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Hydrological Effect of Compaction Associated with Earthworks

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Hydrological Effect of Compaction Associated with Earthworks

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1 Executive Summary

Project and client

Auckland Regional Council's (ARC) Stormwater Action Team engaged Landcare Research to assess the implication of soil compaction associated with earth work for large urbanised greenfield sites in Auckland. The work was carried out over 2006 and 2007.

Objectives

- Review literature on physical characteristics of urban soils, particularly those affecting their capacity to mitigate stormwater run-off issues.
- Review the basis of the Soil Conservation Service (SCS) method as amended for Auckland.
- Recommend strategies that would increase the accuracy of the SCS approach to modelling run-off, and methods of managing soils and pervious open space in urban areas that would increase their ability to mitigate urban stormwater run-off issues.

Methods

Several large subdivisions on greenfield sites were visited to identify current earthworks practice. Literature was reviewed, focusing on the unique and common properties of urban soils with particular emphasis on compaction, infiltration, permeability and stormwater run-off.

Results and conclusions

- Typical earthworks for large greenfield sites and semi-intensive residential subdivisions in Auckland involve stripping of topsoils and non-compactable materials from the entire footprint, excluding perennial streams with their riparian margins. Stripped areas are often recontoured and deliberately compacted to ensure they are geotechnically stable.
- Total and peak stormwater run-off from urban areas is typically increased due to increased areas of impermeable surfaces, accentuated where these surfaces are piped directly to watercourses. Run-off from residual soils also increases due to reduced soil water storage, subsoil permeability, and sometimes decreases in topsoil infiltration rate. All are related to compaction and/or surface stripping. Effects are accentuated when earthworked topsoils are degraded and/or shallower than original topsoils (ie before earthworking). Changes are marked for soils that were originally highly permeable but may be negligible for originally slowly-permeable soils. These changes in soil physical properties are reflected in run-off from small rainfall events that did not generate run-off in pre-development situations; and a higher proportion of winter run-off. Run-off from very large events (1 in 100) may not be vastly different.

- SCS curves have been adapted to Auckland soils (Auckland Regional Council 1999) through choice of an Initial Abstraction value (Ia), selecting three hydrologic classes to represent the major Auckland soil groups, and adapting run-off curves for a range of vegetation cover and land uses. The Ia chosen is conservative and applicable to earthworked sites, with the maximum retention before run-off being 25 mm. SCS curves for hydrologic Class C (Waitemata lithologies) are probably relatively accurate, particularly for imperfectly and poorly drained soils. However, SCS curve numbers for hydrologic Class A (granular volcanic loams) and sandy hydrologic Class B soils are overly optimistic given the large reduction in subsoil permeability, particularly where earthworked topsoils are thinned and degraded, or cuts expose underlying impermeable subsoils. Run-off, particularly in winter, may be underestimated.
- The options for improving permeability and water storage capacity of earthworked soils depend on soil hydrologic group, with most certain results for volcanic loams and least certain results for clay soils derived from Waitemata lithologies. In the latter case, the least risky mitigations are probably to increase topsoil depth, create surface detention volume and build bioretention devices using imported substrates.

Recommendations

Maintaining near-natural volumes (size) and frequency of surface run-off is the overall aim of the Auckland Regional Council. Four ways to achieve this are to (1) manipulate SCS curves for Hydrologic Class A and B soils to reflect decreased storage on large earthworked sites; (2) minimise areas that are stripped of topsoil and contoured, especially areas of highly permeable soils and natural water storage; (3) minimise both the total area covered in impervious surfaces and the proportion of impermeable surfaces directly piped to watercourses; and (4) maximise infiltration, permeability and storage volume of residual permeable surfaces (verges, gardens, parks) and areas not requiring high bearing capacity (sections, driveways and some parking areas).

General recommendations are followed by options to **avoid** or minimise soil degradation and options that **ameliorate** degraded soils or **mitigate** for degraded soils. The key options should be stratified by probable effectiveness and likelihood of uptake. A reduced set of preferred options can then be demonstrated and benefits quantified. General recommendations are to:

- assume all earthworked sites are equivalent to SCS Hydrologic Class C;
- better define run-off from urbanised cut/fill sites by monitoring stream flow and stormwater pond discharge volumes in sub-catchments with Hydrologic Classes A and C;
- identify hot-spots where maintaining or improving permeability has the greatest benefit. In particular, identify areas within Waitemata Formation (Hydrologic Class C) with moderate to high permeability, and promote their use for mitigating stormwater run-off; and

- quantify the impact of changing earthworked sites to Hydrologic Class C on the size of run-off control devices, and amending the base condition of Class C areas containing permeable soils.

