EROSION CONTROL TREATMENT TRIALS ON LOESS SOILS

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ABSTRACT

During earthworks on Canterbury's Port Hills, highly erodible loess sub-soil is exposed to potential erosion. Stormwater discharged from such sites can contain large quantities of fine sediments that stay in suspension and are challenging for treatment systems to remove. The ecological impact of these fine suspended sediments on downstream receiving environments, including the Cashmere Stream, Heathcote River and Avon Heathcote Estuary, is significant. Utilising effective methods to minimise erosion of exposed soils is key to reducing the amount of loess reaching such sensitive receiving environments.

An experimental field study to test the effectiveness of erosion control treatments was commissioned by the Cashmere Working Group of the Christchurch–West Melton Zone Committee and undertaken by EOS Ecology. Five erosion control treatments applied over a loess sub-soil were tested against an exposed loess sub-soil control during multiple controlled one hour rainfall simulations. The study showed that such erosion control treatments were effective in reducing soil loss, but that proper application of the products was critical to their effectiveness. Even at the higher rates of erosion control, suspended sediment in runoff still exceeded most local consent-based limits, reiterating the importance of construction sites needing to use a treatment train solution of erosion control and sediment control measures.

The findings of the study helped inform an update of the Environment Canterbury Erosion and Sediment Control Guidelines and will be useful in developing innovative construction-phase discharge consent conditions, which are flexible enough to be applied during site development while achieving objectives, policies and water quality outcomes set in the Canterbury Land and Water Regional Plan. A collaborative approach to investigating the effectiveness of erosion control measures through field studies in a specific highly-erosive area has been extremely helpful in demonstrating what is required to limit sediment loss from challenging hillside development areas.

KEYWORDS

Canterbury, Loess, Innovation, Erosion, erosion control

PRESENTER PROFILE

Hannah Goslin has been a Consents Planner at the Canterbury Regional Council since January 2014 and is involved in ensuring the consents section is up to date with Stormwater Best Practice. Hannah has a Bachelor of Science Degree from Canterbury University and has experience in providing environmental impact and policy assessments for a range of discharge permits and land use consents in the Canterbury Region. Outside of work Hannah enjoys keeping active and has recently returned from a backpacking adventure in Asia.

1 INTRODUCTION

The lower slopes of Christchurch's Port Hills are favorable sites for urban development and recreation, but represent a significant soil and sediment issue due to the fine loess subsoil that blankets these slopes. During construction, vegetation clearance, cut/fill and re-contouring of existing surfaces regularly disturbs the natural soil profile, exposing loess subsoils and leaving them susceptible to erosion. Periods of exposure occur throughout the entire development phase, which gradually decreases as the development site becomes stabilised by vegetation establishment and impermeable surfaces. However, due to the properties of loess, it is not retained in more commonly used construction-site sediment retention devices (i.e., sediment basins and detention ponds), meaning there is potential for significant sediment release during the construction phase. The subsequent discharge of suspended sediment into the receiving environment of Cashmere Stream (and ultimately through to the Ōpāwaho/Heathcote River and Ihutai/Avon-Heathcote Estuary) has been documented in recent catchment studies (James & McMurtrie, 2009; McMurtrie & James, 2013), which identified the Port Hills sub-catchment as a key source of fine loess particles that detrimentally impact the health of these systems. The aftermath of the Canterbury Earthquake Sequence has meant that development on the Port Hills has increased, thereby increasing the risk of sediment release and thus exacerbating an ongoing issue of poor water quality and significant ecological effects.

The most critical stage for preventing erosion from construction sites is when subsoil is exposed during clearing, re-contouring and construction of infrastructure/dwellings. Applying erosion control (as opposed to sediment control) treatments to exposed loess subsoil is a primary defence against surface runoff. However this requires the adequate installation of the appropriate erosion control in order to significantly reduce the risk of erosion from exposed soils. A wide range of erosion control treatments are available for short-term and long-term soil stabilisation prior to the establishment of vegetative cover or constructed surfaces. However, despite these options, erosion and the resulting water quality issues in Cashmere Stream and its tributary waterways continues and there is limited information available regarding specific performance of such treatments on loess-dominated slopes.

In recent years there has been an attempt to resolve these issues through more locally relevant erosion and sediment control guidelines (i.e., Environment Canterbury, 2007) and resource consent conditions. However ongoing water quality issues and confusion over the most effective erosion control measures to use during construction for the different soil types and topology of Canterbury, has raised questions over the performance of currently available erosion control products. An experimental field study to test the effectiveness of currently available erosion control treatments was commissioned by the Cashmere Working Group of the Christchurch–West Melton Zone Committee and undertaken by EOS Ecology. Five erosion control treatments applied over a loess sub-soil were tested against an exposed loess sub-soil control during multiple controlled one hour rainfall simulations. Results were used to compare effectiveness of each of the trialed products, and to make recommendation for future updates to Environment Canterbury's Erosion and Sediment Control (ESC) Guidelines specific to Port Hills soil. The results will be useful in developing innovative construction-phase discharge consent conditions, which are flexible enough to be applied during site development while achieving objectives, policies and water quality outcomes set in the Canterbury Land and Water Regional Plan (LWRP).

1.1 BANKS PENINSULA LOESS DEPOSITS

Loess deposits are typically homogenous to weakly stratified Aeolian silts with a terrestrial origin, which accumulate downwind of sediment source areas (Pye, 1995).

Loess deposits in the Marlborough and Canterbury Region originate from the Southern Alps greywacke, which accumulated through the Late Pleistocene glaciation. The grinding of rock into fine particles by glacial action concentrated large amounts of light friable material. In Canterbury, this unconsolidated silty material was entrained by strong westerly winds from the plains and Waimakariri River fan, to be deposited on Banks Peninsula (Raeside, 1964; Griffiths, 1974; Tonkin et al., 1974). Loess is the main soil-forming parent material on lower slopes and ridges in Banks Peninsula, with the Birdlings Flat loess (Griffiths, 1974) being of primary concern to this study, as its location commonly coincides with residential developments on the lower slopes of the Port Hills. Loess-derived soils of the Port Hills are predominantly made up of silt (65-80%) with minor amounts of clay (<30%) and sand (<20%), with the bulk of soil particles being in the 2-60 µg range (Jowett, 1995).

1.2 SOIL PROPERTIES

In Banks Peninsula, soil derived from loess deposits are classified as yellow-grey earths. Variability in soil profile development is dependent on slope position, climate, altitude and incorporations of underlying volcanic materials. Typical characteristics of yellow-brown earths derived from loess are a seasonal moisture deficiency and a hard compact layer in the subsoil. Of most relevance to this study is the Takahe series soils that occur from sea level to ~250 m on the lower slopes of the Port Hills. Their concurrence within proposed zones of residential development and their propensity to erode severely means great care is required during construction. A full account of Port Hills soil properties and classification is given in Fitzgerald (1966), Griffiths (1974) and Trangmar & Cutler (1983).

New Zealand soil horizon notation for Takahe series soils is described in Griffiths (1974) and is not used in this report. The simplified and descriptive layering model offered by Huges (1970) defines soil horizons for engineering practice in the Port Hills, by dividing typical loess profiles into three different layers: the surface layer (S-layer), the compact layer (C-layer) and the parent material (P-layer) (Figure 1).

