Engineers & Consultants

Literature Review

Sediment Attributes and Urban Development

Final

Prepared for Ministry for the Environment by Morphum Environmental Ltd
September 2019

09 377 9779 | info@morphum.com | www.morphum.com

Engineers & Consultants

Document Control

Client Name: Ministry for the Environment

Project Name: Sediment Attributes and Urban Development

Project Number: P02173

Document: Literature Review

Revision History

Status	Date Issued (dd/mm/yyyy)	Author	Reviewed By	Released By
Draft	11/04/2019	Jacqui McCord	Andrew Rossaak	Caleb Clarke
Final Draft	04/06/2019	Jacqui McCord	Andrew Rossaak	Caleb Clarke
Final	10/09/2019	Jacqui McCord	Andrew Rossaak	Caleb Clarke

Reviewed by:

Reviewer: Andrew Rossaak **Signature:**

Released by:

Reviewer: Caleb Clarke **Signature:**

Level 1, 86 Symonds Street, Grafton, Auckland 1010
09 377 9779 | info@morphum.com | www.morphum.com

Executive Summary

Morphum Environmental Ltd was engaged by the Ministry for the Environment to undertake a literature review on the primary sources of variability in sediment generation in an urban environment, and the impact of urban development on sediment discharges in the short and long term. The work is to form part of the Ministry for the Environment investigation on sediment attributes for consideration of inclusion with the National Policy Statement – Freshwater Management.

The potential sediment yield of a catchment increases as land use changes from forestry to pasture, and then sharply increases during urban development. Bulk earthworks strip the land of vegetation, leaving bare earth exposed to the erosive forces of rainfall and stormwater runoff. The subsequent effect of urbanisation is an increase in impervious area and the directing of stormwater to streams, which can alter the stream hydrograph by increasing flow volume and velocity and result in increased stream bank erosion.

There are natural sources of variability in sediment yield, as well as construction and planning controls that can assist with reducing potential sediment yield during development. Natural sources include topography, geology, soil type, rainfall and vegetation. Studies show that New Zealand has higher rates of erosion than other countries due to the steep terrain, high rainfall and tectonic activity.

Erosion and sediment control practices can be put in place to reduce the sediment yield. When implemented correctly, these controls can be over 90% effective at reducing sediment yields from development sites. They focus on implementing construction practices that reduce the area exposed at any one time, reducing slope length, and controlling surface water flows as well as retention of sediment laden water on site to allow sediment to settle out. There are limitations to the effectiveness of interventions and devices, and they require ongoing maintenance and monitoring to ensure they are working correctly. They are also designed for a certain magnitude and frequency of storm event and for events beyond this, the efficiencies drop significantly. The requirements of sediment and erosion controls also vary in application around the country between different regional and district councils.

Development can lead to a significant increase in sediment yield in the short term, especially when no erosion or sediment controls are put in place. Following bulk earthworks, there is a secondary development stage of individual lot development, which can lead to another short-term peak of sediment generation. The sediment and erosion control measures required for the smaller scale developments are frequently less extensive and effective than that required for bulk earthworks.

As development slows and a catchment becomes urbanised, there is a period of adjustment as streams adjust to the new hydrograph. The increase in impervious area and the efficient stormwater drainage networks can lead to an increase in volume and peak stream velocities, leading to scouring of the stream banks and beds. The duration of the adjustment period will vary between catchments based on the natural properties of the stream, the impact of development on sedimentation on the stream, and the stormwater collection and diversion measures that have been installed as part of the development.

Long term, as newly developed areas become a mature urban catchment, the sediment yield will reach a point of stability with sediment loads that are often lower than productive use or earthworks stages. However, infill development, maintenance and improvement works will continue over the life of the catchment and continue to provide sources of sediment.

Water sensitive design is a form of urban development that aims to minimise the impact of development on streams. The imperviousness of an area is reduced, and stormwater is collected and directed into soakage and attenuation devices which reduce the volume of water that enters streams during a rain event and the peak velocities. This works to minimise changes to the stream hydrograph and subsequent erosion of the stream, as well as control sediments and other contaminants from mature catchments.

Contents

1.0 Scope and Background

The Ministry for the Environment (hereafter, the Ministry) is currently considering a sediment attribute for inclusion within the National Policy Statement: Freshwater Management. Morphum has been engaged to complete a literature review of the sources and variability of sediment in urban catchments, referred to as the Task 1 Report. This will in turn support three subsequent task reports under this assignment, which review existing plans, perform analysis of available data and finally develop modelling scenarios and financial implications.

In support of this, a literature review of New Zealand and international urban sediment sources and variability has been undertaken. Sediment discharges over short and long-term development scenarios, as well as the natural sources of variability for sediment discharge and variability attributed to development practice are discussed. The relative contribution and magnitude of these sources are reviewed across different regional developments.

The review concludes with a broad list of the most important sources of variability in sediment discharge. This list will be used to evaluate existing sediment control plans (Task 2) and water quality at development sites as part of the impact testing process (Task 3) and inform model parameters (Task 4).

2.0 Natural Sources of Variability

Sediment loads in New Zealand are driven primarily by rainfall, topography and geology. It is estimated that New Zealand contributes approximately 1.7% of the global sediment delivery to oceans but covers less than 0.2% of the land area. This is due to New Zealand's, steep terrain, high rainfall and tectonic activity (Hicks et al., 2011). The highest sediment yields are found in the central Southern Alps and the East Cape.

The natural sources of erosion variability have been used in the River Environmental Classification (REC) dataset (NIWA, 2010). The REC assigns a classification to each reach within the dataset based on groupings of similar factors that influence the natural sources of sediment variability, these being climate, topography and geology characteristics.

The main sources of sediment variability from natural factors are discussed below.

2.1 Topography

The slope length and gradient of a site affects the rate of soil erosion by sheet flow, rill and gully erosion by water and hence, sediment generation. New Zealand topography varies from the flat low lands of the Waikato, to the steep slopes of the Southern Alps. Potential sediment yield increases with steeper gradients and longer slope lengths.

A comparative study was undertaken of potential sediment loss in the Waiarohia catchment, North West Auckland, based on a 3° slope and a 6° slope. This indicated approximately three to four times more sediment being generated when the slope increased from 3° to 6°. It also showed approximately 25 to 30 times more sediment being generated for bare earth when compared with pasture (Collins, 2003). A study of the Mangemangeroa catchment by NIWA and Auckland Regional Council (ARC) concluded that in the Auckland Region, the erosion rate triples as the slope doubles, showing that steeper slopes contribute a disproportionate amount of sediment for the same area disturbed (ARC TP124, 2000).

2.2 Geology

The underlying geology of a catchment strongly influences the erosion rate of materials and the type of sediment supplied to a stream or river system. Sedimentary rocks comprise weakly cemented silt and sand which are more easily eroded compared to hard, crystalline igneous rocks. Geology also affects rainfall infiltration and runoff due to the presence or absence of rock fractures and compaction of sediment.

The New Zealand Land Resource Inventory (Lynn et al., 2009) has defined six broad geology classifications across New Zealand. This has been developed into seven geological categories within the REC, which also considered groundwater storage capacity and transmissivity. The type of geology indicates the potential for erosion and are classified in the Land Resource Inventory is as follows:

- Weak igneous (tuff, scoria, tephras)
- Strong igneous (lavas, ignimbrites, plutonics)
- Loose sedimentary (peat, loess, alluvium unconsolidated sands, silt and clays)
- Weak sedimentary (mudstone, sandstone)
- Strong sedimentary (argillite, greywacke)
- Metamorphic (schist, gneiss, marble)

2.3 Soil Types

Soil type and thickness varies across New Zealand based on the underlying geology and climate processes. The erodibility of material is a function of the grain size. Non-cohesive sands and gravels are more erodible than cohesive silts and clays, but the smaller size of silt and clay particles means that they stay in suspension and can be difficult to trap with sediment control practices.

A study by Auckland Regional Council comparing the performance of straw mulch at an earthworks site in Albany, north of Auckland was undertaken for five land covers, including establish grasses, mulched topsoil, bare topsoil, mulched subsoil and bare subsoil. The highest sediment yields were generated from bare subsoil plots, which were approximately double the load from bare subsoil plots. Similarly, during storm events, applying mulch to bare subsoil was less effective than applying it to topsoil (Basher 2016). This indicates that the subsoils can be more erodible than the topsoil.

2.4 Climate Patterns

The two main climate cycles within New Zealand are the annual, seasonal weather pattern and the El Niño-Southern Oscillation (ENSO). The primary effect of these climate variations on erosion is through changes in the amount of rainfall and the intensity of rainfall.

Modelling undertaken in the Tauranga catchment indicated that doubling of rainfall more than doubled the sediment generated. Rare rainfall events resulted in considerable erosion, with events less than 50 mm a day contributing less than 10% of the sediment load. (Elliot et al., 2010).

Most areas of New Zealand receive between 600 mm and 1600 mm of rainfall annually and generally receive more rainfall during the winter months than the summer months. Sediment loadings increase during rainfall due to rain drop impact dislodging particles, the increase in runoff, and the higher flow and velocity of water travelling through water courses.

