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Predicting sediment loss under proposed development in the Waiarohia catchment

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Predicting sediment loss under proposed development in the Waiarohia catchment

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Executive Summary

NIWA have been commissioned by Auckland Regional Council (ARC), North Shore City Council, Rodney District Council, Waitakere City Council, and Transit NZ to: 1) predict the impact of proposed rural residential developments upon sediment loss in the Waiarohia catchment, and to determine whether the proposed earthworks are to result in a significant change in sediment load compared with the existing land use. Additional aims of the study were: 2) to assess the effectiveness of specified sediment control measures associated with the proposed earthworks; 3) generate information for feeding into the wider Upper Waitemata Harbour (UWH) contamination accumulation study; 4) provide validation (or not) of the need for modelling sediment yield in the UWH study; 5) provide an assessment of the risk of excessive sedimentation occurring in the Upper Harbour as a result of the proposed developed in the Waiarohia catchment

The study focuses upon a 201-hectare parcel of land that lies to the south of the Whenuapai airbase. A physically based field scale computer model GLEAMS (Knisel 1993) is used to predict sediment generation for the existing pastoral landuse and the earthworks phase of the proposed development, both with and without sediment control measures. Three control measures are simulated, both singularly and in combination. These are; sediment retention ponds, a restriction of the earthworks season with earthworks stabilisation in the off-season, and riparian grass buffer strips.

Since it is impossible to forecast rainfall during the actual construction phase, the 'worst-case' phase of development (1.65 km of roads plus 7 house sites) was modelled using a 28-year meteorological time-series. Average, wet and dry year sediment yields are reported. Whilst uncertainty is associated with the absolute model predictions, this is much lower when assessing the relative impact of each scenario. The model predictions are of hillslope sediment loss and do not incorporate in-stream sediment dynamics. We expect that much of the sediment generated on hillsides in the Waiarohia is delivered to the estuary since the downstream travel distance is short. This high delivery, however, does not necessarily apply elsewhere in the UWH catchment.

The proposed 1-hectare developments in the Waiarohia are predicted to increase sediment loss relative to that under the existing pastoral landuse. A 72% increase in average annual sediment load is predicted across the development area under the worst-case (no controls) scenario. This figure is lowered, however, through the incorporation of sediment control measures, and simulation of all three controls in combination is predicted to increase sediment loss across the area by 12% (relative to the existing pastoral land). Only one scenario that incorporates a control measure (grass buffer) predicts an increased sediment loss of > 50%. Simulation of a 2-hectare

development scenario results in a small decrease in average sediment loss relative to the 1-hectare predictions.

Retention ponds are predicted to be the most effective single control measure (67% average efficiency), whilst seasonal restrictions to earthworks (31%) and a grass buffer (20%) have less impact. Observed data from field studies in the Auckland region provide some validation of the predicted control measure efficiencies. There is marked variation between years in predicted sediment generation and the efficiency of control measures, with far more sediment likely in wet years. During very large events, control entrapment efficiency can approach zero.

The modelling results have utility in identifying appropriate levels of sediment control for the proposed development across the UWH catchment. They are also applicable to areas of proposed rural residential development across the UWH catchment, particularly those upon alluvial soils and flat or gently sloping land.

Since the proposed developments are predicted to increase sediment yield; 1) earthworks phase modelling is desirable (and underway) for the wider UWH study; 2) there is potential for excessive (i.e., posing a risk to biota) sedimentation occurring in the harbour, particularly given the relatively small estuary with its restricted outlet. However, quantifying the risk to biota requires feeding predictions of event based catchment sediment loss to an estuarine model to determine sedimentation rates. These sedimentation rates then need to be coupled with an understanding of their impact upon biota, to determine risk.

1. Introduction

NIWA have been commissioned by Auckland Regional Council, North Shore City Council, Rodney District Council, Waitakere City Council, and Transit NZ, to predict the impact of proposed rural residential developments upon sediment loss in the Waiarohia catchment, and to assess the effectiveness of specified sediment control measures associated with the proposed earthworks. The study aims to determine whether the development will result in a significant change (> ±50%) in sediment loss relative to the existing pastoral landuse. This work programme is an initial component of the larger Upper Waitemata Harbour (UWH) contaminant accumulation study, and the results have utility in identifying appropriate levels of sediment control for the proposed development across the UWH catchment.