Figure 1: A cut and severely eroding surface at an abandoned construction site, Gerkins Road, Port Hills annotated using the descriptive method after Huges (1970) and showing the highly erodible nature of loess subsoil. Sheet wash at the top of the slope rapidly transitions to rilling on the lower half. Note how erosion affects the P-layer more severely. Image © EOS Ecology.

1.3 WHY DO THE PORT HILLS LOESS ERODE SO SEVERELY?

When the protective surface soil (S-layer; cf. Figure 1) is removed, highly erodible loess subsoil is exposed to erosive processes. Erosion is exacerbated due to key physical characteristics of loess subsoil; low infiltration rates and dispersion. Such processes gives rise to rilling, gully, and tunnel gully erosion often seen on unprotected loess subsoils (Figure 1).

Below the compact C-layer the parent P-layer material has low cohesion and is dominated by silt and fine sand sized particles (Figure 1). This subsoil tends to be internally homogenous with low permeability, resulting in high runoff coefficients (low infiltration rates).

Banks Peninsula loess subsoil is also highly prone to dispersion, a process whereby soils rapidly dissolve when submerged in water. Dispersive soils contain a higher percentage of sodium relative to other exchangeable cations (calcium, sodium, potassium, magnesium) and are termed sodic soil. Sodicity and soil dispersion are often positively correlated, meaning a soil containing excessive sodium will often be dispersive. When exposed to water sodic soil aggregates disperse by a process known as deflocculation. This chemical process occurs because excessive sodium (Na^+) cations occupy exchange sites of clay particles. Sodium cations have a relatively weak attractive force when compared with potassium, magnesium or calcium cations that usually occupy exchange sites on clays. These weak attractive forces allow loess particles to disperse in water and remain suspended, resulting in a cloudy suspension of fine clay and silt particles.

2 METHODS

2.1 PRODUCTS TESTED

The scope of this study was to test the performance of readily available erosion control products to protect loess subsoil during construction. Therefore the focus was placed on treatments that could be used to provide short-term protection during the construction phase, prior to long-term erosion control treatments and the establishment of vegetation. During construction, exposure of loess subsoil occurs during clearing and grading of the site. When considering which erosion control treatments for short-term site stabilisation would be relevant to trial, treatments were selected using the following criteria:

- Commercially available and listed within Canterbury’s ESC Guidelines (Environment Canterbury, 2007).
- Easy and rapid application.
- Suitable for coverage on a range of slope angles.
- Lesser-used or innovative products that may be particularly beneficial for reducing erosion from loess subsoil.

Treatments selected included top soiling, straw mulching, coconut fibre rolled erosion control product (RECP), and two hydraulically applied soil stabilisers – WRD-L and Vital Bon-Matt Stonewall, which are described below in more detail.

- **Topsoil:** Although not a recommended treatment to prevent erosion, topsoiling is common practise when preparing loess slopes for eventual stabilisation by vegetative cover – thus it was considered important to gain an understanding of runoff and soil loss from topsoiled surfaces.

  Topsoil is typically stockpiled on earthworks and construction sites for later reapplication over contoured surfaces, thus the topsoil used here was comprised of S-layer material collected from the test site, which was applied to the recommended 100mm depth over the loess subsoil.

- **Straw mulch:** Spreading straw across an exposed soil surface is a commonly used method to reduce erosion. Straw breaks the impact of raindrops and impedes water flow across the soil surface. Straw is typically used as a short term erosion control treatment on gentle slopes during the establishment of grass cover.

  Straw was spread evenly over the plot surface at an application rate of 4,000 kilograms per hectare (as per the recommendations of Environment Canterbury, 2007), which provided a relatively good coverage although there remained some small areas of exposed soil.

- **Coconut fibre RECP mat:** RECPs typically come as large rolls of biodegradable material that are rolled out over exposed soils. Coconut RECP mat is made from reinforced coconut fibre and is commonly used as long-term erosion control treatment on moderate to steep slopes prior to the establishment of vegetation.

  This undisclosed generic coconut RECP matting was purchased from a local hardware store. Its construction consisted of a coconut fibre core held in place by a fibrous mesh. This product had a 350 g/m^2 weight and is 100% biodegradable. In general this product provided even soil coverage, but in places the coconut fibre core was thin, exposing plot soil below. The coconut RECP mat was cut to size and covered the entire plot surface (2 m^2), with small pins formed from galvanised wire used to hold it in position during the simulation.

- **WRD-L:** This product is a hydraulically applied lignosulphate-based soil stabiliser, which is supplied as a concentrate that is suitably diluted and applied over exposed soils. The large molecular weight of the calcium lignosulphonate molecules improves the binding properties of soil particles, hence the product is commonly used to suppress dust and reduce erosion from wind. Being water soluble, calcium lignosulphonate is not typically used as an erosion control product to protect soil from the effects of heavy rainfall, but was used here to test its potential capacity to provide short term erosion control and reduce erosion from complex surfaces during on-going bulk earthwork phases.

  The product was applied by the supplier, who first pre-wet the soil plots with one litre of a solution containing anionic surfactant Marine 3 Technologies (an ALS Marine product), so as to reduce surface tension and allow deeper penetration of the WRD-L treatment. Two litres of 10% WRD-L solution was then applied to the pre-wetted surface, which was then left to dry for more than 24 hours prior to commencing the rainfall simulation. Application was performed using a combination of watering can and spray bottle for all three simulations. In the third simulation the product supplier used a slightly different formulation. As a result summary figures that both include and exclude the result for this test plot have been provided.

- **Vital Bon-Matt Stonewall:** This product is also a hydraulically applied copolymer soil stabiliser that comes in a concentrated emulsion that is diluted in water before application. The proprietary co-polymer technology is specifically designed to protect against erosion from exposed soil surfaces. It contains a green dye for application purposes, and provides short-term protection. This product could be suitable for erosion control on steep and complex sites during and after bulk earthworks and the establishment of permanent soil stabilising measures.

  The product was applied by the supplier, who first pre-wet the soil plots with one litre of water, followed by two litres of 10% Vital Bon-Matt Stonewall applied via a watering can. The plots were then left to dry for more than 24 hours before commencing the rainfall simulation. During the drying process a sheet of plastic disturbed the wet surface of the third plot, creating numerous small holes in the application. The supplier was allowed to reapply a small amount (approximately 200 mL of 10% solution) using a spray bottle to patch holes prior to rainfall simulation. This resulted in close to a 100% product coverage for the third simulation. Subsequently summary figures that both include and exclude the result for this test plot have been provided.

All of these treatments are currently used on the Port Hills area to some degree as erosion control measures during development. To effectively test the capacity of these erosion control treatments to protect loess subsoils on Port Hills construction sites, test results were compared to an untreated loess subsoil control.

2.2 TEST SITE LOCATION

Test sites were required to be within or adjacent to an active construction site, and thus was located in an area of future development. The test sites were all in Redmund Spur, located within the Cashmere Stream catchment of the Port Hills of Christchurch City (Figure 2). The landscape is made of rounded toe slopes of a prominent spur with underlying basalt covered by loess soils. Slopes range from 10° to 20° and are covered by improved pasture dominated by Brown Top grass (*Agrostis capillaris*). Test sites had a natural hummocky morphology that ranged between 5° - 15°.