Studies undertaken in Manukau, Auckland, and the Wairua catchment, Northland, found sediment loads to increase more than 50% from summer to winter (Bibby & Webster-Brown, 2004; Dymond et al., 2017).

The ENSO climate pattern occurs in New Zealand every 2 to 7 years and typically lasts from 6 to 18 months. The effects vary across New Zealand; generally, over northern New Zealand, an El Niño event produces below average rainfall while a La Niña event produces higher than average rainfall. The effects are reversed over southern New Zealand (Scarsbrook et al., 2003).

Global climate change is a factor that must be considered as the predicted effects include more intense and frequent storms as well as longer dry spells that will lead to more sediment deposition in downstream environments, including estuaries, rivers and harbours. A study on Tauranga Harbour looked at the effects of climate change on estimated sediment yields in the year 2051. The modelled catchments were a combination of pasture, forest, bush and scrub, and urban land use, based on the predicated future land use scenario. The model indicated that climate change would increase the sediment runoff in each catchment with the sediment load being transported to the harbour to increase by 42.8% over the 50 year modelling period when compared to the same future land use scenario with no climate change. (Elliot et al., 2010).

2.5 Vegetation

Vegetated land cover can be broadly grouped into native forest, plantation forest, bush/scrub and pasture. Within a catchment, vegetation can exert an important influence on sediment generation. A study of water quality and sediment from the hill country surrounding the Mangaotama Stream, west of Hamilton, indicated a three-fold increase in sediment within a pasture catchment compared to the adjacent native forest catchment (Quinn & Stroud, 2002). Vegetation and associated ground cover and organic topsoil provide a physical barrier to rain drop erosion. Forested surfaces have a higher roughness than pasture or bush/scrub. Increased roughness increases the potential to retard water flow across the surface, which in turn reduces the velocity of run off.

Table 1-2 from Auckland Council TP124, quantifies the time taken for water to travel across various surfaces, and is shown in Table 1, below.

Table 1: Time Taken for Water to Travel Over Various Surfaces

Surface	Roughness Coefficient (n)	Travel Times (hours[1])
Bare soil	0.011	0.014
Pasture	0.13	0.093
Grass (short)	0.15	0.109
Grass (taller)	0.24	0.159
Bush (light understory)	0.40	0.24
Bush (dense understory)	0.8	0.447

[1]Assumed 50 m length, 12% slope and 83 mm of rainfall. Source ARC TP124

3.0 Sources of Sediment Generation in Urban Environments

3.1 Overview

In an urban environment, the greatest source of sediment occurs during development, when the land is stripped of vegetation. The increase in sediment yields during development can be over 100 times greater than from undisturbed land (ARC, 1994).

Following development, there is a period of stabilisation as the main construction phase is completed and the urban area matures. During this period, the sediment yield will decrease and reach a new equilibrium. Urban areas have high impervious area cover, which provides a barrier to prevent erosion. However, urbanisation introduces other sources of sediment. These include:

- Road deposited sediment from both anthropogenic and natural sources
- Small construction sites (infill development, improvement works)
- Non-consented works
- Minor earthworks/landscaping
- Gravel surfaces (roads, pathways, road shoulders)
- Other urban activities such as grass verge parking, gardening
- Bare earth (road side cuts, pathways)
- Abandoned development sites
- Land slides

The urban environment has an increase in impervious areas as well as an effective stormwater collection system, which moves stormwater quickly to and through the drainage system. This alters stream hydrological processes and results in higher and quicker flows and greater sediment loads, which can result in an increase in streambank and bed erosion and stream widening.

Urban areas are generally located in the lower areas of a catchment. As such, sediment within the catchment may also originate from upslope sources, such as pasture and forest clearing. Changes in the upslope, non-urban catchment may lead to increased sediment within the urban catchment.

A summary chart of the sources of sediment in an urban environment is attached in Appendix 1.

3.2 Large Scale Urban Development

Land development is the most significant contributor to sediment within an urban environment. During development, the land is stripped of vegetation, exposing bare earth which is susceptible to erosion. Sediment control measures can be effective at reducing sediment but the effectiveness reduces during storms.

A study was undertaken by ARC in 1994 that measured suspended sediment yields during storms at five small basins in Auckland under varying land use including urbanising, mature urban and pasture. The highest sediment loads were found within the urbanising catchments. Within the urbanising catchment, the sub-catchments that were undergoing construction were estimated to have over 100 times the sediment yield compared to undisturbed parts of the sub-catchment.

Other studies show uncontrolled urban earthworks to increase the sediment yield over that of pasture by 43 times (Elliot, 2010) and 32 times (Collins, 2003). The variations between studies is likely due to variations in the natural parameters in the model such as topography, geology and rainfall. Regardless, the impact of uncontrolled earthworks is considerable.

3.2.1 Sediment Control

Numerous studies have been undertaken to assess the effect of development on sediment generation. One such assessment was undertaken on the effects of development on the Okura Estuary in Auckland (Yaldin & Moores, 2014). The modelling looked at the effects of development on sediment generation compared with sediment generation from the existing pastoral land use. They also looked at the effectiveness of different commonly implemented erosion and sediment control measures and the effect of storms on sediment generation.

The results are summarised in Table 2 below and show the percentage sediment load changes from the existing pastoral land use to the estimated sediment load generated during development. Sediment generation was calculated based on four earthwork areas for the earthworks season when bulk earthworks are undertaken; the civil season; when the land is stabilised and minor earthworks occur, such as service installation; and the stabilised period following completion of works.

Table 2: Percentage Sediment Load Changes Over Base Level Sediment Loads in Okura Estuary Modelled Earthworks Areas

	No Sediment Treatment			Sediment Treatment		
Climate Conditions	**Earthworks Season**	**Civil Season**	**Stabilised**	**Earthworks Season**	**Civil Season**	**Stabilised**
Mean Annual Sediment Load	1430% - 1643%	449% - 496%	268% - 285%	32% - 61%	65% -70%	Not Assessed
2yr ARI	975%-1063%	227% - 245%		-42% - -45%	-81% - -83%	
50yr ARI	1180% - 1487%	256% - 329%		163% - 294%	-71 - -74%	

As shown in Table 2, without sediment treatment, there is a significant increase in sediment generation during development, especially during the earthworks season. The inclusion of erosion controls and sediment treatment devices significantly decreases the sediment generation across the development phases. Sediment controls during the earthworks season can reach approximately 90% effectiveness at reducing sediment load, with this effectiveness reducing as the storm intensity increases. In practice, effectiveness is also subject to variability in maintenance and operational producers.

We point out the significant increase in sediment during the stabilised period, as shown in Table 2. The stabilised period is the time between earthworks and civil construction seasons, and following completion of works, when bulk earthworks have ceased, and treatment devices may no longer be in place or maintained. During the stabilised period, the land is bare and often covered with hay to provide a barrier between the elements and the soil. Sediment treatment was not modelled during the stabilisation phase in the Yaldin and Moores 2014 study as treatment devices are often removed at the completion of earthworks. The stabilisation period therefore has the potential to generate high sediment loads. If treatment measures were to remain in place following the completion of earthworks, the reductions are expected to be similar to what was modelled during the earthworks and civil seasons.

Modelling of the effect of future land use change for the Tauranga Harbour was undertaken, which compared sediment yield to streams for land which the same slope, soil type and rainfall. The modelling found that uncontrolled earthworks have the highest sediment yield when compared to pasture, forest and urban grassland. The model also predicted that the use of sediment controls was predicted to be up to approximately 90% effective at reducing sediment yield when compared to uncontrolled earthworks (Elliot et al., 2010; Hume et al., 2010).

A study was undertaken of development of one hectare blocks in a pastoral catchment in Waiarohia, North West Auckland (Collins, 2003). It was predicated that sediment controls, including retention ponds, grass buffers, and seasonal earthworks restrictions, would be approximately 81% effective. Retention ponds were the most effect control device, being 67% effective when used on their own. Seasonal earthwork restrictions were modelled as being 31% effective and grass buffers were 21% effective.

3.2.2 Effects of Storms

A comparison was undertaken on sediment yield and storm frequency events from urbanising and mature urban environments (Hicks, 1994). The results of the study are shown graphically in Figure 1. The urbanising basin (Alexandra Stream), with a high percentage of bare earth ground cover, indicated sediment yield in the order of ten times greater across all considered rain events (return periods) compared with other catchment types. The relationship between storm sediment yield and storm return period was also steep for the urbanising Alexandra catchment, indicating a higher sediment generation as storm intensity increases.

In comparison, the mature urban catchments (Wairau and Pakuranga) have a flatter relationship between storm sediment yield and storm return period, indicating that the sediment generated from rare storm events is not considerably different than for more frequent events. These results indicate that for stable, urban areas, the best sediment management approach is for frequent, sub yearly storms.