The study focuses upon a 201-hectare parcel of land in the Waiarohia catchment (delineated in red, Figure 1) that lies between the Whenuapai airbase and SH18. The land is currently predominantly pastoral but a development of 118 1-hectare lots is proposed. A physically based field scale computer model GLEAMS (Knisel 1993) is used to predict sediment generation for the existing pastoral landuse and the earthworks phase of the proposed development, both with and without sediment control measures. Three control measures are simulated, both singularly and in combination. These are; sediment retention ponds, a restriction of the earthworks season with earthworks stabilisation in the off-season, and riparian grass buffer strips.

Since it is impossible to forecast rainfall during the actual construction phase, the 'worst-case' phase of development (1.65 km of roads plus 7 house sites) was modelled using a 28-year meteorological time-series. Average, wet and dry year sediment yields are reported.

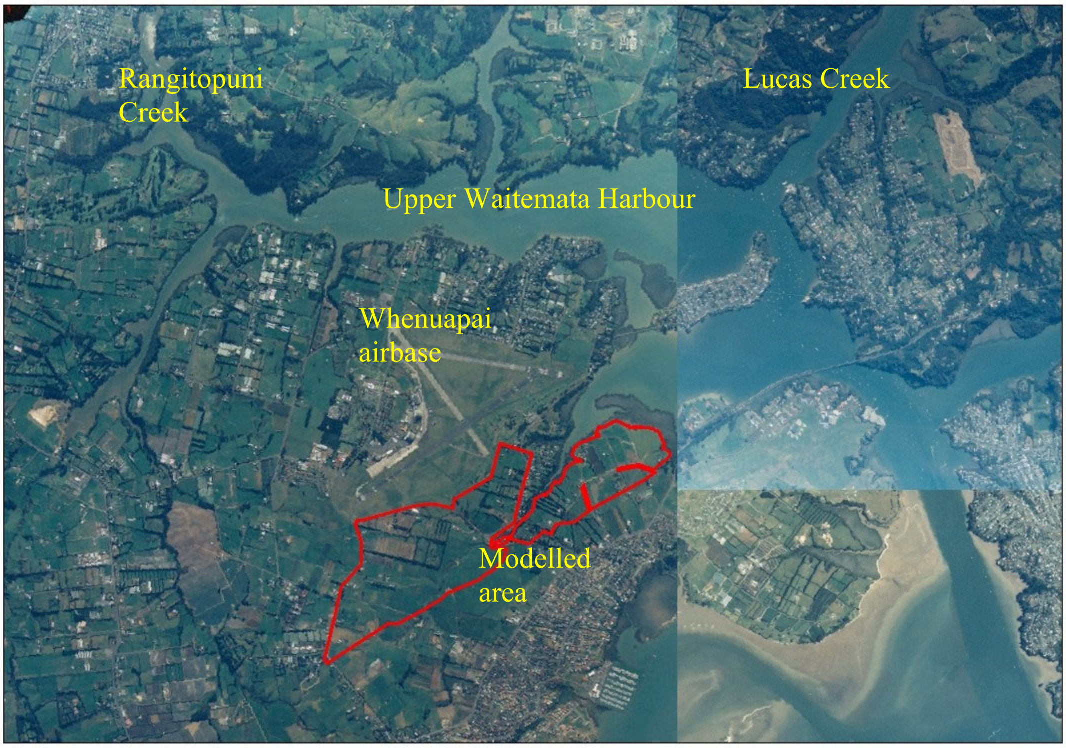

Figure 1: Location of the modelled Waiarohia development area.

2. Methodology

2.1 Modelling Approach

The results are derived in a 2-stage process (Figure 2, sections 2.1.1 and 2.1.2). The predictions from stage 1 enable a direct comparison of the impact of control measures, whilst the results from stage 2, weighted to account for the relative proportions of pasture and earthworks, enable impact assessment over the development area as a whole. Results from both stages are expressed as kg/ha of sediment loss but it is important to note the difference in their derivation since they yield markedly different values.