The strategy of **avoiding degradation** is suited both to larger subdivisions with permeable soils and/or wetlands and to individual sites in older suburbs, particularly where houses are established on piles, and can include the following:

- In sites with Hydrologic Class A, sandy Class B soils, and wetlands, restrict earthworks to roads and building footprints, and avoid trafficking areas for stormwater disposal and passive recreation.
- In extremely sensitive areas, build houses on piles (not slab on grade) to avoid cut/fill.
- Exclude root systems of existing large trees from traffic and protect against later compaction. This approach is already used in small sections, and could be expanded to areas receiving run-off.

Amelioration and mitigation can take the following forms:

- Increase the depth of topsoil applied to road verges and/or amend topsoil with compost to increase water storage volume and permeability.
- Encourage dense, tall plant cover on public areas by managing mowing height and increasing tree canopy cover. Large trees require a substantial rooting volume – this could be achieved by manipulating road verges and/or including favourable (structural) soils under footpaths.
- Promote lateral movement of water across compacted subsoils to an under drainage or retention system to shorten the saturation period, thereby increasing retention capacity.
- Increase permeability and water storage capacity of residual, permeable areas around houses by:
    a. ripping, subsoiling or cultivating, well- to imperfectly drained subsoils to relieve compaction and the sharp textural contrast typical of replaced soil profiles;
    b. aerating using hollow tines and backfilling with organic matter or sand; and
    c. amending topsoils with compost.
- Require footpaths, driveways and paved surfaces around houses to have minimum permeability and detention storage volume.
- Replace soil in radial trenches around existing trees in compacted road verges or parks to maximise tree root volume, evapotranspiration, longevity and canopy cover (rain interception).

2 Introduction

Auckland Regional Council's Environmental Programme Team engaged Landcare Research to assess the accuracy of Soil Conservation Service (SCS) curve values for large urbanised greenfield sites in Auckland. The work was carried out in 2006 and revised in 2007.

2.1 Reason for this review

Urbanisation – the transformation of land to residential, industrial or commercial uses – is associated with increased stormwater run-off, largely due to an increase in impervious surfaces and hydraulically efficient pipes connecting impervious surfaces to surface waters. This increased stormwater volume (even from small events) and speed of run-off modifies stream channels, generally increasing stream erosion and downstream flooding risks, and degrading both aquatic and riparian environments. Auckland Regional Council (ARC) is charged with protecting Auckland's environment. A key policy to protect watercourses in urbanising areas is to require subdivisions to not increase peak-flow volumes discharged to watercourses up to a specified storm event size. The US Soil Conservation Service (SCS) model is currently used to estimate run-off volumes and size flow detention devices such as ponds and infiltration devices (eg rain gardens and swales) (Auckland Regional Council 1999). Research indicates soil infiltration and storage properties are significantly degraded during subdivision so that some compacted pervious areas can approach the infiltration behaviour of impervious surfaces (eg Gregory et al. 2006).

Auckland Regional Council requested Landcare Research to assess the likely accuracy of the current SCS curve values in modelling run-off volumes from large "greenfield" subdivisions in the Auckland Region by reviewing published and unpublished research, and to recommend practical strategies that could reduce run-off volumes from urban areas, with a focus on enhancing soil infiltration and storage. Results of this review have implications for conventional subdivisions, through potentially requiring larger stormwater conveyance, retention and detention devices, and also for subdivisions adopting Low Impact Urban Design and Development (LIUDD) which typically minimise run-off by reducing impermeable areas and directing stormwater from impermeable areas to infiltration areas.