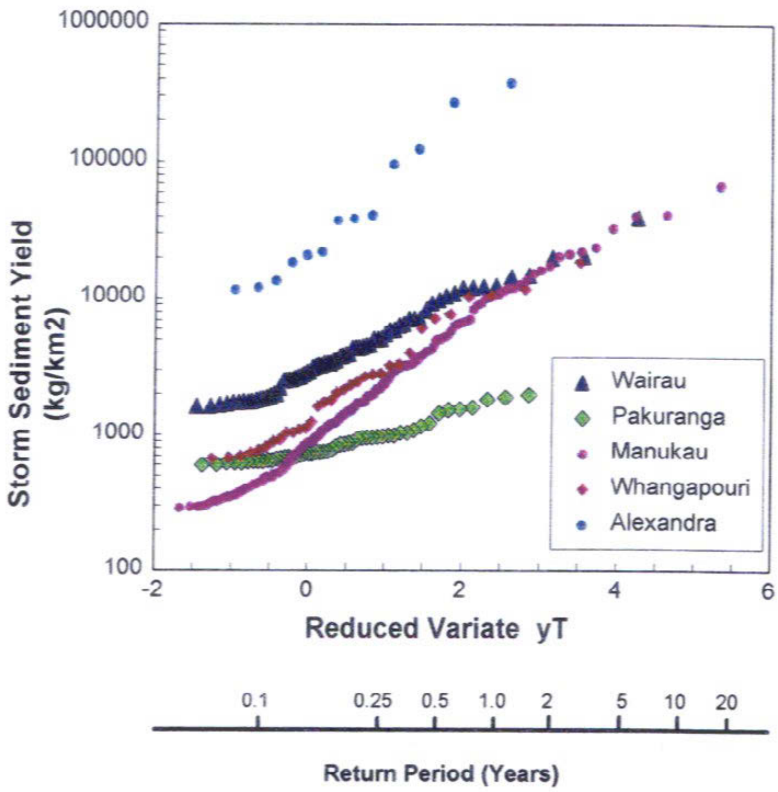


Figure 1: Magnitude-Frequency Relationship for Storm Sediment Yields at Study Basins. The Reduced Variate Abscissa Scale Relates to Monthly-Exceedance Series (Source ARC, 1994).

The incorporation of best practice sediment controls can have a significant impact on reducing erosion and subsequent transport of sediment to streams. However, the effectiveness of stormwater treatment reduces with storm intensity (Yaldin & Moores, 2014). As discussed above for the urbanising Alexandra Stream, it is the rare events that should be targeted when developing sediment control structures to reduce sediment yield (Hicks, 1994).

3.2.3 The Area of Disturbance

The potential for erosion increases when a greater area is disturbed and cleared of vegetation. This is due to:

- Longer exposure and increased likelihood of being subject to rainfall events.
- Increasing slope length, which increases velocity of run off.
- Increasing catchment area increases the potential for sheet flows to concentrate resulting in greater shear stress and generating rill and gully erosion.
- Reduced roughness of the surface increasing runoff velocity

ARC undertook land use scenario modelling in the Mahurangi catchment and investigated the increase in sediment yield over the existing pasture (ARC TP124, 2000). The effects are shown graphically in Figure 2, and they clearly illustrate the increase in sediment yield as the area for disturbance increases.

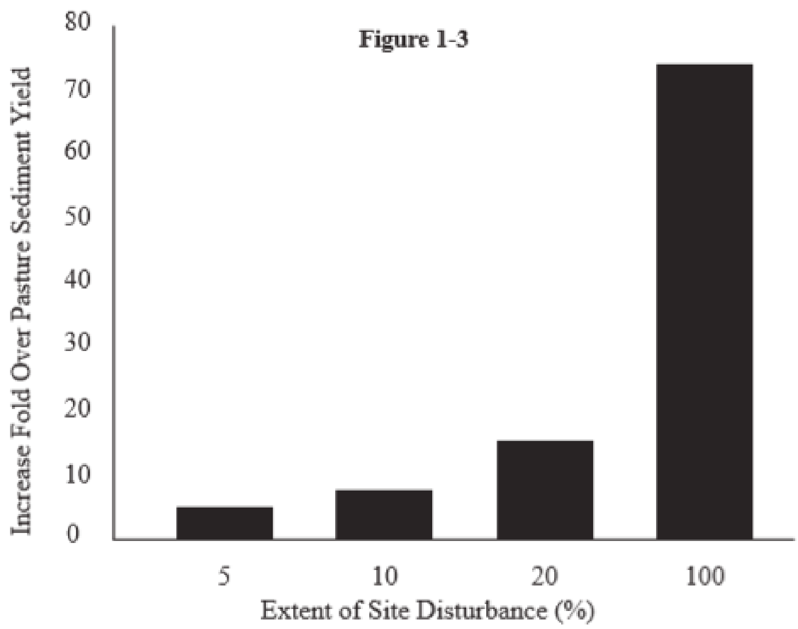


Figure 2: Increase in Sedimentation Yield at Various Site Disturbance Levels (Source ARC TP124, 2000).

3.3 Streambank Scour

Streambank scour is another major source of urban sediment. Urban development can alter the flow regime within watercourses, which increases the rate of erosion. This is due to several factors:

- Increased runoff from impervious areas entering streams.
- Effective stormwater network discharging high volume flows within shorter time frames.
- Shorter time for peak flow volumes to be reached increasing the likelihood of fast-moving storms generating flow from a greater portion of the catchment at one time.
- Removal of vegetation alongside stream banks, which removes natural stabilisation.

The increase in impervious areas and effective stormwater networks means that rain water travels quickly to and through the drainage networks, resulting in high flow volumes and increased flow velocity. During construction, the sediment supply can exceed the streams' transport capacity leading to sediment deposition. With the increased runoff and flow velocity following development, the deposited sediments are re-mobilised and the channel is also enlarged due to the higher velocity flow. (Williamson, 1993).

Studies undertaken in the United States and the United Kingdom indicate that peak discharge in storm events commonly increases by two to four times following urban development and that lag times decrease to one-half to one-fifth of the former value (Chin, 2006).

3.4 Mature Catchment Sources

Mature urban catchments have widespread sediment sources that can be efficiently transported to receiving waters via the stormwater network, however, the sediment loads are considered to be much lower than urbanising catchments. A study of four urban catchments in Hamilton indicated suspended solid concentrations in stormwater in a mature urban environment to be half of that in a developing catchment (Hickey, 2001).

It is difficult to quantify the potential sediment generated within a mature urban environment and it will vary based on land use (residential, commercial or industrial) and age of the development with best practice sediment and stormwater control measures improving over time. Also, urban catchments are never free of development, with on-going infill development, renewal, improvements and maintenance (Russell et al. 2017).

The National Policy Statement for Freshwater Management (NPS-FM) requires Councils to manage all freshwater for ecosystems health and human health for recreation. A study was undertaken by NIWA in 2016 to look at a range of future urban development scenarios on water quality within the Lucas Creek catchment in North Auckland. The study investigated the source of sediment and the effect of water sensitive design measures on sediment generation, as well as assessing variations between areas of low density and high-density development. It was found that there is a significant reduction in urban sediments expected following greenfields development when current best practice contaminant controls and water sensitive design are incorporated. In mature catchments with infill development, the inclusion of best practice contaminant controls and water sensitive design has little effect due to the remainder of the area not having such controls in place (Moores et al., 2016).

The study of contaminant loads within Hamilton City identified industrial and residential sources to be a higher contributor to total suspended soils than commercial areas. This was attributed to regular street sweeping in commercial areas (Hickey, 2001).

Sediments in mature urban catchments can be from both natural and anthropogenic sources. The anthropogenic particles are often coarser, supplementing the coarse sediment loadings in urban streams, and can make up a significant portion of the bed, which has been found in international studies to be approximately 2-21% (Russell et al., 2017).

Further details on potential sources are discussed in Sections 3.4.1 to 3.4.4 below.

3.4.1 Road Deposited Sediment

Road Deposited Sediment (RDS) can result from many sources, both natural and anthropogenic. Natural sources include soil fall off from tyres, windblown dust, leaf and plant litter, gravel shoulders, and scour from road cuts. Anthropogenic sources include tyre wear, break-lining material, vehicle crash debris, road salt, building and construction material and litter (Taylor & Owens, 2009).

Street sweeping can be an effective means of reducing RDS. Studies have found that rotary type street sweepers removes a greater proportion of RDS from street surfaces, but vacuum based street sweepers are better at removing the finer grain fractions (Taylor & Owens, 2009).

3.4.2 Small Earthworks Sites

Sediment controls on smaller sites, i.e. individual lot development, do not require the same level of sediment controls and compliance that is often required for bulk earthworks, with often only a silt fence required and monitoring reduced. These measures may prevent sediment laden water from entering the stormwater network in small rainfall events, but they do not prevent the sediment from being deposited onto impervious surfaces to be later mobilised as windblown dust or transported during storm events. Often these small sites are developed as permitted activities requiring no environmental monitoring, notification or consent, and thus are not subject to any oversight.

3.4.3 Unconsented and Non-Complying Works

It is inevitable that unconsented activities are undertaken that likely have no sediment controls in place. These works could include building works, dumping of spoil and work in streams.

It is also likely that some works are also undertaken that do not comply with council sediment and erosion control regulations and/or permitted activity standards. Procedures are often in place to manage non-compliance and deter people from undertaking unconsented activities, such as fines and abatement notices, but it must be expected that non-compliance will continue to occur. In many cases these non-complying activities are often only discovered following a discharge event and public complaints.

