, M.E. 1967: Influence of soil cultivation on earthworms at Pukekohe. *New Zealand Soil News 15*: 86-88.

Gradwell, M.W. 1973: Internal properties of soil aggregates from the market gardens of Pukekohe. *New Zealand Journal of Agricultural Research 16:* 463-75.

Gradwell, M.W. 1987: Comparison of the available water capacities of Patumahoe clay loam under pasture and cultivation. *New Zealand Journal of Agricultural Research 30:* 367-72.

Gradwell, M.W.; Arlidge, E.Z. 1971: Deterioration of soil structure in the market gardens of the Pukekohe district, New Zealand. *New Zealand Journal of Agricultural Research 14:* 288-306.

Gradwell, M.W.; Birrell, K.S. 1979: Methods for physical analysis of soils. *NZ Soil Bureau Scientific Report 10C*, Department of Scientific and Industrial Research, Wellington.

Hewitt, A.E. 1992: New Zealand soil classification. *DSIR Land Resources Scientific Report No. 19*, Department of Scientific and Industrial Research, Wellington.

Hicks, D. M. 1990: Suspended sediment yields from pasture and exotic forest basins. In: *Proc. 1990 N.Z. Hydrological Society Symposium*, Taupo, Nov. 1990.

Hicks, D.M. 1994: Storm sediment yields from basins with various landuses in Auckland Area. *ARC Environment Division Technical Publication No. 51*, Auckland Regional Council, Auckland, 34p.

Hicks, D.M. 1995: Sediment yields from a market-gardening basin near Pukekohe. *ARC Environment Division Technical Publication No. 61,* Auckland Regional Council, Auckland, 24p.

Kingett-Mitchell 1988: Manukau Harbour Action Plan: assessment of the recent sedimentation history of the Manukau Harbour. Prepared for Auckland Regional Water Board, Auckland.

Molloy, L.F. 1988: *Soils in the New Zealand Landscape.* Mallinson Rendel and the New Zealand Society of Soil Science, Wellington, 239p.

Orbell, G.E. 1977: Soils of part Franklin county, South Auckland, New Zealand. *NZ Soil Bureau Soil Survey Report 33,* Department of Scientific and Industrial Research, Wellington.

Stout, J.D.; Dutch, M.E. 1967: Differences in biological activity in the Patumahoe soil under cultivation, pasture and forest. *New Zealand Soil News 15:83-85.*

Zuur, B. 1989: The quality of surface waters in the Pukekohe area. *Waikato Catchment Board Technical Report 1989/7.*