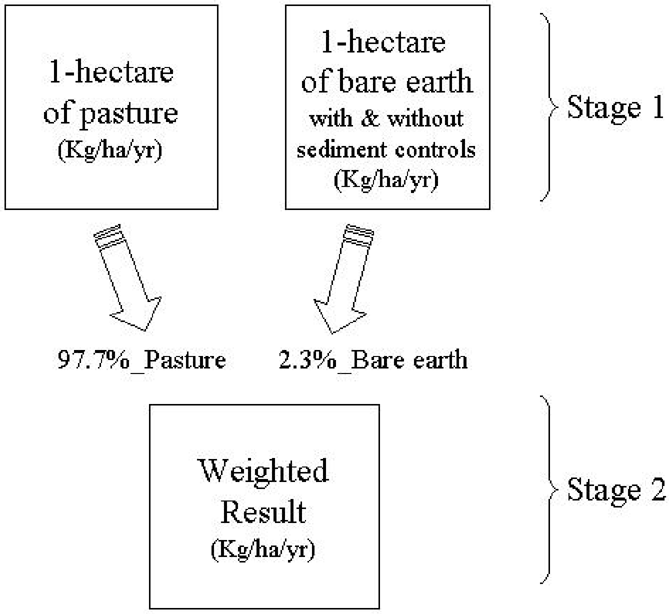

Figure 2: The 2-stage modelling methodology.

2.1.1 Stage 1

Simulations are conducted at a 1-hectare scale for the dominant combination of existing landuse and soil, and mean slope angle (pasture, silt loam and 3°, respectively; section 2.4) within the Waiarohia development area. GLEAMS is then re-run using the same soil type (but with the topsoil removed reflecting earthworks practice) and slope angle, with i) bare earth and ii) bare earth with sediment control measures.

2.1.2 Stage 2

Predicted sediment yields from stage 1 are combined based on the relative proportions of pasture and bare earth (97.7% and 2.3% respectively; section 2.4.1) across the Waiarohia development area.

2.2 Sediment Control Measures

The effectiveness of three sediment control measures is assessed both individually and in combination. This assessment is made with respect to both individual storm events and annual averages.

2.2.1 Sediment Retention Ponds

GLEAMS is able to simulate the impact of a sediment retention pond located downslope of earthworks. The model determines a daily water balance for the pond, accounting for rainfall, evapotranspiration, predicted inflow, and percolation through the base. The mass of sediment retained by the pond is derived on a daily basis from the inflow of water and sediment, pond volume and depth, and the settling velocity of the eroded sediment. The simulations in this study incorporate a design criteria whereby the retention pond is 2% (by volume) of the contributing catchment area; i.e., for every hectare (10,000 m^2) of earthworks there is 200 m^3 of pond. Average settling velocity in the simulations reflected that of silt-sized particles that are predominant in the Waiarohia soil. Since uncertainty is associated with the derivation of the settling velocity, a further simulation was conducted whereby the velocity of smaller silt-clay particles was represented.

2.2.2 Seasonal Earthwork Restrictions

The simulations incorporated a seasonal restriction upon earthworks, limiting them to between 1st October and 30th April inclusive, with earthworks stabilisation in the off-season. The off-season stabilisation is modelled within GLEAMS as a mulch cover overlying the (otherwise exposed) subsoil. The mulch cover reduces raindrop erosion of the soil and decreases the velocity and, therefore, the erosive power of overland flow (surface runoff).

2.2.3 Riparian Grass Buffer Strips

Grass buffer strips are represented in GLEAMS by an area encompassing 10% of that upslope and characterised by a high hydraulic roughness coefficient (Mannings N). This results in a reduction in the momentum, and hence sediment transport capacity, of overland flow washed into the buffer from earthworks upslope. The simulated buffer roughness coefficient was 0.3. This is the value suggested by the GLEAMS model documentation (Knisel 1993) for a dense grass buffer.

2.3 The Model

GLEAMS uses climatic, topographical, soils and land use data to derive a daily water balance, proportioning incoming rainfall between surface runoff, storage in the soil profile, evapotranspiration and percolation beneath the root zone. A long-term rainfall record (this study used a 28-year record) is used to drive the model, thereby incorporating inter-annual rainfall variability into the simulations. The erosion component of GLEAMS uses the daily predictions of surface runoff, coupled with soil properties, vegetation cover and topography to predict sediment generation, on a daily basis. The model predictions are of hillslope sediment loss and do not incorporate in-stream sediment dynamics.