3.4.4 Other Sources

There are many sources of sediment generation in a mature urban environment. These sources are generally small scale and are expected to only generate small sediment loadings. These sources include:

- Wastewater overflows
- Garden soil that is mobilised either through run off or wind
- Sediment from small scale landscaping activities that expose soil temporarily
- Grass verge parking that removes grass exposing bare soil
- Gravel pathways, including within parks and reserves
- Gravel parking areas
- Gravel road shoulders
- Exposed earth in road side cuts
- Abandoned works

While loadings from individual areas may be low when compared to catchment wide influences, on-going maintenance can provide a steady source of sediment. For example, gravel surfaces such as paths, road shoulders and parking areas are often replenished as the gravel material is removed through use and erosion.

Development can cease for many reasons, leaving the site abandoned. If this happens when the site soils are exposed, it is likely that no stabilisation measures will be put in place to protect exposed surfaces, and any measures previously in place will not be maintained. Vegetation will slowly regrow, but there can be a significant period of time that the bare soils are exposed before works either recommence or vegetation increases sufficiently in density to cover bare soils.

3.5 Rural Sources

Forest clearing and pasture are shown to be high contributors of sediment (Hicks 2009; Moores et al. 2016, Hickey et al. 2001). When urban development is located on the lower portion of the catchment, there may be considerable sediment input from upstream sources that are impacting on sediment indicators within the catchment.

3.6 Landslides

Landslides can take place for a number of reasons but occur more frequently on steep terrain which is cleared of vegetation and following periods of heavy rainfall. In an urban environment, landslides can occur due to:

- Incorrect stabilisation of cut faces during earthworks
- Over-steepened cut faces adjacent to roadways
- Insufficiently compacted fill
- Over steepened fill batters
- Landslides within parks and reserves
- Concentrated run off onto a slope

The size of landslides can vary greatly, but all result in bare and loose earth being exposed. Where landslips affect important services such as roads, they are cleared quickly, but where the landslide is not causing any immediate impact, the slumped material is often left for some time before being cleared, or it may never be removed.

Models indicate that for similar slope, soil and rain fall conditions, the relative sediment yield from the bare earth exposed from landslides is approximately 48 times greater than that of pasture cover (Elliot et al., 2010).

During a study by Quinn and Stroud (2002) in the Mangaotama catchment, a landslide occurred in one of the study catchments. The pasture catchment without a landslide had a three-fold increase in sediment loss to streams, measured in kg ha^{-1} yr^{-1} when compared to the adjacent native forest catchment. In comparison, the mixed pasture and forest catchment where a landslide occurred had an eight-fold increase in sediment loss to streams compared to the native forest catchment, one to two years after the slip occurred.

4.0 Urban Development Sources of Variability

4.1 Urban Development Lifecycle

Urban development goes through a cycle of land-use change, which drives a change in sediment yield and channel response. The widely accepted model of sediment supply in urban catchments was proposed by Wolman in 1967, Figure 3. There are three stages in the cycle:

- Stage 1: The forested or agricultural watershed where sediment supply is relatively stable.
- Stage 2: Construction phase where the increase in bare earth exposed increases sediment yield
- Stage 3: The watershed is dominated by urban land cover and sediment yield decreases with time. Streams will adjust to the new hydrological regime and erosion may occur.

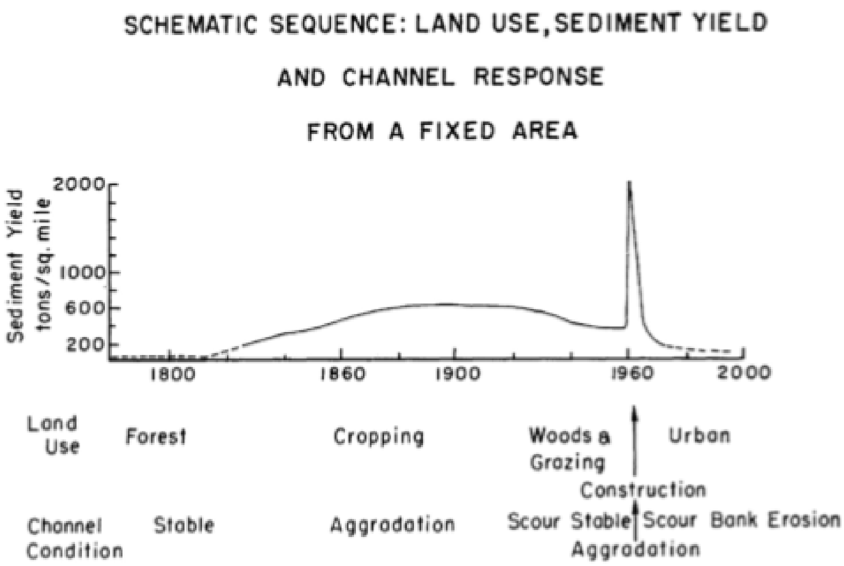


Figure 3: Cycle of Land-Use Change, Sediment and Channel Behaviour (Source: Wolman, 1967).

Russel et al. (2017) undertook a global study on sediment yields in urban and urbanizing catchment to refine the Wolman model as the effect following urbanisation is not well understood, as shown by the dotted line in Figure 3. Different studies from around the world were assessed and sediment yields from forested, agricultural and urban construction corresponded with the Wolman model. It was found that sediment within an urbanised environment was greater than what was predicted by Wolman. Generally, the measured urban sediment yields were approximately three times higher than yields in rural catchments. The revised conceptual model based on the assessment by Russel et al. (2017) is shown in Figure 4.

The results indicate that sediment yields in an urban environment are higher than those that are forested or in pasture. New Zealand research indicates that pasture is a higher contributor of sediment and that the calculated rate of sediment yield on pasture is greater than in an urban environment (Moores et al., 2016; Hicks, 2009; Collins, 2003). This may be attributed to the high sediment yield of New Zealand due to the rainfall and the geology.

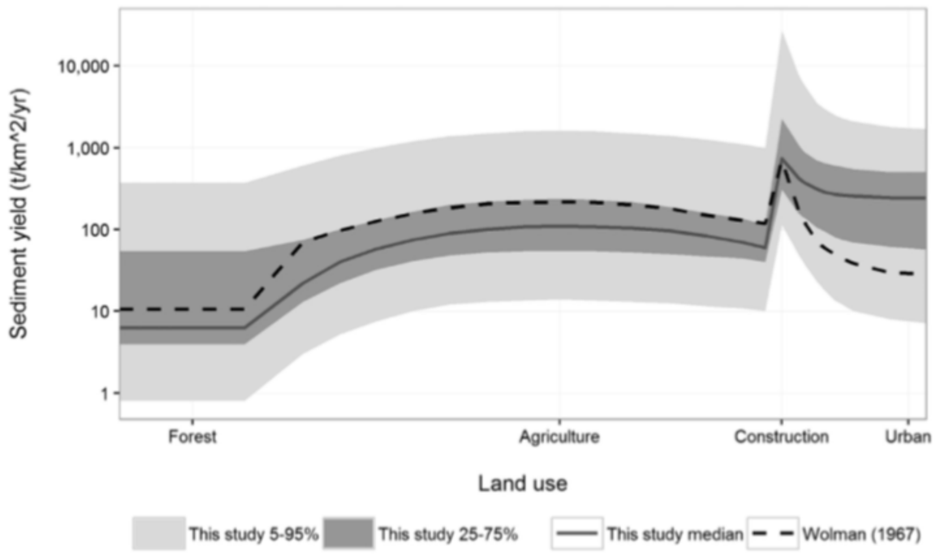


Figure 4: Revised Conceptual Sediment Yield Curve Compared with Conceptual Model of Wolman (1967) (Source: Russell et al., 2017).

The construction period often has two phases, the bulk earthworks associated with the large-scale development of an area, followed by individual, smaller lot construction. The length of time for stabilisation of sediment within the urban environment will vary per catchment depending on the rate of development. On-going infill development, landscaping works and maintenance will also occur within mature urban areas which will continue to supply sediment.

4.1.1 Short-term Urban Development Impacts

It is widely documented that uncontrolled development is the largest source of sediment in urban environments. Studies show that the use of sediment and erosion control practices can significantly reduce sedimentation if installed and maintained correctly, as discussed in Section 3.2.1. Council regulations for erosion and sediment controls vary around New Zealand resulting in regional variations in sediment yields during construction.

The Universal Soil Loss Equation (USLE) is a widely used calculation for sediment generation and takes account of the rainfall, soil erodibility factor, slope length and steepness, ground cover and soil roughness. Earthworks remove vegetation and increase the area of bare earth exposed to weathering. With a greater area exposed, there is the potential for longer slope lengths, which can increase runoff velocity. The roughness of the surface also decreases, which can lead to increased surface run off flow velocities.

Erosion and sediment controls can be an effective means of reducing construction induced sediment, however, they must be correctly installed and maintained for continual effectiveness. Erosion and sediment control practices following completion of bulk earthworks must also be considered as this period has been shown as a large source of sediment (Yaldin & Moores, 2014).

Staging of projects to minimise the area exposed at any one time has two benefits. The first is that the area exposed is minimised and the length of time for each stage is reduced. If forward weather outlooks are taken into account, areas can be earth worked and then re-stabilised during a dry weather period, significantly reducing erosion from rain. The second benefit is that slope lengths can be reduced, and in turn, the potential velocity and erosion potential of runoff will also be reduced. On the flip side, the overall earthworks period could be longer and the more complex operations could incur greater comparative costs.