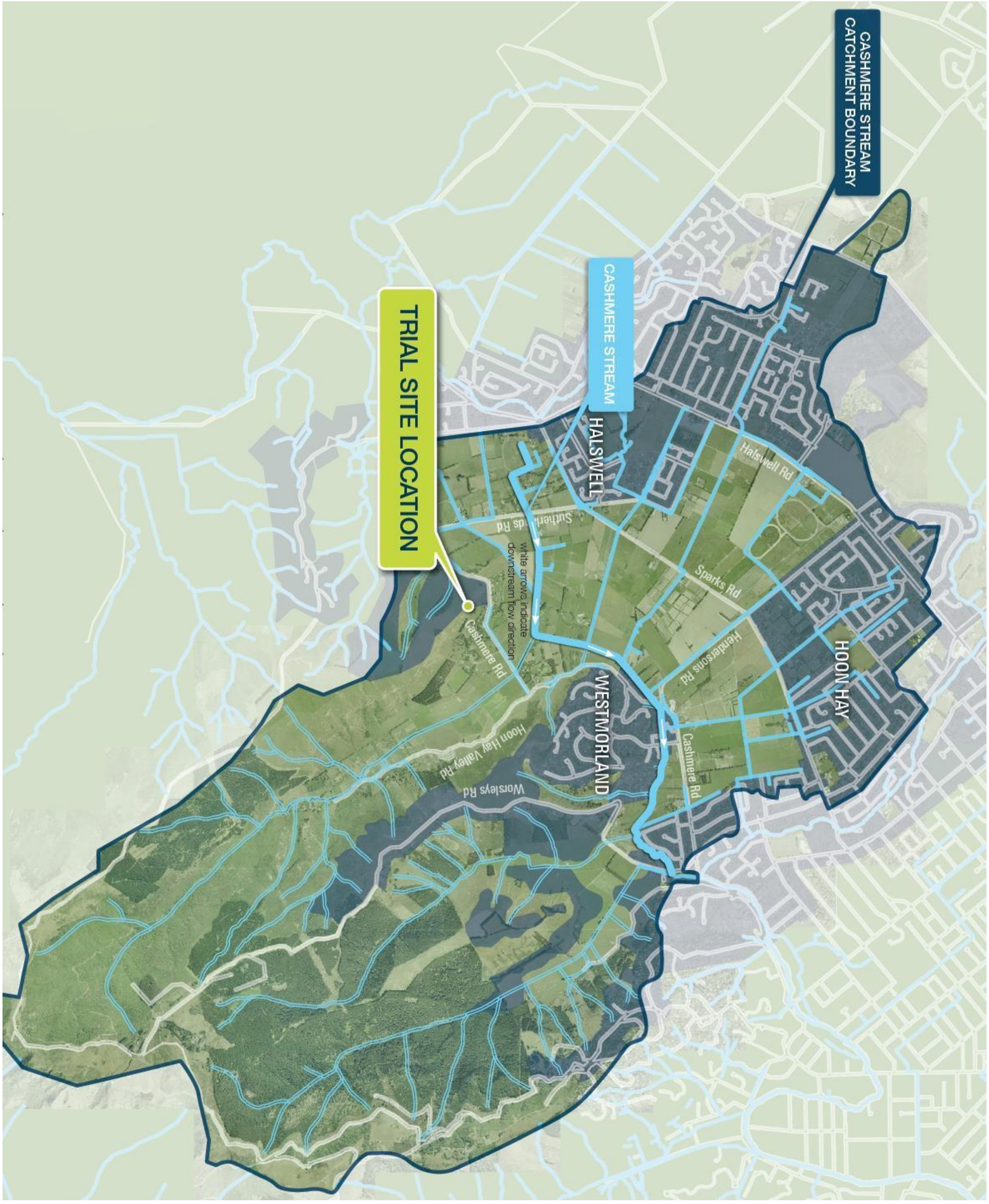

Figure 2: Location of the trial site in the Redmund Spur development area) within the Cashmere Stream catchment, Christchurch, Canterbury. Map © EOS Ecology.

2.3 TEST SOILS

The study was conducted on constructed field plots filled with a mix of C-layer and P-layer horizon subsoil ('test soil') excavated from a depth of 400-1000 mm from the adjacent Redmund Spur construction site. The test soil had a single origin and was piled and covered until used in experiments. Hard fragments of C-layer origin gave stockpile test soil a heterogeneous texture, meaning the screening of soil was required to remove large fragments. Post screening maximum particle size was approximately 5 mm.

The test soils are mapped as Takahe series soils (Griffith, 1974). Screened soil had a loamy sand to sandy texture, and contained sparse reddish-brown mottles and iron-magnesium concretions. Small fragments of basalt within test soils indicate colluvial processes have reworked the original loess stratigraphy. The presence of healed tunnel gullies and surface slips at the area of the field experiment and test soil source indicates recent erosion processes have affected the slope. No soil samples were sent for analysis of chemical and physical properties.

2.4 TEST APPARATUS & SAMPLE COLLECTION

The five erosion control treatments and loess control were tested during three separate one hour controlled rainfall simulations (Figure 3) giving 18 individual one hour–long simulations. Due to limited room, only six soil boxes were able to be installed on site, so following each test, soil was removed from soil boxes and discarded, and new soil and treatment applied for the following test until the required number of simulations was complete. Simulations were undertaken during three weekends in February 2016, to allow the inclusion of community members (including some from the Cashmere Working Group of the Christchurch–West Melton Zone Committee, and from the Cashmere Stream Care Group). Under direction of EOS Ecology, these volunteers helped to set-up the experiment, collect samples and take associated notes throughout the experiment. In excess of 180 hours of volunteer time was utilised to complete this experiment.

Due to a very dry El Niño summer, a rainfall simulator was used to test soil treatments in a controlled runoff plot setting. A Norton-Style Multiple Rainfall Simulator with a two head configuration was used to simulate natural rainfall over a 1.5 m wide by 2 m long area. The system operates using a submersible pump that delivers water at 41 N/m2 (6 pounds per square inch (psi)) to two oscillating spray nozzles (VeeJet 80100) with an exit velocity from the nozzle of 8.8 m/s, where drops produced 1.8 m above the plot surface impact close to their terminal velocities. The rainfall simulator control box allowed for variable rate rainfall application, which was set at the same rate for all tests. Calibration tests during simulations gave an average rainfall rate of 29 mm/hour; approximately equivalent to a 50 – 60 year annual recurrence interval for the trial site (NIWA High Intensity Rainfall Design System (HIRDS) hirds.niwa.co.nz). In general conditions on site were amenable to the use of the rainfall simulator. On a few occasions there was a very light breeze which may have affected the fall of the rain from the simulator, and thus wind breaks were installed around the simulator as needed to control this.

Six soil plots were constructed by excavating a 0.3 m x 1 m x 2 m slice of clod surface soil. Constructed soil boxes were seated within the excavated sites to sit close to the original surface profile and set to an average angle of 11°. Soil boxes were constructed to have an internal dimension of 0.1 m x 1 m x 2 m, giving a test surface area of 2 m^2. Drainage holes were drilled in the lower quarter of soil boxes to allow excess water to move through test soil (note that during simulations no water was observed moving through these holes). PVC flumes were fitted to the downslope end of the soil boxes to direct runoff to a collection area where sampling took place.