2.4 Input Data

Daily rainfall data was obtained from NIWA's climate database for the Whenuapai airbase site from 1965 to 1992. Mean annual rainfall over this period was 1301 mm, but ranged from 953 mm (1982) to 1800 mm (1979). GLEAMS requires mean monthly meteorological data that were obtained from numerous sites in the Auckland region because no single site held a complete, unbroken record. Soils information for the study area was obtained from a database held by Landcare Research and, where required, interpreted for use in the model by Malcolm McLeod (Soil Scientist, Landcare Research). The area is encompassed by a silt loam (alluvial soil) characterised by a low permeability in the subsoil below 35 cm. Landuse, currently dominated by pasture, (Figure 1) was derived from aerial photographs provided by Auckland Regional Council. A 30 m resolution digital elevation model held by NIWA showed that 65% and 35% of land within the study area falls within the 0-3° and 3-6° slope categories respectively. Mean slope angle is approximately 3°, and this value was used in the model simulations.

2.4.1 Proposed Development

Waitakare City Council (WCC) provided information describing future development in the Waiarohia study area. This indicated that 118 1-hectare sized lots are to be developed across the 201-hectare (2.01 km^2) study area over a period of approximately 15 years. The proposed final development has, therefore, a density of one house per 1.7 hectares. Seven 1-hectare lots are to be developed per year with each development exposing 0.1875 hectares of bare earth. In addition, 1.65 km of road (20 m wide) is to be built and it is assumed that this road building will be completed within 1 year. Modelling of the proposed development focuses upon the worst-case stage that encompasses both house and road building. 4.6-hectares of bare earth are to be exposed during the worst-case stage: 1.3 and 3.3 hectares under house and road building respectively. This area of bare earth represents 2.3% of the total area under development.

3. Results

3.1 Stage 1

Stage 1 of the modelling methodology provides predictions of sediment loss from 1-hectare cells. These are not weighted to account for the relative proportions of pasture and earthworks of the study area, and hence they enable a direct comparison of the efficiency of the sediment control measures. Simulations of existing pastoral land and 8 earthworks scenarios are described and the results summarised in Table 1.

3.1.1 Existing Pastoral Landuse

Predicted mean annual sediment generation (over the 28-year period) under the existing pastoral land use is 448 kg/ha/yr and therefore lies within the range (100-3000 kg/ha/yr) typically observed under pastoral land (e.g., Van Roon 1983, Wilcock 1986, Griffiths 1982). In addition, this figure is comparable to a yield of 421 kg/ha/yr estimated from spot sampling of the Waiarohia stream, Van Roon (1983). Predicted annual sediment loss ranges markedly between 37 (1981) and 1747 (1966) kg/ha/yr reflecting inter-annual variability in rainfall.

3.1.2 Scenario 1; bare soil without sediment control measures

Predicted mean annual sediment loss from bare soil is 14,400 kg/ha/yr, an increase of ×32 relative to that simulated under pastoral land. The magnitude of predicted increase lies within the range (×10-100) reported by Ng and Buckeridge (2000) in a review of sediment yields from construction sites within the Auckland region. Inter-annual bare earth sediment losses range between 5,000 (1981) and 36,000 (1966) kg/ha/yr, whilst the predicted daily loss of sediment peaked at over 26,000 kg/ha/day in February 1966.

3.1.3 Scenario 2; bare soil with a sediment retention pond

Predicted mean annual sediment loss from bare soil with a downslope sediment retention pond is 4,800 kg/ha/yr. This simulation was conducted using an average settling velocity based on silt-sized particles. The results represent an average decrease in sediment loss of 67% relative to that under bare soil alone but an increase of more than ×10 relative to pasture only. The predicted average pond efficiency (67%) is slightly lower than the range observed (71-83%) in short-term studies of retention ponds in the Auckland region (Auckland Regional Council 2002). Short-term studies are unlikely to capture large events, however, and probably overestimate the efficiency. Longer-term studies in the U.S. indicate pond efficiencies of about 65% (Daly and Wright 1993).

Annual losses vary between 131 and 25,400 kg/ha/yr, reflecting pond efficiencies (averaged over the year) of 97 % and 30 % respectively. Pond removal efficiency varies markedly with event size, ranging between 7 and 100%, Figure 3.

The predicted efficiency of retention ponds is sensitive to the average settling velocity. A simulation using an average settling velocity based on silt-clay sized particles yielded an efficiency of 50 %.