The incorporation of low impact, water sensitive design (WSD) can also minimise the impacts of urban development on on-going sediment loads (Moores et al., 2016). The aim is to reduce stormwater infrastructures such as pipes and concrete channels which can concentrate stormwater flows and result in high volume and high velocity flows, and instead reduce or eliminate stormwater runoff generation though source control and by utilising the natural systems. WSD can include rain gardens, swales pervious paving, green roofs and water reuse.

4.1.2 Hydrological Adjustment and Long-Term Impacts

Streams are a dynamic system that are constantly changing by aggradation and erosion in response to variations in sediment load and hydraulic forces, which are themselves influenced by soil type, geology vegetation and climate. Momentary changes to a system due to drought or storms result in changes to the river channel such as scour and aggradation as the channel adjusts to the short-term natural changes.

There is extensive literature available regarding stream geomorphology and response to change. What is clear from the literature is that major changes to the prevailing conditions in a drainage basin will result in changes in channel form and behaviour (Wolman, 1967). The main impact of urbanisation on river systems is a change to the flow regime from the increased impervious surfaces and drainage channels, and a change to sediment load.

The period of hydrological adjustment of the stream to the new sediment and flow regime from urban development cannot be easily defined. For a stream to reach a new equilibrium, construction must cease, and sediment sources must stabilise. Secondly, the impervious surfaces and the drainage network must be completed. On-going development in the catchment may make it difficult to achieve a steady state of equilibrium.

A study of global urbanised catchments found that, following urbanisation, there is an initial lag time before the effects of development are evident in streams. This can vary from months to years. Following development, the time for the increased sediment yield to be flushed out of the system varies considerably from years to decades and the morphological change of the river to adjust to the new sediment and hydrological regime can similarly take anywhere from years to decades (Chin, 2006), as shown in Figure 5. The variations in responses globally are due to natural factors such as geology, climate, vegetation and slope, but also anthropogenic responses such as urban structures and channelisation.

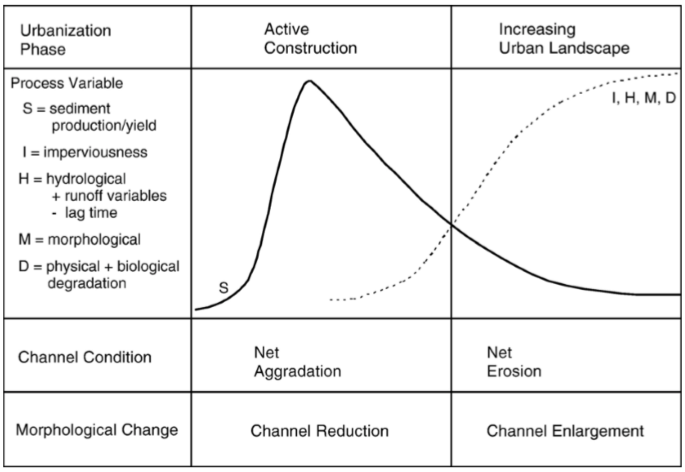


Figure 5: General Phases of Urbanisation with Associated Process Changes, Channel Conditions and Morphological Adjustment. Source: Chin, (2006).

Stream bank erosion occurs via two main processes, fluvial erosion and mass wasting. Fluvial erosion is where the force of the water removes sediment from the stream banks and bed and can result in undercutting and scouring of the stream banks. Mass wasting occurs when the stream banks slump, slough or slab off into the stream. As downcutting of a stream increases, the stream banks become more susceptible to mass wasting.

Increased erosion within streams can also be impacted by other factors of urbanisation. This includes removal of stream bank vegetation, which can remove root structures that help to support the stream banks and can result in increased erosion. Similarly, anthropogenic assets or detritus can cause constriction in the stream, altering the flow path and flow velocity and resulting in localised increased erosion.

Urbanisation can also be a source of coarse grained material transport to streams, such as rip-rap, gravel, asphalt and concrete. This can lead to aggradation of the coarser material and an increase in stream bedload. These coarser particles generally only become mobile during high flow events and can result in clogging of the channel with coarse sediment. However, it is also possible that the use of stormwater treatment measures, such as sediment ponds and catch pits will interrupt the natural coarse sediment supply. The bedload can provide protection to the stream bed and introduce natural riffles to reduce flow velocity. The removal of coarse sediments can therefore also exacerbate channel instability and degradation (Russell et al., 2017; Vietz et al., 2015).

4.2 Construction Practice and Compliance

As identified above, land disturbing activities have the potential to generate large amounts of sediment-laden water that can be discharged into the receiving environment.

The Resource Management Act 1991 (The RMA), is the primary piece of legislation controlling natural and physical resources, including land and freshwater, in New Zealand. The purpose of the RMA is to promote the sustainable management of natural and physical resources, placing a general duty on every person to avoid, remedy or mitigate any adverse effects of activities on the environment. Sections 9, 12, 13, and 15 of the RMA restrict and regulate activities relating to the use of the land, works in the coastal marine area, works on the bed of freshwater bodies and the discharge of sediment into the environment.

Authorisation to undertake land disturbance and the associated discharges (i.e. sediment-laden water) is provided through a rule in either a Regional or a District Plan, or through a resource consent. Each Regional and District Council sets its own Plan. As such there is a variety in the nature, flexibility, constraints and rules within the planning provisions that relate to land disturbing activities across the country. Some councils require an Erosion and Sediment Control Plan (ESCP) to be submitted with a consent application to demonstrate how sediment-laden flows will be managed during land disturbing activities (Leersnyder et al., 2016).

Erosion controls focus on measures that reduce the potential for erosion to occur through either non-structural or structural approaches (Ibid). Non-structural controls relate to how earthworks are conducted and include minimising disturbance, staging construction, protecting slopes and watercourses and stabilising areas rapidly. Structural approaches relate to the management of water runoff both from within an earthworks site and from the surrounding catchment and aim to reduce the volume and velocity of water runoff and thereby minimise erosion.

Sediment controls, or sediment retention devices, focus on measures to trap any sediment before it moves off site and into waterways. A wide variety of sediment controls are used across the country depending on the land use and type of erosion (Basher et al., 2016). Basher et al. (2016) found that the performance of sediment control practices increases as the detention time, and the time sediment-laden flows are retained within a sediment control device increase. Continual improvements are being made as to what is best practice. For example, there is increasing recognition within some regions that chemically aided flocculation and coagulation (commonly referred to as chemical treatment) can be applied to some sediment control devices to improve their sediment removal efficiency.

The application of erosion and sediment controls is not uniform across the country and the appropriateness of a given control will depend on the site characteristics and the nature of the earthworks being undertaken. This is reflected in there being various regional specific erosion and sediment best practice guidelines published by Regional Councils across the country.

The effectiveness of erosion and sediment controls varies. Variations can be due to the natural factors as described above, as well as how the earthworks are physically undertaken. There is also variability between the sediment removal efficiency between different types of sediment control.

Councils also have a duty to undertake compliance, monitoring and enforcement (CME) to ensure compliance with the RMA (Ministry for the Environment, 2018).

A range of formal enforcement tools are available to councils to respond to non-compliance. Guidance from the Ministry for the Environment (2018) encourages councils to undertake CME on a risk-based approach. This means that the level of CME effort expended is proportional to the risk of adverse environmental effects from the monitored activity.

4.3 Development Planning and Infrastructure Provision

There is increasing recognition that how urban areas are developed effects environmental outcomes, not just during construction but throughout the life-cycle of development. In New Zealand, the concept is known as Water Sensitive Design (WSD) and goes by other names globally such as water sensitive urban design (WSUD) in Australia, low impact development (LID) in the United States and sustainable drainage systems (SuDS) in the United Kingdom.

WSD is a design approach based on a set of guiding principles that aim to balance land development with the ecosystem services necessary to support it. Broadly, the guiding principles, taken from Lewis et al. (2015) are:

- Reduce stormwater runoff - reduce stormwater runoff volume and peak flow to predevelopment levels.
- Manage stormwater quality - manage stormwater quality to avoid adverse environmental effects.

- Minimise soil disturbance - minimise sediment in stormwater runoff, especially during construction, and protect site soil resources from modification.
- Promote ecosystem health - promote the health of regional ecosystems and their associated environmental services through the management of stormwater at the catchment and site scale.
- Deliver best practice - deliver best practice urban design and broader community outcomes as part of stormwater management delivery.
- Maximise return on investment - achieve maximum value from stormwater management through the consideration of a broad range of benefits.

The Lucas Creek study by NIWA (2010) indicated that the incorporation of best practice contaminant controls and WSD approaches significantly reduces the expected sediment yield of a mature urban environment. It also has the ability to address long term impacts for stream scour and sediment generation from stabilised catchments by attenuating flow during rainfall events and minimising changes to stream velocities.

The requirement that development complies with WSD principles can be incorporated into Regional or District Plans as a way to minimise adverse effects to the environment cause by urban development and changes to stream hydrographs.