Soil boxes were filled with test soil, compacted and levelled. Three basic soil cores were collected from soil plots to estimate soil density. After drying soils thoroughly, an average test plot density was calculated at 1,738 kg/m^3. This result is similar to dry density results from loess soils studied by Jowett (1995), which ranged from 1,550–1,830 kg/m^3. Test compaction, thickness, roughness and moisture content varied slightly between each of the 18 plot sites constructed and tested, thus erosion control treatments tested were randomly assigned to each plot to better account for such variation.

Product suppliers LAS Marine LTD and Vital Chemicals LTD undertook the product preparation and application of WRD-L and Vital Bon- Matt Stonewall treatments, respectively. Application strength and methods of these two products was at the discretion of the supplier. EOS Ecology staff applied all other treatments.

Water samples were collected at five minute intervals following the initiation of runoff, and continued until the end of the one hour rainfall simulation. The time taken to fill each one litre sample bottle was recorded to establish runoff rates. In total 208 samples were collected, with either 11 or 12 samples collected during each simulation, dependent on when runoff was initiated. During each simulation treatment performance and erosion process were noted to assist with the final interpretation of the data.

On return to the EOS Ecology laboratory, the collected samples were treated with a flocculent (AquaSplit, a LAS Marine Product) to separate suspended sediment particles from water. Superfluous water was then decanted and samples dried. Dried soil was reweighed to determine sediment concentration as grams per litre (g/L).

Figure 3: Runoff plot and rainfall simulator setup for field experiments. Image © EOS Ecology.

2.5 DATA ANALYSIS

The sediment concentration for each sample was used to calculate how much soil was lost during each one hour simulation. The time recorded to fill each one-litre sample bottle was used to determine the discharge rate (Q = mL/Min). This was then combined with the sediment concentration values to calculate the soil detachment rate (Di = $g/m^2/s$).

Sigma Plot curve fitting software was used to define an average discharge rate for each of the three replicate simulations for each treatment type. This was done to remove any environmental noise in individual results so discharge rates for each treatment type could be effectively compared. In addition, cumulative sediment yields were calculated by the cumulative sum of the soil detachment rate (Di) per each one second interval (s or time in seconds) after runoff (i.e., the sum of the soil detachment rates for each of the 3600 seconds (60 minutes) of simulation: $S_{cum} = \Sigma (Di \times s)^n$). To effectively compare the total soil loss between each treatment type, Sigma Plot curve fitting software was then used to define a curve of best fit for cumulative sediment yield (g/m^2) for each of the three simulations for each treatment type, resulting in an average sediment yield per treatment type. This information allows powerful deduction about erosion rates and behaviors throughout the one hour simulations. It should be reiterated that these results are based on the average of all three simulations for each treatment type. This approach was taken to incorporate environmental variability expected on any earthworks or construction site where these treatments may be used.

No attempt was made to statistically analyse results as the main aim was to test the relative effectiveness of erosion control treatments, not variability between tests. There was also inadequate repetition to warrant a rigorous statistical analysis of data.

3 RESULTS

Discharge from the loess control plots occurred soon after simulation began and plateaued within the first ten or so minutes (Figure 4). The rapid runoff indicates low infiltration and surface sealing which are key characteristics that exacerbate erosion from exposed loess subsoil. Runoff from the coconut RECP mat and straw mulch treatments commenced later than in the control or other tested products, as a result of the bulky materials absorbing water. Subsequently both treatments took longer to reach a stabilised discharge rate, which was just above that of the rainfall application (Figure 5), thereby increasing runoff over time. This was related to the bulky nature of these treatments, which retained water by slowing surface flow before reaching saturation. Once the holding capacity of the product was reached, it then resulted in a higher (yet stable) discharge than the rate of rainfall application, as the saturated media became a source of water release. In contrast runoff in the remaining three treatments (topsoil, WRD-L and Vital Stonewall) commenced earlier, with stabilised discharge rates below the rainfall application rate and loess control discharge rate; resulting in a reduced surface runoff and thus increased infiltration rates.

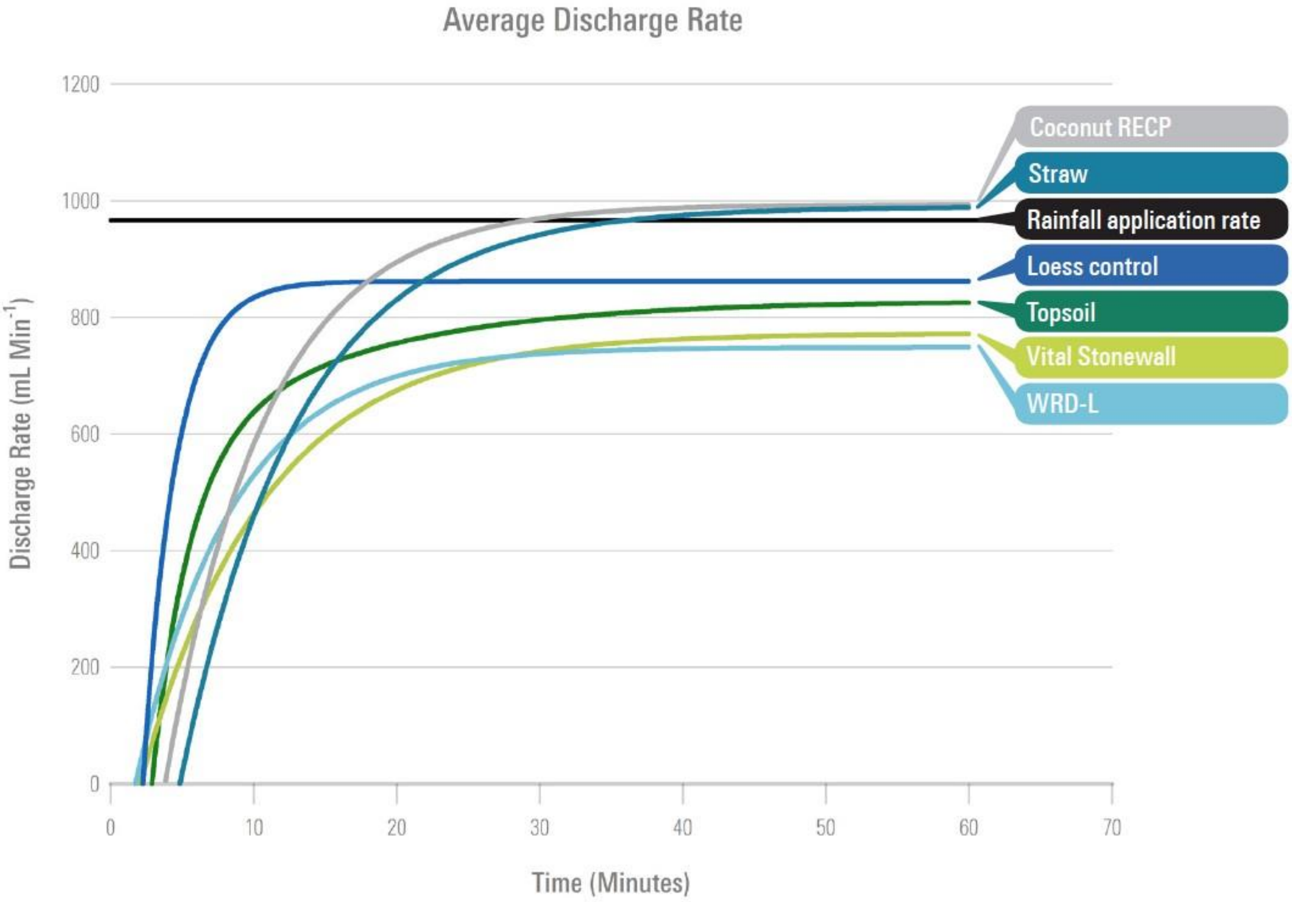

Figure 4: Summary plot showing the average discharge rate (millilitres per minute) for the five treatment types and loess control plots. Each curve is an average of three separate test plots for the same treatment. The black line shows the constant rainfall application rate of 966 mL/Min for reference.