2.2 Methodology

Two Several North Auckland subdivisions were visited in summer 2005/06 to confirm current earthworks practice. The assessment confirmed key practices likely to affect the hydrological cycle and soils, and allowed targeting of a literature review covering the following areas:

- Properties of urban soils, with a focus on infiltration and permeability of urbanised soils vs greenfields soils. Existing and unpublished Auckland soil data collected by Landcare Research from 1997 to 2003 was assessed, including comparisons of paired sites in Waitakere City of pasture and/or native forest with urban road verges or cut/fill sites.
- Key factors influencing the impacts of earthworks/subdivisions on soils and relationships between compaction, stormwater infiltration and run-off at discrete point sources and at a sub-catchment scale.
- The relationship between infiltration and stormwater run-off as embodied in the run-off curves in ARC Technical Publication 108 (ARC 1999).
- Techniques for ameliorating degraded soils and enhancing soil properties important for stormwater management such as infiltration, moisture storage and detention. The results are described from four Auckland trials:
    - An investigation of the effectiveness of adding sand to increase permeability of a clay soil (Ultic Soil, hydrologic class 3) from North Shore.
    - Ripping and mulching compacted soils in Waitakere City riparian parks.
    - Ripping compacted clay soil (Granular Soil) in Pukekohe market gardens.
    - Ripping undisturbed and compacted clay soil (Ultic Soil) in Riverhead Forest.

The review does not include any new field measurements of infiltration, as the impacts of earthworks were considered to be severe and no existing “subdivision” practices were identified that aimed to ameliorate compaction.

3 Impacts of Earthworks on Streams

3.1 Observations from site visits

In December 2006 North Shore City subdivisions adjacent to Schnapper Rock Road and Otehi Valley Road, were visited, including the large, multi-year Oakway subdivision. These subdivisions were regarded by Auckland Regional Council as including earthworks typical of semi-intensive subdivision on rolling landscapes in Auckland. The aim of the visits was to identify both the main pressures associated with subdivision that affect infiltration rates and the volume of water stored in the soil profile, and key areas where infiltration could be enhanced post-development.

Oakway subdivision was covered with Ultic Soils, some of which were used for growing strawberries, and had deeper topsoils and better drainage than typical of most Ultic Soils. A small stream with riparian vegetation of mature kanuka and young totara (3–5 m tall) receives stormwater from the subdivision through a single discharge point from a pond at the bottom of the site. As with many modern subdivisions on rolling topography, most of the site is terraced, and retaining walls (Figure 1) are used to create level, elevated sites and maximise views. Houses will have rain tanks, and all roads and drains behind each retaining wall will be piped to the pond. Topsoil, and any other materials with poor compaction characteristics[1], was removed before the site was cut and filled. The whole site, excluding the riparian zone, was deliberately compacted to achieve specified levels to support road and house foundations before 100–150 mm of topsoil was temporarily replaced on the compacted subsoil. The majority of this topsoil is then removed when individual houses are built, with a house and its paved areas likely to cover 60–70 per cent of each site. The Oakway subdivision used lime stabilisation; however, this was limited to the road footprint and difficult sections (the technique is expensive), so is likely to have a very minor impact on site-wide infiltration.

Typical compaction pressures are likely to be similar across Auckland, as all subdivisions must meet the same compaction standard to support concrete slab building foundations[2]. This compaction standard generally ensures infiltration and permeability of the subsoils is negligible, particularly on fill sites where multiple layers of compaction prevent continuous pores and movement of water into subsoil. The original deep, freely-draining soil profiles are generally lost and topsoils – the best-drained and water-retentive material – degraded and redistributed. Compaction pressures on topsoils are highly variable, depending on the type of machine that strips and spreads the topsoil, the moisture content at the time of spreading and during subsequent trafficking, and to what extent (and by what) the topsoil is trafficked after

[1] Substrates with poor compaction characteristics include peaty or organic-enriched colluvium often associated with seepage zones, the base of historical slips and ephemeral watercourses ("mullock"). Within the dominant Ultic Soils that overlying Waitemata geology are also small areas of soils high in the clay mineral Allophane – these also have poor compaction characteristics (Ross 2007).

[2] One of the few exceptions would be subdivisions on peat soils.

spreading. In some cases, topsoils are friable[3] with high permeability and support vigorous temporary grass/clover swards; however, in many cases topsoil is partly mixed with subsoils. This reworked topsoil typically supports a low-density sward that becomes dominated by clover and flatweeds – plants indicative of low nitrogen levels and compaction. Such swards are particularly common where subsoils are of low quality for plant growth, eg many Ultic Soils.

Figure 1
Terracing at Oakway subdivision, North Shore, creates alternating truncated and filled soil profiles. Soils are mainly fine-textured, Ultic Soils on Waitemata Group geology. Pale soil colours often indicate low organic matter contents associated with degraded soils.