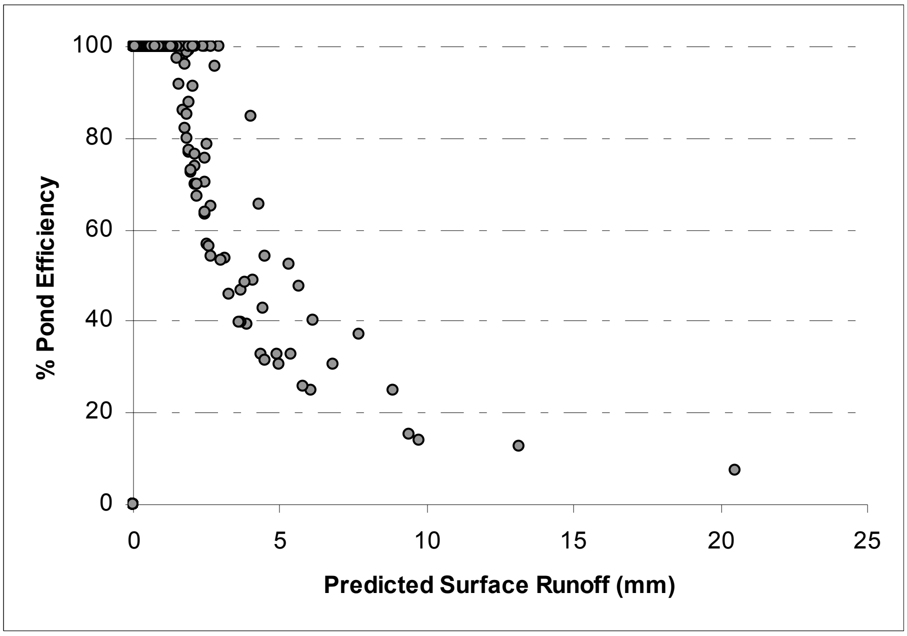

Figure 3: The predicted variation in sediment pond efficiency with event size.

3.1.4 Scenario 3; bare earth with seasonal restriction

Predicted mean annual sediment loss under bare earth with seasonal earthworks restrictions is 10,000 kg/ha/yr. This represents a mean annual decrease of 31% relative to that under bare soil alone and a mean annual increase of more than ×22 relative to pasture only. Annual losses range from 3,500 to 32,200 kg/ha/yr.

The mean annual reduction in sediment loss relative to bare soil alone rises from 31% to 81% when a comparison is made over the winter months only (1st May to 30th September), when there is no construction and earthworks are stabilised. This latter figure is comparable to the 85% reduction observed under mulch-covered subsoil by Bennett (2000) who studied the effectiveness of stabilisation techniques in reducing winter-only sediment loss from earthwork sites in Auckland.

3.1.5 Scenario 4; bare earth with a grass buffer strip

Predicted mean annual sediment loss under bare earth with a grass buffer strip is 11,600 kg/ha/yr, a mean annual decrease of 20% relative to that under bare soil alone. The simulated impact of the grass buffer is therefore less than that of the sediment retention pond and seasonal restriction of earthworks. Trapping efficiency of the buffer varies markedly with event size, as illustrated for 1966, the year with the greatest simulated sediment loss (Figure 4).

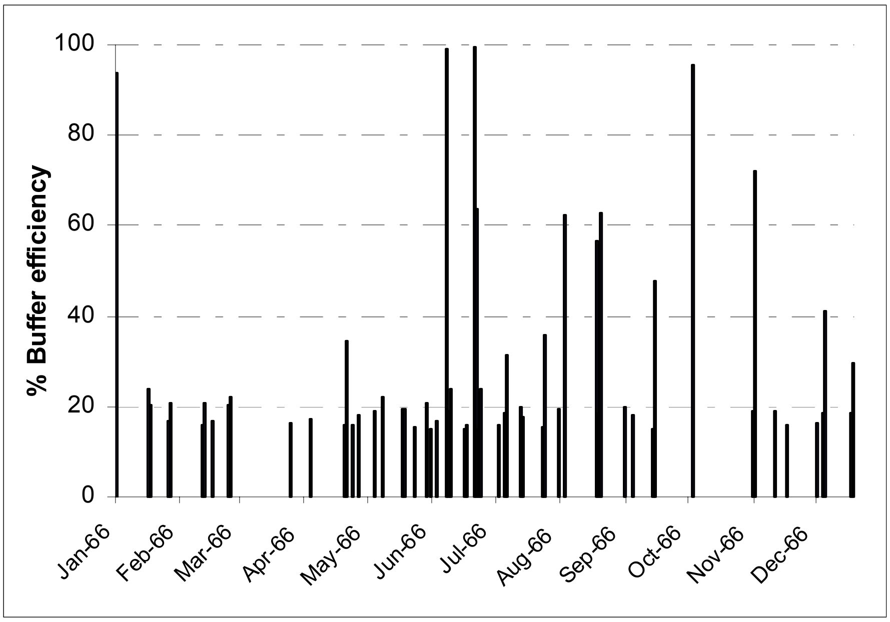

Figure 4: Predicted variation in grass buffer efficiency during 1966.