Runoff from the three loess control plots contained very high sediment concentrations (on average 151.5 g/L) and typified erosion processes on unprotected Port Hills worksites. In all three simulations, strong sheet wash was observed as an initial erosion process, with the lower half of the plots becoming populated by small (5 mm) anastomosing channels. In the first simulation, shallow localisation of channeled flow created shallow (>5 mm by 300 mm long) rills where the soil surface was slightly convex in the lower portion of the plot. Deposition within the test plot was observed in all three loess simulations; with fine sand-sized particles typically setting out as a fan in the lower portion of the soil box. In the first simulation this depositional process was strong and affected test outcomes, as soil detachment rates were significantly less than for the other two simulations.

The coconut RECP mat produced the most consistent and repeatable soil detachment rates of all products tested, with all three simulations producing consistent, stable sediment detachment rates over the length of the simulation. In contrast the straw mulch simulations produced disparate soil detachment rate curves for all three simulations, whilst the remaining products produced comparable soil detachment rate curves for two of the three simulations. Three of the five product simulations as well as the loess control produced relatively similar discharge rate curves. However topsoil had one slightly lower discharge curve compared to the other two simulations, and strong winds and machine failure at 48 minutes into the third Vital Bon-Matt Stonewall simulation resulted in an inconsistent discharge rate for the last quarter of the simulation.

The average cumulative sediment yield for loess produced a total of 3,726 g/m^2 (Figure 5, Table 1). However there was a reasonable difference in sediment yield between the first and latter two simulations, which varied from 1,751–5,233 g/m^2 for the first and third simulation (Table 1). As discussed above, the lower sediment yield in the first simulation may have been caused by released sediment settling on the lower portion of the soil box.

When comparing cumulative sediment yields (g/m^2) for each treatment type it was evident that all five erosion control treatments tested reduced sediment yields in comparison to the bare loess control plots (Figure 5, Table 1). The average reduction in sediment yield (i.e., soil loss) compared to the control plots were (in decreasing order of efficiency) 95% (coconut RECP mat), 94% (straw), 90% (Vital Bon-Matt Stonewall), 86% (topsoil), and 48% (WDR-L; or 65% if the third simulation is excluded).

The sediment yields for WRD-L were the highest of the five treatment products tested, averaging 1,955 g/m^2 across the three simulations. The highest yield was from the third simulation (3,234 g/m^2), implying that the altered formulation reduced rather than improved product performance. Alternatively this may have been due to variation in coverage of the product, but as the product was not tinted it was not possible to assess and difference in product coverage. Of interest was the slight steepening of the cumulative sediment yield curve for WRD-L over time. This was likely due to the degradation of the WRD-L, which is a water soluble product. Sheet flow was the dominant sediment transport mechanism observed. As runoff increased, small anastomosing surface flows developed, with small gaps in application gradually growing from small divots and pits that slowly linked. In the third simulation these grew to small localised channel and initial rill formations.

A large variation between the first two and the third simulation for the hydraulically applied Vital Bon-Matt Stonewall was also evident (Table 1). Soil detachment rates for the first two simulations were close to 0.2 g/m^2/s whereas the third simulation had a rate close to 0.002 g/m^2/s, or two orders of magnitude lower. This was reflected in the dramatically lower cumulative sediment yield of 6.1 g/m^2 for the third simulation compared to greater than 500 g/m^2 for the first two simulations. This difference can be attributed to the near 100% product coverage achieved in the final simulation. In all three simulations, rapid runoff containing low suspended sediment was initially produced. However, where 100% coverage was not achieved (i.e., the first two simulations), raindrop impact gradually increased the size of small soil surface exposures. Soil dispersion and sheet flow exacerbated this point erosion, resulting in a visible increase in suspended sediment in the runoff. Where 100% coverage was achieved (i.e., the third simulation), runoff remained clear throughout the simulation.

Cumulative sediment yields for the three coconut REPC mat simulations were remarkably consistent, providing yields in a tight range (172.7 g/m^2 to 206.5 g/m^2, or a 0.9% variation). Such consistent results can be considered an attribute of a roll-out product where variability in product application is reduced. Similarly straw mulch had a relatively low variation between the three cumulative sediment yields (5.1%). Slight variations between the three cumulative sediment yield curves is likely attributable to some variation inherent in applying such a product, where density and the angle of straw fibers could affect rainfall penetration and runoff. The best-fit average cumulative sediment yield calculated for straw also gave the lowest average for all treatments (175 g/m^2, Table 1).

Despite topsoil not being regarded as a erosion control method per se, with an average cumulative sediment yield of 553 g/m^2 it provided an 86% reduction in sediment loss compared to the loess control (Table 1). One of the three cumulative sediment yields was almost twice that of the other two simulations, which may have been attributable to a slightly more compacted surface, which reinforces the importance of not over-compacting topsoil.

Despite the reductions in soil erosion from test plots by the treatments tested, all but two sediment concentrations (g/L) measured in runoff samples collected during this experiment still exceeded typical consented limits for construction phase stormwater discharge (typically 0.1 to 0.15 g/L). The maximum and minimum sediment concentrations for individual samples recorded from the treatment plots were 239.6 g/L (loess control plot) and 0.028 g/L (Vital Bon-Matt test plot) respectively. When considering the average sediment concentrations for all samples collected, for each of the treatments, the maximum and minimum values ranged from 95 g/L (WRD-L at a 48% average reduction rate) to 6.9 g/L (for straw at a 95% average reduction rate). Further details of the results can be found in the full report (see Adamson, 2016).