3.2 Impacts of urbanisation on soil

The properties of topsoil and upper subsoil layers containing the majority of plant roots largely control a soil's response to stormwater. While undisturbed soils reflect underlying pedogenic processes, urban soils often reflect the method of their disturbance, as a large proportion of urban soils are truncated, added to (fill, gravel, sand, compost), compacted and/or drained. Soil-forming factors have little time to act on urban soils so profile development is often weak (ie AB soil horizons may be thin to absent). The most altered soils are found on terraced landscapes, poorly drained soils, and under roads or slab-on-grade buildings.

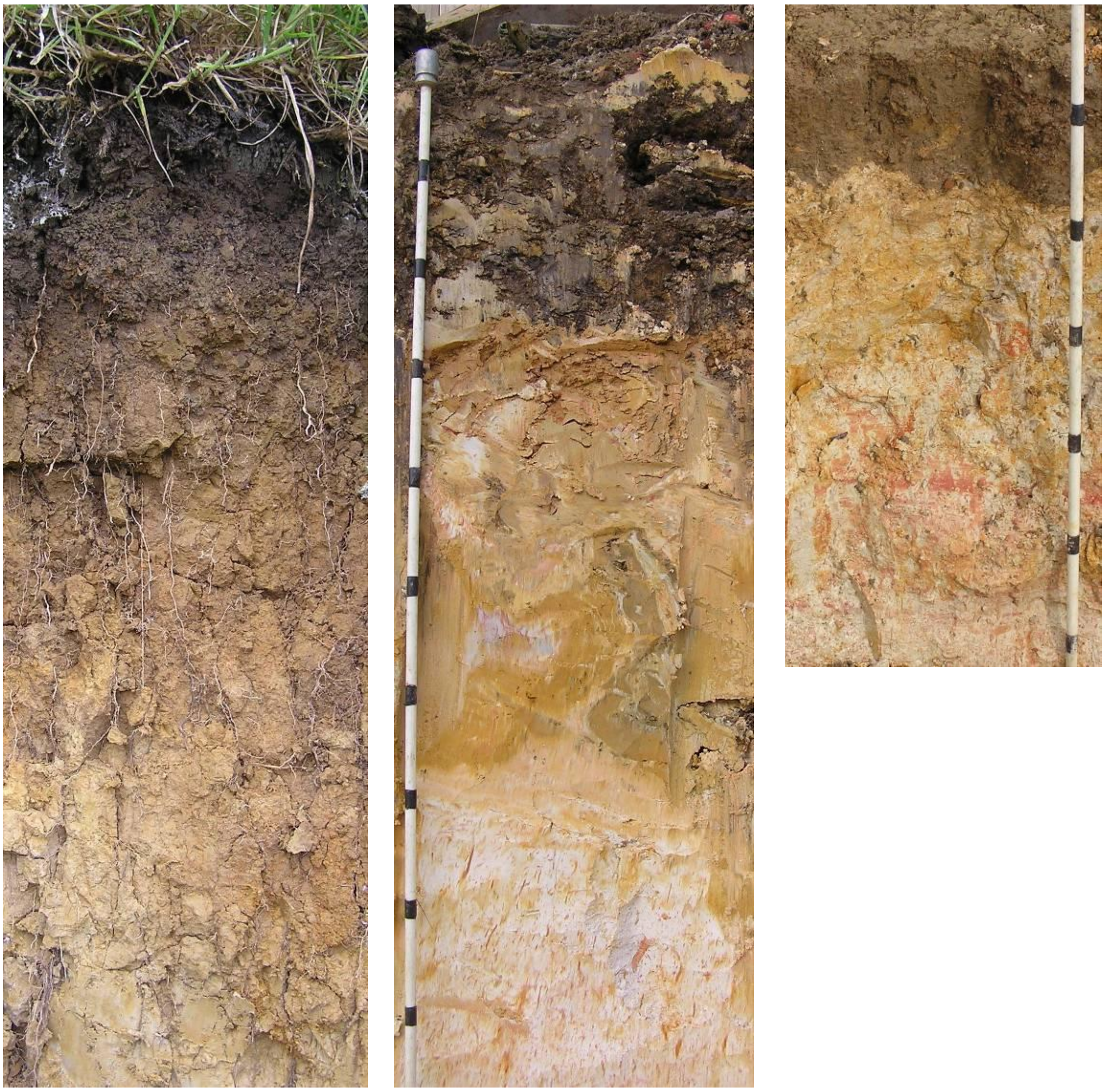
Urban soils typically show abrupt changes both vertically (Figure 2) and spatially – they lack the horizontal continuity typical of natural soils, instead showing sharp interfaces between different soil materials. Despite this variability, urban soils are typified by low porosity, high bulk density (Yim & Ng 2000), and low infiltration and permeability rates