5.0 Economic Aspects of Sedimentation

There is a financial cost to addressing sedimentation that occurs both during and after development. Erosion and sediment controls are often required during development and incur additional cost for the construction, monitoring and maintenance of the devices, and for the incorporation of stormwater attenuation devices. There are also post development costs associated with the ongoing monitoring and maintenance of sedimentation control devices that are installed. There are also environmental, economic, social, and cultural costs of increased in-stream sediment (Krausse et al., 2001).

5.1 Pre-development

In their paper, Greenhalgh et al. (2017) utilise a cost-benefit model which incorporates ecosystem services. Using the model, the authors discuss the economic impacts of development on ecosystem services, which cannot always be measured in monetary terms. Greenhalgh et al. (2017) used two developments in Pukekohe, South Auckland to showcase the importance of site selection for urban development.

Although the results of the cost-benefit were not definitive, knowing where the greater benefits and costs accrue, decision-makers can be informed of where to develop and recognise potential trade-offs. The study also urged that decision-makers should consider one-off costs verses irreversible costs, for example the one-off higher cost of construction in a more difficult to access area (Northeast Pukekohe), as opposed to the irreversible loss of agricultural soils and production in the region (West Pukekohe).

5.2 During Development

The implementation of sediment controls during the earthworks and construction phase is recognised as a cost-effective means to control sediment. A case study by New Zealand Transport Agency (Redmond, 2011) used three roading infrastructure projects; SH20 Mount Roskill Extension, SH18 Greenhithe Deviation and Christchurch Southern Motorway, to assess the cost of adopting an Erosion and Sediment Control Standard. The case study found that there was almost no difference in the costs associated with the consenting process and erosion and sediment control design. Of the three projects, Greenhithe Deviation (0.8% increase), was the only project which had a noticeable increase in construction costs as a result of adopting the standard.

For developers and governing bodies, the most significant cost associated with implementing robust erosion and sediment controls during the development stage would be associated with monitoring the effectiveness of the sediment controls on watercourses in the urban environment and the receiving coastal environments (Redmond, 2011).

A common misunderstanding of WSD in urban development is that the approach increases costs and reduces profit margins. However, Shaver (2009) used nine case studies of urban developments in New Zealand and the USA to show that WSD developments had lower costs than conventional development (Table 3).

A key outcome of the Auckland Council report by Shaver (2009) was that WSD can provide for more user-friendly communities by incorporating additional amenity and open spaces, and reduce the impacts to natural systems, generally with no additional construction costs. The small difference in costs associated with conventional and WSD construction approaches is attributed to less earthworks and impervious surfaces that are required for site development. The primary reason for the reduced cost is that the design approach reduces impervious surfaces and the amount of earthwork required for site development (Shaver, 2009).

A study was undertaken by Morphum Environmental in 2018 which looked at the costs and benefits associated with stream retention through subdivision design alternatives in the Greater Wellington Region. The alternative designs looked to reduce stream loss by creating public space alongside streams, integrating stormwater management into the development with WSD practices, using a range of dwelling typographies, and reducing the requirement for level sections, by stepping houses downslopes. It was found that in the alternative designs, the yield of dwellings is similar between the design approaches. The life cycle costs were similar between the different design approaches however the earthwork volumes and costs would likely reduce, and resilient green infrastructure would reduce on-going maintenance costs through the WSD scenario. However, subsequent development of dwellings on sloping sites can occur additional costs. The real benefit is seen in the ecology and natural character that is retained and enhanced by WSD practices.

In selecting the most efficient and cost-effective WSD approaches for new developments, studies have examined the operation and maintenance costs of various devices. For example, Kim et al. (2010) assessed three devices; porous pavement, green roof and infiltration basins and found that porous pavements were the most effective and cost-effective means of managing runoff and sedimentation in 2, 10, 50 and 100-year flood events. Generally, studies have found that the cost of construction and maintenance of devices can be reimbursed through the benefits of mitigated pollution damage control costs over a period of five to ten years (Copper et al., 2019).

Table 3: Summary of Cost Comparisons Between Conventional and WSD Urban Site Developments

Project	Country	Conventional development Costs ($)	LID cost ($)	Cost differential ($)	Percent difference (%)
Heron Point	New Zealand	1,844,000	1,590,000	254,000	14
Palm Heights	New Zealand	7,218,000	5,936,000	1,282,000	18
Wainoni Downs	New Zealand	5,963,000	4,478,000	1,485,000	25
Chapel Run	USA	2,460,200	888,735	1,571,465	64
Buckingham Green	USA	541,650	199,692	341,708	63
Tharp Knoll	USA	561,650	339,715	221,935	39
Pleasant Hill Farm	USA	1,284,100	728,035	556,085	43
Gap Creek	USA	4,620,600	3,942,100	678,500	15
Auburn Hills	USA	2,360,385	1,598,989	761,396	32

5.3 Post-development

Studies have looked at the adverse impact of sedimentation on receiving environments and the cost to remedy these adverse effects. For example, NIWA (2017) assessed the cost of managing mangrove expansion in the Whangamata Harbour as a result of increased sediment runoff from the surrounding land and catchments, and activities such as causeway construction altering hydrodynamic conditions. The report by NIWA estimates that the physical removal of mangroves can cost between $1000 to $5000 per hectare, with ongoing seedling removal costing about $1000 per hectare per year. In addition, each mangrove removal operation requires consent, which can cost between $12,000 (non-notified) to $230,000 (notified consent) (NIWA, 2017).

Similarly, Oldman (2017) reports that methods to control or remove sediment in the receiving environments is an expensive and labour-intensive activity. Oldman (2017) discusses the use of catchment planting initiatives to reduce sediment yields in the urban stream, Lucas Creek in Auckland. This shows that planting can reduce he sediment yield by between 30 and 85%, depending on the type of mitigation used. The assessment of the costs associated with sediment removal in the urban environment should also consider health and safety costs. Lastly, non-monetary values such as loss of amenity values or potential recreational areas due to sedimentation should also be considered.

The cost of retro-fitting water sensitive design is much higher than incorporating the approach at the early design stage. Dixon and Earnes (2013) discuss the challenges of urban retrofit and found that reasonable paybacks were difficult to achieve due to the high cost of purchasing land, design, construction and maintenance costs in a densely developed area. In addition to the costs, there are considerable feasibility options, and liaisons with additional stakeholders such as local government public spaces bodies and private residents (Wilson, Crane & Chryssochoidis, 2015).

6.0 Proposed Schema of Sediment Sources and Variability

Natural Sources	
Factor	
Topography	With increasing slope steepness and length, the velocity of run off increases.
Geology	The underlying rock type effects the erosion rate of the material and sediment generation.
Soil type	Grain size effects erodibility.
Rainfall	Increasing rainfall increases sediment generation.
Vegetation/roughness	The presence of vegetation adds a roughness to a surface which reduces runoff velocity. It also reduces raindrop impact erosion.
Development Sources	
Area exposed	With increased bare earth exposed there is more area exposed to rainfall. Run off velocity can increase due to longer slope lengths and there is greater chance of sheet flow concentrating.
Sediment control measures	Reduce sediment yield by trapping sediment on site.
Erosion control measures	Reduce sediment yield by implementing practices that minimise sediment generation.
Storm event design sizing	Sediment and erosion controls are designed for a certain sized storm event. If an event exceeds the design, efficiencies reduce.
Sediment control following completion	Erosion and sediment controls are removed following completion of bulk earthworks. Sites are stabilised, but effectiveness of sediment controls is reduced.
Maintenance and compliance of controls	Ongoing maintenance is required to ensure controls are working efficiently. Compliance measures are used to ensure correct controls are in place.
Mature Urban Catchment Sources	
Consented building works	Sediment controls for small scale works have no to low level sediment control measures.
Road deposited debris	Sediment deposited on roads can be washed.
Non-consented & non-compliance works	No sediment controls will be in place and can involve dumping of material near to streams.
Minor earthworks	No sediment controls will be in place.
Gravel sources	Gravel is common surface material used in the urban environmental. It is replenished by on-going maintenance creating a continual sediment supply.
Garden soil	Bare earth is exposed in gardens and is subjected to the erosive effects of wind and rain.
Grass verge parking	Removes grass cover over time and exposes bare earth to the erosive effects of wind and rain.
Landslides	These can be considered to be infrequent events by can create a large sediment supply in a discrete location.

Stream erosion has been omitted from this list as stream erosion is a natural process. Urbanisation increases stream erosion by altering sediment loading and hydrological regimes. Improvements to sediment and erosion control during development and the incorporation of water sensitive design in urban areas to reduce the impacts of impervious area on stormwater runoff will reduce the effects of urban environments on streams.

7.0 Summary

The largest contributor to sediment in an urban environment is during the development stage when bulk earthworks are undertaken. The added effect of urbanisation is the increase in impervious area and the collection and diversion of stormwater to streams. This leads to changes in the hydrograph of a stream and increased stream scour and sediment generation.

The potential sediment yield varies across New Zealand and is influenced by natural factors, these being topography, geology, soil type, rainfall and vegetation cover. Steep areas, with softer rock geology and higher rainfall will experience higher sediment yield than low lying areas and areas with hard rock geology and drier climates. Areas that are vegetated in mature forest also experience lower sediment yields than equivalent areas that are in pasture or bare earth.