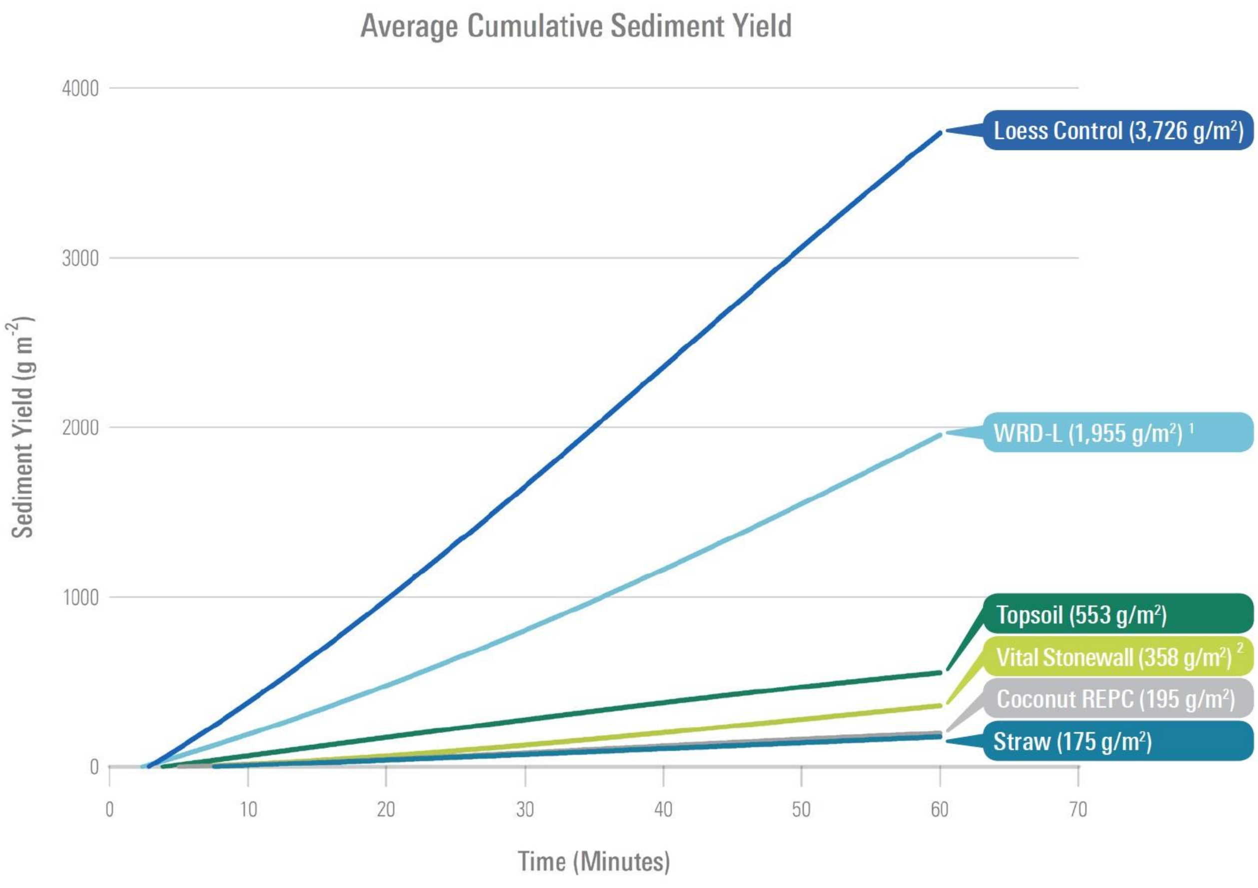

Figure 6: Summary plot showing all average cumulative sediment yields (g/m^2) for the five treatment types and loess control plots. Each curve is an average of three separate test plots for the same treatment. The final value (at 60 minutes) represents the total average sediment yield for that treatment at the end of the hour-long rainfall simulation (the amounts are provided in parentheses).

Table 1: Summary of figures for soil loss results, showing the cumulative sediment yields (g/m2) for each simulation, the average across all simulations, and reduction in sediment yield compared to the loess control and the variation between the reduction rates with each treatment set.

Treatment	Cumulative sediment yield for each rainfall simulation (g/m^2)			Average cumulative sediment yield (g/m^2)	% reduction in sediment yield[3]	% range between the three simulations[4]	Average % reduction in sediment yield[5]
	01	02	03				
Bare Loess (control)	1,751.2	4,257.7	5,233.1	3,726	n/a	n/a	n/a
Straw Mulch	264.9	175.8	72.5	175	92.9% - 98%	5.1%	95%
Coconut RECP Mat	172.7	208.9	206.5	195	94.4% -95.3%	0.9%	94%
Vital Bon Mat Stonewall	533.2	543.9	6.1	358 [2]	85.4% - 99.8%	14.4%	90% (71%) [6]
Topsoil	457.4	819.6	389.3	553	78% - 89.6%	11.6%	86%
WRD-L	1,423.2	1,214.2	3,233.7	1,955 [1]	13.2% - 67.4%	54.2%	48% (65%) [6]

[1] Or 1,319 g/m^2 if the third simulation with the altered product formula is removed.
[2] Or 533.6 g/m^2 if the third simulation with additional coverage is removed.
[3] Percentage reduction in sediment yield when compared against the average cumulative sediment yield for the bare loess control plots. The values presented are the range between the three rainfall simulations.
[4] The variation in the % reduction values for the three rainfall simulations (i.e., for the straw treatment, the range in the three percentage reduction values was 5.1%).
[5] The average reduction in sediment yield compared to the average for the bare loess control plots.
[6] Values in parentheses exclude the third simulation where product application was different (via a variation in formulation or coverage).

4 DISCUSSION

The results showed that exposed and untreated loess soils produce large amounts of sediment equating to an average sediment yield of 3,726g/m^2 over an hour long 29 mm/hr simulated rainfall event. The rainfall simulation test results showed that most treatments reduce runoff rate and promote infiltration, and result in reduced sediment yields compared to the bare loess soil control. When looking at the average reduction in sediment yields, while four of the five treatments achieved a reduction rate between 86-95% of the sediment yield of bare loess, the total sediment yields at these reduced rates still equates to 175-553g/m^2. The WRD-L treatment (which achieved a 48% reduction in sediment yield), resulted in a more substantial average sediment yield of 1,955g/m^2.

Loess control plots demonstrated in a very visual way how much soil can be lost from a two metre square area of exposed loess subsoil on an active earthworks or construction site. One loess control plot lost the most soil of all simulations, equating to 10.46 kg over the length of the simulation. The strong dispersive characteristics of Port Hills loess subsoil makes it highly susceptible to erosion. Observation of loess control test plot surfaces before and after simulations showed that soil dispersion effectively sealed the upper surface of the test plot causing rapid runoff and entrainment of sediment. Discharge rates for loess control plots were more rapid on average than treated plots. This rapid runoff and low infiltration rates need to be considered when sizing erosion and sediment control mitigations on Port Hills earthworks and construction sites.

The very high suspended sediment content in runoff from loess test plots was dominated by sand particles. In one loess control plot, a portion of this sand–dominated loess was deposited in the lower portion of the test plot reducing total cumulative sediment yield. Results from this test plot demonstrate how over a large and complex earthworks or construction site, the sand size fraction from loess may settle out of suspension where sediment control mitigations (i.e., silt fences, check dams etc) are put in place. However, smaller silt and clay particles will remain in suspension due to the dispersive properties of loess soils. Chemical treatment with a suitable flocculant or infiltration are two methods whereby fine suspended sediment derived from loess subsoils can be treated.

It was interesting to note that while applying top soil is not necessarily regarded as an erosion control treatment, on average it performed as well as some other treatment types in the simulations. This is primarily due to two key factors the less dispersive characteristics of topsoil compared to parent loess, and higher infiltration rates due to permeable soil structure which in turn reduces runoff rates and the erosive power of water. The use of top soil in itself as an erosion control measure during the construction phase is not recommended, but the results do show the importance of reinstating topsoil to a site following the completion of works. Therefore, there is the potential to use topsoil or similar mulch products in combination with other products to provide erosion control.

For the straw and coconut REPC mat treatments that provided bulky surface cover over loess test soils, slow initiation in runoff followed by an increased discharge rate are important observations. The physical mass of these treatments protects the soil surface from rain splash and sheet flow. Post simulation, both treatments had prevented infiltration in the upper portion of the test plot while the lower half of the plot was saturated, indicating that the reduced initial runoff rates of sheet flow held water in the lower portion of the slope, causing saturation. Under prolonged wet-weather conditions this has the potential to cause slumping and slippage of surface soil. Conversely in lower intensity storms, where used appropriately, straw and coconut REPC mat (and similar products) will provide good protection for loess slopes, and possibly prevent runoff occurring. Furthermore, REPC type products should be used in combination with topsoil where possible to promote permanent stabilisation by vegetation.