3.1.6 Scenarios 5-8; bare earth with multiple sediment control measures

As expected, the simulation of combined control measures generally yields greater reductions in sediment loss than any single measure (Table 1). The exception to this is the combination of a grass buffer with earthwork restrictions (scenario 7), which is less efficient than the use of a retention pond alone (scenario 2). Combining earthwork restrictions with either a retention pond or a buffer strip yields reductions in excess of 70%. Combining the 3 control measures yields an 81% decrease in sediment yield.

Table 1: Predicted mean annual sediment loss (kg/ha/yr), and sediment control efficiency (%, relative to bare earth alone) under each scenario.

Scenario	Description	Sediment Loss	Efficiency
Baseline	Pasture	448	
1	Bare Earth	14,425	
2	Bare Earth & Pond	4,793	67%
3	Bare Earth & Restrictions	9,991	31%
4	Bare Earth & Buffer	11,554	20%
5	Bare Earth & Pond & Restrictions	3,450	76%
6	Bare Earth & Pond & Buffer	3,848	73%
7	Bare Earth & Buffer & Restrictions	7,924	45%
8	Bare Earth & all 3 controls	2,817	81%

3.2 Stage 2

Stage 2 of the modelling methodology involved weighting the mean annual pastoral and bare soil losses according to the relative area they encompass under the worst-case stage of development (97.7% and 2.3%, respectively). This provided predictions of sediment loss across the Waiarohia development area, expressed as kg/ha and illustrated in Table 2. The percentage change relative to the existing pastoral land is also shown.

Table 2: Predicted mean annual sediment loss (kg/ha/yr) and % increase (relative to pasture only) under the 1-hectare development, weighted to reflect the proportions of pasture and bare earth across the Waiarohia development area.

Weighted Scenario	Description	Sediment Loss	Increase
Baseline	100% Pasture	448	
1	97.7%_Pasture + 2.3%_Bare Earth	769	72%
2	97.7%_Pasture + 2.3%_Bare Earth & Pond	548	22%
3	97.7%_Pasture + 2.3%_Bare Earth & Restrictions	667	49%
4	97.7%_Pasture + 2.3%_Bare Earth & Buffer	703	60%
5	97.7%_Pasture + 2.3%_Bare Earth & Pond & Restrictions	517	15%
6	97.7%_Pasture + 2.3%_Bare Earth & Pond & Buffer	526	17%
7	97.7%_Pasture + 2.3%_Bare Earth & Buffer & Restrictions	620	38%
8	97.7%_Pasture + 2.3%_Bare Earth & all controls	502	12%

Predicted weighted mean annual losses range from 448 to 769 kg/ha/yr under the baseline and worst-case (72% increase, scenario 1) scenarios, respectively. All the bare earth scenarios predict an <u>increase</u> in sediment loss, regardless of the control measures simulated. The relative effectiveness of the control measures reflects that shown by the stage 1 results. Of note are the combinations of earthwork restrictions with a pond, and buffer that result in moderate increases of 15 and 17% respectively. Simulation of bare earth with all three control measures yields the lowest sediment loss, with a 12% increase over that of pasture alone.

3.3 Two-Hectare Development

Using results from the proposed 1-hectare development of the Waiarohia area, NIWA were requested to assess the impact of 2-hectare developments upon sediment generation. WCC advised that the following assumptions should be made under this scenario:

1. Relative to the 1-hectare scenario, half as much bare earth associated with house development would be exposed in the worst-case year.

2. The extent of new roads is the same as that under the 1-hectare scenario. Under the 2-hectare scenario, 3.95-hectares of bare earth are to be exposed during the worst-case stage of development, this represents 1.9% of the Waiarohia development area. The weighted results (Table 3) show a further moderate decrease in predicted sediment loss, relative to the 1-hectare scenario, under all scenarios.

Table 3: Predicted mean annual sediment loss (kg/ha/yr) and % increase (relative to pasture only) under the 2-hectare development, weighted to reflect the proportions of pasture and bare earth across the Waiarohia development area.