The development stage strips the land of all vegetation, leaving it bare and subject to the effects of rainfall, leading to erosion through rainfall impact and through the flow of water over the bare surface. Uncontrolled earthworks are shown in many studies to dramatically increase potential sediment yield. The incorporation of erosion and sediment control best practice can reduce the potential sediment yield, however the effectiveness will depend on the ongoing maintenance and monitoring of devices. The devices are also only designed for a certain rainfall event and the effectiveness reduces significantly when a rainfall event exceeds the design or when the frequency of rainfall events overwhelms the device capacity.

Following bulk earthworks and decommissioning of erosion and sediment controls, there is typically a secondary development stage where individual lot construction takes place and the area becomes fully urbanised. In an urbanised catchment, there are numerous sources of sediment generation, such as gravel paths, road deposited debris and infill development. Information quantifying the sediment yield from these sources is limited, but in general these sources are localised in extent and are of short duration. The overall land-based contribution of sediment is expected to be low in comparison to the development stage, but it must be acknowledged that in a mature environment, there will be ongoing maintenance, infill development and new developments that will be a continual source of sediment generation.

Urbanisation changes the streams hydrograph which increases erosion and sediment generation. The increase in impervious area and the piping of stormwater to streams increases the runoff volume, flow velocity and the peak flow rates and results in stream incision and widening. The incorporation of water sensitive design features into new development can minimise the effect of urbanisation on the stream hydrograph by reducing imperviousness and decreasing inflow to streams by incorporating stormwater infiltration, evapotranspiration, reuse and attenuation devices into the development.

A conceptual summary of the change to sediment yield with different land use is shown in Figure 6 (orange line). This is demonstrated in sediment yield increases as land is changed from forest to pasture, and then increases significantly during development. There are two stages of development, the bulk earth works stage (bulk) and individual lot development (site). Following development, there is a period of stream erosion as the stream adjust to the new hydrological and sediment regime. The sediment yield then reaches a period of stability with small scale fluxes. The use of sediment and erosion control practices during development and better farming practices can greatly reduce sediment yield. When combined with the incorporation of water sensitive design into urban developments, the changes to the hydrological regime can be minimised which reduces additional stream erosion (blue line).

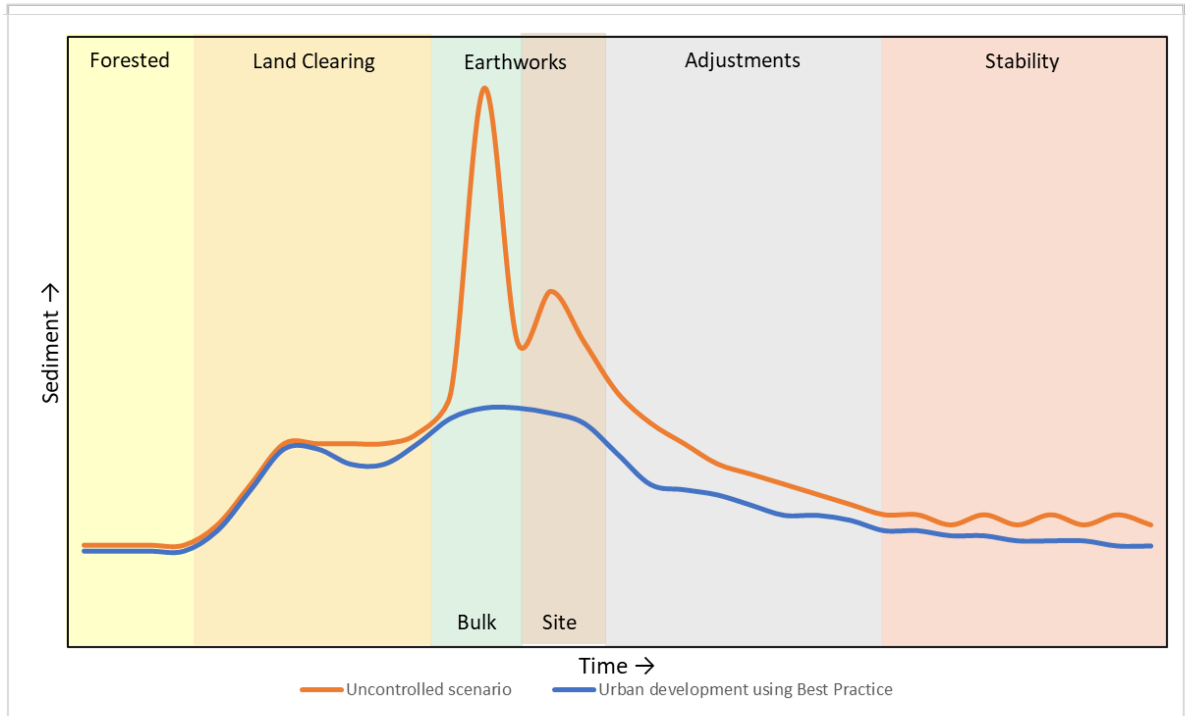


Figure 6: Conceptual Pattern of Sediment Yield with Varying Land Use

8.0 References

Auckland Regional Council, 2000. Low impact design manual for the Auckland region. Auckland Regional Council Technical Publication No. 124, April 2000.

Basher, L. Moores, J. & McLean, G. 2016. *Scientific basis for erosion and sediment control practices in New Zealand,* report prepared for Tasman District Council. Landcare Research Contract Report: LC2562.

Bibby, R. L. & Webster-Brown, J. G. 2004. Characterisation of urban catchment suspended particulate matter (Auckland region, New Zealand); a comparison with non-urban SPM. *Science of the Total Environment* 343: 177-197 p.

Chin. A. 2006. Urban transformation of river landscapes in a global context. *Geomorphology 79 (2006)*: 460-487

Clarke, C., Burns, Andrew., Thompson, N.,. 2018. Stream Retention Through Subdivision Design Alternatives. Prepared by Morphum Environmental Ltd for Greater Wellington Regional Council. Project Number P01904.

Collins, R. 2003. Predicting sediment loss under proposed development in the Waiarohia catchment. NIWA Client Report: HAM2003-063, prepared for Auckland Regional Council, August 2003.

Copper. R., Battams, Z., Pearl, H. and Hiscock, M. 2019. Mitigating river sediment enrichment through the contruction of roadside wetland. *Journal of Environmental Management, 231,* 146- 154

Dixon, T., & Eames, M. (2013). Scaling up: the challenges of urban retrofit.

Dymond, J. R. Davies-Colley, R. J. Hughes, A. O. & Matthaei, C. D. 2017. Predicting improved optical water quality in rivers resulting from soil conservation actions on land. *Science of the Total Environment* 603-604: 584-592 p.

Elliot, S. Parshotam, A, & Wadhwa. S, 2010, Tauranga Harbour Sediment Study: Catchment Model Results. Prepared by NIWA for Environment Bay of Plenty. NIWA Client Report: HAM2009-046.

Greenhalgh, S., Samarasinghe, O., Curran-Cournane F., Wright, W. and Brown, P. (2017). Using ecosystem services to underpin cost-benefit analysis: Is it a way to protect finite soil resources?. Ecosystem Services, 27 (1)

Hickey, C. Macaskill, B. Martin, M. Scarsbrook, M. & Williamson, B. 2001. Hamilton City Stormwater: Assessment of contaminant loads and impacts on the Waikato River. Prepared by NIWA for Hamilton City Council. NIWA Client Report: HCC00210.

Hicks, D. M. 1994. Storm Sediment Yields from Basics with Various Landuses in Auckland Area. Prepared by NIWA for Auckland Regional Council. Consultant Report ARC802/1.

Hicks, D. M. Hoyle, J. Roulston. H. 2009. Analysis of Sediment Yields within Auckland Region. Prepared by NIWA for Auckland Regional Council. Auckland Regional Council Technical Report 2009/064.

Hume, T. M. Green, M.O. & Elliot. S., 2010, Tauranga Harbour Sediment Study: Assessment of predictions for management. Prepared by NIWA for Environment Bay of Plenty NIWA Client Report: HAM2009-139.

Krausse, Michael; Eastwood, Callum; Alexander, Robert R. (2001). Muddied waters : estimating the national economic cost of soil erosion and sedimentation in New Zealand. Landcare Research Report. http://doi.org/10.7931/DL1C01

Lee, K., Kim, H., Pak, G., Jang, S., Kim, L., Yoo, C., Yun, Z. and Yoon J. (2010). Cost-effectiveness analysis of stormwater best management practices (BMPs) in urban watersheds. Desalination and Water Treatment, 19, 92 – 96.

Leersnyder, H., Bunting, K., Parsonson, M. and Stewart, C. (2016) Erosion and sediment control guide for land disturbing activities in the Auckland Region. Auckland Council Guideline Document GD2016/005. Prepared by Boffa Miskell for Auckland Council.

Lewis, M., James, J., Shaver, E., Blackbourn, S., Leahy, A., Seyb, R., Simcock, R., Wihongi, P., Sides, E., & Coste, C. 2015 *Water sensitive design for stormwater.* Auckland Council Guideline Document GD2014/004. Prepared by Beca Ltd and SouthernSkies Environmental for Auckland Council.