The suspended sediment contained within runoff from straw and coconut REPC mat was dominated by fine silt and clay particles. Sand size particles all remained within the structural lattice of these treatments. This slowing and pooling of runoff aids the settling of sand sized particles, dramatically reducing sediment yields. Runoff from these treatments was however very turbid and would require further treatment to reduce the suspended sediment content to an acceptable level.

Both hydraulically applied soil stabilisers, Vital Bon-Matt Stonewall and WRD-L, had soil detachment rates and cumulative sediment yields that show increasing soil erosion over the duration of the one hour simulations, and thus reflecting degradation of these treatments over time. For Vital Bon-Matt Stonewall this degradation was caused by small holes in the application that were soon enlarged by rainfall impact, allowing the exposed loess to then rapidly erode. For the WRD-L treatment, small gaps and potential solubility of the product likely contributed to this acceleration in erosion throughout the simulations. Although runoff initiated rapidly from these two treatments, both of these treatment types aided infiltration by maintaining surface soil structure and reducing surface sealing caused by dispersion. Visual assessment of runoff from test plots treated with Vital Bon-Matt and WRD-L contained suspended sediment particles of sand, silt and clay sized fractions.

The replicate rainfall simulations showed that there was variation in the detachment rate curves and cumulative sediment yield between rainfall simulations within the same treatment type, despite relatively similar discharge rates. This within-treatment variation could have numerous origins ranging from slight variation in the treatment application, plot slope, test soil density, antecedent test soil moisture content and environmental conditions during simulation. Of these variables, it is likely that the application method and thus final coverage of the treatment had a large part to play in the variability in tests. Coconut RECP mat was the one treatment type that allowed for the least variation in application, due to the fact that the mat is laid out in one continuous roll across the plot, and subsequently there was the least variation in results between the three rainfall simulations. In contrast, hydraulically applied products such as Vital Bon-Matt Stonewall and WRD-L had an obvious variation in the coverage of the spray application, which was reflected in the results. This indicates the importance of ensuring complete coverage of the treatment type in order to achieve maximum results. Because the modeled or intended sediment yields for construction sites are based on ideal (i.e., or optimal) performance standards, if the application does not meet these optimal standards then the increased sediment yield will put additional pressures on secondary downslope sediment retention/treatment devices (if indeed there are any).

Despite the reductions in soil erosion from test plots by the treatments tested, all but two sediment concentrations (g/L) measured in runoff samples collected during this experiment still exceeded typical consented limits for construction phase stormwater discharge (typically 0.1 to 0.15 g/L). This finding reflects the importance of having downslope treatment devices given that primary erosion protection treatments, whilst shown here to be effective in reducing sediment yields, are still not sufficient to reduce sediment concentration in discharges from loess subsoils to acceptable levels. For larger earthwork and construction sites such treatment devices would include appropriately sized sediment retention pond and the associated use of chemical treatment (flocculation). Increased runoff rates (coefficients) for loess slopes should be accounted for in any downslope sediment control systems to ensure adequate sizing of these devices.

4.1 EROSION CONTROL TREATMENT SELECTION

As each erosion control treatment has unique physical properties, different erosion control situations will require different treatment types, depending on the site conditions. For example while this study has shown straw to be effective at reducing sediment yields because it is not a fixed-down product, it could be susceptible to redistribution by wind; and as such may not be appropriate for exposed sites. In contrast, spray-on products would prove useful on steeper or more exposed slopes where straw or mulch may not hold. As a result of these considerations, a combination of erosion control treatments will likely be required to protect sites over the duration of soil disturbance.

Another important consideration for erosion control is the need for both short–term or long–term erosion control solutions. Short–term control is needed on sites where construction activities are ongoing and short term protection is needed between site staging. For sites in their final stages of construction (or abandoned sites) long-term erosion control treatments are needed prior to the establishment of vegetation and eventual site stabilisation.

4.2 CURRENT CANTERBURY PLANNING FRAMEWORK

The current operative regional plan to manage land and freshwater resources in the Canterbury Region is the Canterbury Land and Water Regional Plan (LWRP). The purpose of this plan is to identify the resource management outcomes or goals (i.e., objectives) for managing land and water resources in Canterbury to achieve the purpose of the Resource Management Act 1991. The LWRP identifies the policies and rules needed to achieve the objectives, and provides direction in terms of the processing of resource consent applications. The LWRP recognises that land and water are taonga to Ngai Tahu, and the life-giving and life sustaining properties of water are intrinsically linked to spiritual, cultural, economic, environmental and social well-being.

Objectives and policies focus on maintaining or improving water quality, and are consistent with the requirements in the National Policy Statement for Freshwater Management 2014. In terms of rules, Plan Change 4 of the LWRP introduced a rule cascade specifically to address the discharge of construction-phase stormwater into land and surface water. Conditions of this rule limit the amount of disturbed land the discharge is generated from. The limit for High Soil erosion risk areas (i.e., areas such as the Port Hills) is 1000m^2. Given the results of this study, sediment yields from this amount of exposed loess subsoil could be substantial. The conditions of these rules also set maximum limits of the concentration of total suspended solids in the discharge.

The Canterbury Water Management Strategy (CWMS) was developed to foster a more collaborative approach to the management of water within the Canterbury region. The strategy is based on collaboration and integrated management to maximise opportunities for the community, environment and economy within a framework of environmental sustainability. The strategy encompasses the interests and perspectives of many stakeholders and interest groups considering cultural, social and environmental perspectives in managing water resources. The strategy is led by the Canterbury Regional Council, Ngai Tahu and Canterbury's District and City Councils, and seeks to empower local communities to find solutions and prioritise local water issues. Canterbury is divided into ten zones each with a zone committee. The Port Hills fall within the Christchurch West Melton zone, the committee regularly brings local people together to contribute to workshops and meetings. Committees are guided by the targets agreed to in the Strategy and Zone Implementation Program (ZIP) and are tasked with making recommendations for the best way to manage water in their area. Councils are tasked with putting these recommendations into action with the help of other groups and agencies.

The Cashmere Stream catchment has been identified as one of four priority catchments by the Christchurch West Melton Zone Committee. As a key work program to achieve targets in the Strategy and ZIP, the committee has agreed to work with the Cashmere Stream Care Group, landowners and practitioners to identify effective measures to reduce sediment discharges. A highlight of this work has been the undertaking of this study.

In auditing resource consents for developments on the Port Hills statutory direction is sought from the National Policy Statement for Freshwater Management (NPSFM) and the LWRP, however consideration of the targets in the CWMS and ZIP are additional considerations in decision making.

4.3 REVISED APPROACH TO EROSION CONTROL

The findings of this study, along with the direction of the LWRP and targets in the CWMS discussed above, has highlighted the importance of good erosion control, as once loess becomes suspended in water, it is extremely difficult to manage, resulting in poor water quality and degraded ecological health. This has informed an update of the 2007 Environment Canterbury Erosion and Sediment Control Guidelines.