Weighted Scenario	Description	Sediment Loss	Increase
Baseline	100% Pasture	448	
1	98.1%_Pasture + 1.9%_Bare Earth	713	59%
2	98.1%_Pasture + 1.9%_Bare Earth & Pond	530	18%
3	98.1%_Pasture + 1.9%_Bare Earth & Restrictions	629	40%
4	98.1%_Pasture + 1.9%_Bare Earth & Buffer	659	47%
5	98.1%_Pasture + 1.9%_Bare Earth & Pond & Restrictions	504	13%
6	98.1%_Pasture + 1.9%_Bare Earth & Pond & Buffer	512	14%
7	98.1%_Pasture + 1.9%_Bare Earth & Buffer & Restrictions	590	32%
8	98.1%_Pasture + 1.9%_Bare Earth & all controls	493	10%

4. Discussion

A field-scale computer model has been used to predict sediment generation under proposed developments in the Waiarohia catchment, and to assess the effectiveness of sediment control measures. Since it is impossible to forecast rainfall during the construction phase, the worst-case stage of development was modelled using a 28-year meteorological record. This approach enabled assessment of the impact of average, wet and dry years upon sediment loss from earthworks. Uncertainty is associated with the absolute model predictions, however, it is much lower when assessing the relative impact of each scenario.

The proposed rural residential developments in the Waiarohia are predicted to increase sediment loss relative to that under the existing pastoral landuse. A 72% increase in average annual sediment load is predicted across the development area under the worst-case (no controls) scenario. This figure is lowered, however, through the incorporation of sediment control measures, and simulation of all three controls in combination is predicted to increase sediment loss across the area by 12%. Under only one scenario incorporating a control measure (grass buffer) is an increased sediment loss of > 50% simulated.

Retention ponds are predicted to be the most effective single control measure (67% efficiency), whilst seasonal restrictions to earthworks (31%) and a grass buffer (20%) have less impact. ARC soil conservators (Stroud and Cooper 1999) assign an efficiency of about 70% to on-site sediment control measures. Thus silt fences (not modelled within this study) can be assumed to be about as effective as sediment retention ponds, and the modelling results pertaining to retention ponds can therefore also be taken to apply to silt fences.

The results of this study are dependent upon the density of ongoing earthworks: During the worst-case stage, ongoing development of 7 houses and 1.65 km of roads is expected for the 201-hectare area. The Waiarohia development area is characterised by a mean slope angle of about 3°, and is therefore relatively flat compared to some areas in the wider UWH catchment. However, the modelling results are broadly applicable to areas of proposed rural residential development across the UWH catchment, particularly those upon alluvial soil and flat or gently sloping land. The sensitivity of some of the predictions to slope angle is illustrated in Table 4, whereby sediment losses upon a 6° slope are substantially higher than those upon 3°.

Table 4: The predicted impact of slope angle upon sediment loss (kg/ha/yr) from single cell, unweighted (stage 1) simulations.

Scenario	Sediment loss_3°	Sediment loss_6°
Pasture	448	1,716
Bare earth	14,425	40,581
Bare earth & pond	4,793	13,679

Variation in rainfall characteristics causes markedly large inter-annual variations in sediment loss. For example, although average annual loss from a hectare of bare soil (without control measures) is 14,400 kg/ha/yr, loss over the year with the most erosive rainfall (1966) reaches 36,000 kg/ha/yr. Similarly, average annual loss under bare earth with a pond is 4,800 kg/ha/yr, but rises in excess of 25,000 kg/ha/yr during 1966.

The efficiency of the sediment control measures is simulated to be strongly dependent upon event size and, during very large storm events, entrapment efficiency can fall almost to zero. This has important implications for the impact upon estuarine biota which have been shown to be impacted by sediment deposition during single events (Norkko et al. 1999).

Since the modelling predicts an increase in sediment yield under development there is potential for excessive (i.e., posing a risk to biota) sedimentation occurring in the harbour, particularly given the relatively small estuary with its restricted outlet. However, quantifying the risk to biota requires feeding the predictions of event based catchment sediment loss to an estuarine model to determine sedimentation rates. These sedimentation rates then need to be coupled with an understanding of their impact upon biota, to determine risk.

As mature urban land generates broadly the same amount of sediment as flat to rolling pastoral land (Williamson 1991) post development sediment yield in the Waiarohia is expected to be similar to that under the existing, predominantly pastoral land.

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