Lynn, I, H., Maderson, A. K., Page, M. J., Harmsworth G. R., Eyles, G.O., Douglas, G. B., Mackay, A.D., Newsome P. J. F., (2009). Land Use Capability Survey Handbook – a New Zealand handbook for the classification of land 3rd ed. Hamilton, AgResearch: Lincoln, Landcare Research; Lower Hutt, GNS Science. 163p.

Ministry for the Environment. 2017. *National Planning Standards: Zones and overlays – spatial layers in plans: Discussion paper C.*. Wellington: Ministry for the Environment Publication number ME 1319.

Ministry for the Environment. 2018. *Best Practice Guidelines for Compliance, Monitoring and Enforcement under the Resource Management Act 1991.* Wellington: Ministry for the Environment Publication number ME 1376.

Moores, J. Gadd. J. Yalden. S, & Batstone. C. 2016. Urban Development and the NPS-FML Lucas Creek Catchment Case Study. Prepared by NIWA for the Ministry for Primary Industries Technical Paper No: 2016/66.

NIWA. (2017). Guidelines for Managing Mangrove Manawa Expansion in New Zealand.

NIWA (2010). New Zealand River Environment Classification User Guide. Prepared by NIWA for the Ministry for the Environment. Publication Number: ME1026.

Oldman, J. (2017). The generation and fate of sediment in the Lucus Creek catchment. Prepared by DHI Limited for Auckland Council.

Quinn, J. M. & Stroud, M. J. 2002. The quality and sediment and nutrient export from New Zealand hill-land catchments of contrasting land use. *New Zealand Journal of Marine and Freshwater Research* Vol 36: 409-429 p.

Redmond, C. (2011) Erosion and Sediment Control Standard for State Highway Infrastructure. New Zealand Transport Agency.

Russell, K. L, Vietz, G. J, Fletcher, T. D. 2017. Global sediment yields from urban and urbanizing watersheds. *Earth-Science Reviews* 168: 73-80.

Scarsbrook, M. R. Mc Bride, C. G. McBridge, G. B. Bryers, G. G. 2003. Effects of climate variability on rivers: consequences for long term water quality analysis. *Journal of the American Water Resource Association*. 1435 – 1447 p.

Shaver, E., 2009. Low Impact Design Versus Conventional Development: Literature Review of Developer-related Costs and Profit Margins. Prepared by Aqua Terra International Ltd. for Auckland Regional Council. Auckland Regional Council Technical Report 2009/045.

Taylor, K.G. Owens, P.N. 2009. Sediments in urban river basins: a review of sediment-contaminant dynamics in an environment al system conditioned by human activities. *J Soils Sediments* (2009) 9:281-303.

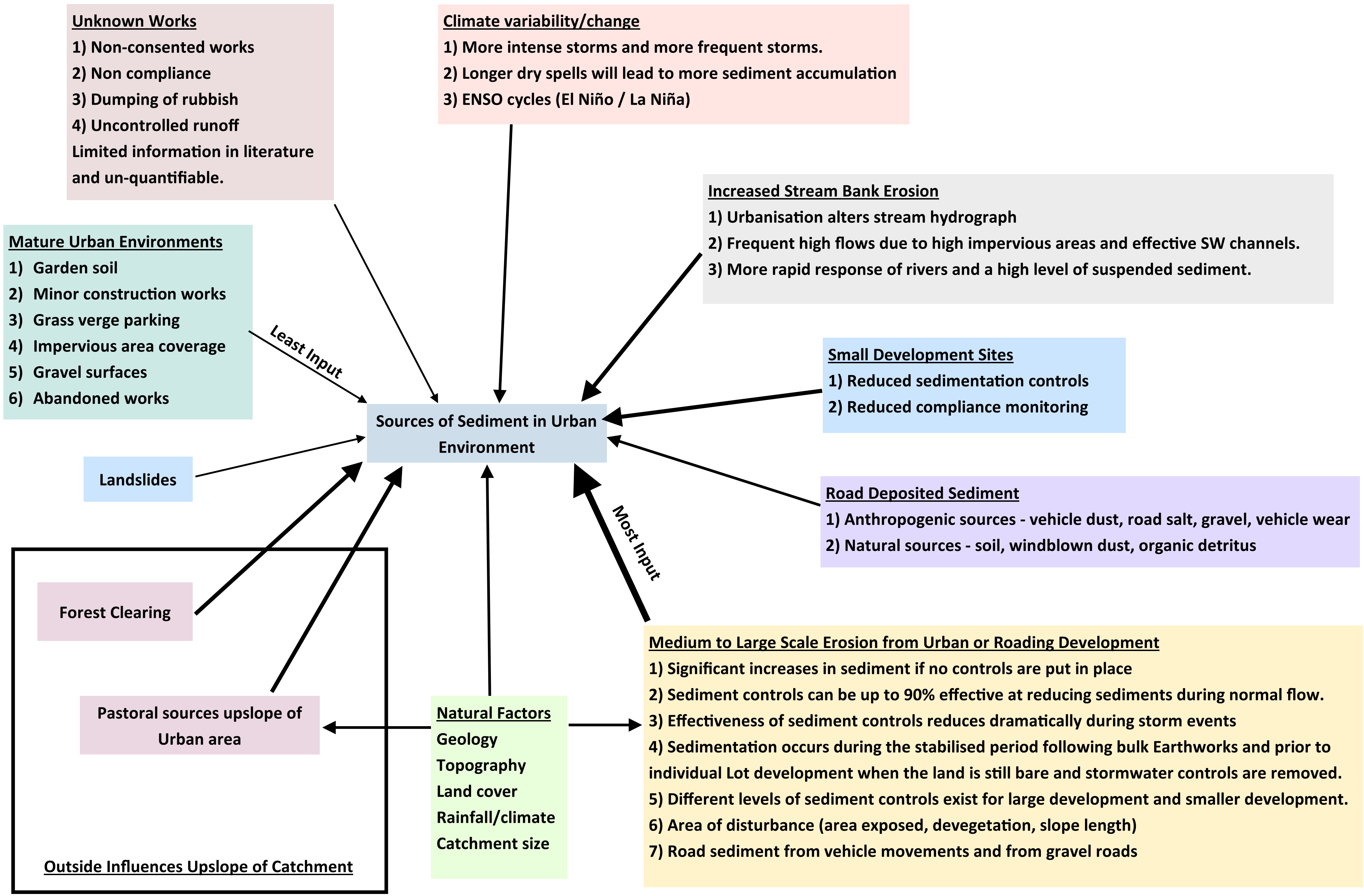
Vietz, G. J. Rutherford, I. D. Fletcher. T.D. Walsh, C.J. 2015. Thinking outside the channel: Challenges and opportunities for protection and restoration of stream morphology in urbanizing catchments. Landscape and Urban Planning 145 (2016): 34-44.

Williamson, R. B, 1993. Urban runoff data book: a manual for preliminary evaluation of stormwater impacts (2nd Ed). Water Quality Centre Publication No. 20, NIWA.

Wilson, C., Crane, L., & Chryssochoidis, G. (2015). Why do homeowners renovate energy efficiently? Contrasting perspectives and implications for policy. Energy Research & Social Science, 7, 12-22.

Yaldin, S, Moores, J. 2014. Assessment of Potential Effects of Land Development on Okura Estuary. Prepared by NIWA for Todd Property Group. NIWA Client Report No: HAM2014-106.

Appendix 1 Sources of Sediment in an Urban Environment



Unknown Works
1) Non-consented works
2) Non compliance
3) Dumping of rubbish
4) Uncontrolled runoff
Limited information in literature and un-quantifiable.
Climate variability/change
1) More intense storms and more frequent storms.
2) Longer dry spells will lead to more sediment accumulation
3) ENSO cycles (El Niño / La Niña)
Increased Stream Bank Erosion
1) Urbanisation alters stream hydrograph
2) Frequent high flows due to high impervious areas and effective SW channels.
3) More rapid response of rivers and a high level of suspended sediment.
Mature Urban Environments
1) Garden soil
2) Minor construction works
3) Grass verge parking
4) Impervious area coverage
5) Gravel surfaces
6) Abandoned works
Least Input
Sources of Sediment in Urban Environment
Small Development Sites
1) Reduced sedimentation controls
2) Reduced compliance monitoring
Landslides
Road Deposited Sediment
1) Anthropogenic sources - vehicle dust, road salt, gravel, vehicle wear
2) Natural sources - soil, windblown dust, organic detritus
Most Input
Forest Clearing
Medium to Large Scale Erosion from Urban or Roading Development
1) Significant increases in sediment if no controls are put in place
2) Sediment controls can be up to 90% effective at reducing sediments during normal flow.
3) Effectiveness of sediment controls reduces dramatically during storm events
4) Sedimentation occurs during the stabilised period following bulk Earthworks and prior to individual Lot development when the land is still bare and stormwater controls are removed.
5) Different levels of sediment controls exist for large development and smaller development.
6) Area of disturbance (area exposed, devegetation, slope length)
7) Road sediment from vehicle movements and from gravel roads
Pastoral sources upslope of Urban area
Natural Factors
Geology
Topography
Land cover
Rainfall/climate
Catchment size
Outside Influences Upslope of Catchment