The new guidelines titled 'The Erosion and Sediment Toolbox for Canterbury' is being released in March 2017. The toolbox covers a range of topics and gives readers an understanding of why erosion and sediment control in the Port Hills is significantly more challenging than when working in flatter areas. The toolbox has been informed by the findings of this study and urges users to "not disturb what can't be managed", "to manage what you disturb" and highlights the importance of ongoing maintenance and monitoring of erosion and sediment control measures as keys to success. The guidelines also suggest that a blanket approach to erosion control may not be appropriate and users should consider a range of available options.

A flexible approach is needed when consenting and managing erosion from earthworks and construction sites. Flexibility in approach also encourages innovative methods for erosion and sediment control. In terms of auditing resource consent applications, all applications for earthworks on the Port Hills are considered 'high risk'. The applicant is required to supply an erosion and sediment control plan of how they propose to mitigate the effects of the construction phase activities with their consent application. At this stage, the plan is not fixed as it may require modification as the development progresses, in order to apply more relevant and effective mitigation. In terms of conditions of the resource consent, the consent holder is required to submit a revised erosion and sediment control plan to Canterbury Regional Council-Compliance and Monitoring Team for certification prior to works at the site commencing. Depending on the site and sensitivity of the receiving environment, a pre-construction meeting with the Canterbury Regional Council may also be a requirement. This establishes a productive relationship between contractors and council staff early in the construction stage to support good practice.

Due to the high risk status of earthworks on the Port Hills, an applicant's proposed erosion and sediment control measures are the focus of the consent audit. This results in conditions being placed on the consent to limit the area of loess soil able to be exposed at any one time, to manage the risk of a sediment–laden discharge beyond the boundary of the site. Resource consents resulting in a discharge of stormwater to surface water on the Port Hills also requires the inclusion of a water quality monitoring regime to measure compliance with water quality limits included in the conditions.

Water quality limits included in resource consent conditions for Port Hills developments are likely to only be achievable with both the use of appropriate erosion control measures as well as the aid of chemical flocculants dosed at appropriate rates into a sufficiently sized sediment retention pond. The use of chemical flocculants requires the need for a proposed Chemical Treatment Plan to be provided with the consent application and as part of the consent conditions. The Chemical Treatment Plan requires a documented flocculant bench test to be completed by a suitably qualified person. Also required in the Chemical Treatment Plan is the dosing method and rate, flocculant specifications, mixing technique and pond design. This is intended to reduce the trial and error dosage approach commonly encountered in the past.

5 CONCLUSIONS

The adverse effects of discharges of stormwater containing loess sediment as a result of earthwork developments on the Port Hills in aquatic receiving environments is significant. Results from this study show untreated loess plots had an average sediment yield of 3,726 g/m^2 over a one hour long 29 mm/hr simulated rainfall event. All five erosion and control treatment tested in this study reduced sediment yields in comparison to the bare loess control plots. Of these, four of the five treatments were considered to be most effective in reducing erosions and sediment runoff from test soil plots. The average reduction in sediment yield (i.e., soil loss) compared to the control plots were (in decreasing order of efficiency) 95% (coconut RECP mat), 94% (straw), 90% Vital Bon-Matt Stonewall) and 86% (topsoil). The WDR-L performed to a lower standard, achieving a 48% average reduction in soil loss compared to soil plots.

Despite the reduction in sediment yield through the use of these erosion control measures, there was still a reasonable sediment yield, which resulted in suspended sediment concentrations generally in excess of accepted limits for construction-phase stormwater discharges. This highlights the need to always include sediment control (i.e., downslope treatment devices) along with erosion control measures at a site. Given the dispersive properties of loess soil in water, any sediment control measures would require the use of flocculants to remove the finer soil particles from the water. The study also shows that even small exposed areas can be significant sources of erosion, meaning that it is essential to cover any area of exposed loess.

Based on observations made during rainfall simulations, variation in the application of erosion control treatments had an influence on soil detachment rates and sediment yields, with greater detachment rates and sediment yields where application was less than optimal. This indicates the importance of ensuring complete coverage of the treatment type in order to achieve the maximum results, particularly given that application is one environmental variable within complete control of the contractor. Because the modelled or intended sediment yields for construction sites are based on ideal (i.e., optimal) performance standards, if the application does not meet these optimal standards, then the increased sediment yield will put additional pressures on secondary downslope sediment controls (i.e., retention/treatment devices). Effective erosion control also relies on selecting the treatment appropriate to the site conditions and staging of the construction (i.e., short term versus long term erosion control measures).

Findings of the study have also been useful in developing innovative construction-phase discharge consent conditions, which are flexible enough to be applied during site development while achieving objectives, policies and water quality outcomes set in the Canterbury Land and Water Regional Plan and other planning documents.

As a result of this study and an increase in development pressure in the Port Hills area, the Canterbury Regional Council has amended their approach to providing advice on and auditing resource consent applications for such proposals. The upcoming Erosion and Sediment Toolbox for Canterbury will provide contractors, engineers, consultants, developers and council staff with better advice to more effectively manage Port Hills soils under various rainfall conditions. Over time, minimising the input of loess runoff into surface water bodies will result in an improvement in water quality and ecology in these valued receiving environments, including Cashmere Stream, Opawaho/Heathcote River and Avon Heathcote Estuary/Ihutai.

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REFERENCES

Adamson, T. (2016) Erosion control treatment trials on Port Hills loess: Cashmere catchment 2016. EOS Ecology Report No. ENV0115035. EOS Ecology, Christchurch. 76 p.

Environment Canterbury 2007. Erosion and Sediment Control Guidelines. Environment Canterbury, Christchurch.

Fitzgerald, P. (1966) Soils of Heathcote County, Canterbury, New Zealand. New Zealand Soil Bureau Report 1/1966. 33 p.

Griffiths, E. (1974) Soils of part of the Port Hills and adjacent plains, Canterbury, New Zealand. New Zealand Dept. of Scientific and Industrial Research, Wellington 36 p.

Huges, P.J. (1970) Tunnel erosion in the loess of Banks Peninsula. Unpublished Thesis, University of Canterbury.

James, A. & McMurtrie, S. 2009. Sources of sediment input into Cashmere Stream. EOS Ecology, Christchurch. EOS Ecology Report No. 08031-ENV01-01. 54 p.

Jowett, T.W.D. (1995) An investigation of geotechnical properties of loess from Canterbury and Marlborough. Unpublished thesis, University of Canterbury.

McMurtrie, S. & James, A. 2013. Cashmere Stream - reducing the pressures to improve the state. EOS Ecology, Christchurch. EOS Ecology Report No: 10049-ENV01-01. Environment Canterbury Report No. R13/20. 50 p.

Pye, K. (1995) The nature, origin and accumulation of loess. Quaternary Science Reviews 14(7):653-667.

Raeside, J.D. (1964) Loess Deposits of the South Island, New Zealand, and Soils Formed on them. New Zealand Journal of Geology and Geophysics 7:4:811-838.

Tonkin, P.J.,Runge, E.C.A. & Ives, D.W. (1974) A study of Late Pleistocene loess deposits, South Canterbury, New Zealand. Quaternary Research 4(2):217-231.

Trangmar, B.B. & Cutler, E.J.B, (1983) Soils and erosion of the Summer region of the Port Hills, Canterbury, New Zealand Soil Bureau, Dept. of Scientific and Industrial Research, Lower Hutt. 52 p.