[3] Sometimes soils are sieved before being replaced on site.

– all of which are related to compaction. Urban trees affected by compaction typically have reduced root growth and rooting depth and increased lateral rooting (Schleuss et al. 2000; Smith et al. 2000); increased surface rooting increases footpath heaving. The lack of usable volume for root growth is seen most severely in pot-bound street trees with root girdling (Craul 1992) and increased risk of toppling. Compaction is reflected in poor tree performance, ie lower canopy height, shorter life and greater vulnerability to drought.

Figure 2

Impact of typical earthworks associated with subdivision on an Auckland Ultic Soil. The natural soil with gradual transition to pale-coloured subsoils (left) is replaced by truncated soils with sharp transition to impermeable, compacted subsoil (right two profiles). Photos by Craig Ross, 2007.



Water tends to pond on top of the least permeable (most compacted) soil layer creating a perched water table. Water also ponds upslope of barriers to drainage paths, such as foundations, roads, retaining walls and footpaths. This localised ponding is partnered with localised drying downslope of barriers and where flows are piped.

Together these create hydrologic discontinuity. This impact is particularly severe in areas with perched water tables, such as many Ultic Soils (Waitamata geology), where winter rainfall naturally flows laterally through topsoil above the subsoil. Normal hydrological surface flows from high to low points on the landscape are also disrupted. Together these disruptions can alter locations of springs and ephemeral waterways (Hazelton & Beecham 2000).

Many urban pressures contribute to compaction, which is visible as massive or platy soil structures (Figure 2). Earthworks, ie soil stripping, stockpiling and spreading by machines, and deliberate compaction with rollers are the main causes of compaction. Low-ground-pressure tracked vehicles such as hydraulic excavators and bulldozers compact the ground less than high-ground-pressure wheeled vehicles. The key factors that make a soil vulnerable to compaction are:

- A well-graded particle size distribution (silt loam), with a high fraction of silt and fine sand.
- Absence of a protective surface layer of dense vegetation, mulch or leaf litter as these materials absorb and disperse compactive force.
- Low initial bulk density or high macroporosity (no prior compaction). This is why most compaction is achieved in the first few machine passes in many soils.
- Low proportion of iron and aluminium oxides and clays rich in kaolin or smectite, eg Ultic Soils and Recent Alluvial Soils.
- Low organic matter (carbon). Soils with low carbon contents often have weak aggregates (organic matter is a key "glue" in aggregates) and low elasticity – the ability to bounce back from an applied force.
- Weak structure. Multiple handling of soil materials and intensive cultivation using rotary hoes degrades and weakens soil structure.
- Low biological activity, particularly earthworms and other macro-organisms that improve soil structure and create large drainage pores.
- Moderate moisture content. Soil bearing strength decreases with increasing soil moisture content, with maximum compaction often achieved about "field capacity". Saturated soils cannot compact, as water is not compressible, but they do deform, loosing structure.

The organic matter content of a soil affects many properties. Soils with low carbon levels are generally less stable, hold less water, and are more vulnerable to physical degradation as organic matter acts a "glue" that stabilises soil aggregates. Mixing of topsoil and subsoil during stripping lowers the organic matter content of topsoil. This is exacerbated if soils are not planted and/or if clippings and leaves are removed, as both reduce nutrient cycling and restrict soil biological activity, eg, earthworms.

Soil temperature regimes are altered in urban areas that have a high proportion of impermeable surfaces, as a lot of heat is adsorbed and re-radiated by roads and buildings. The greater heat loading elevates both day and night temperatures. Heat flux is generally vertical in natural soil but may be horizontal in urban soils, contributing to increased evaporation, plant water use and moisture fluctuations. The effect of warmer soils can be reflected in fungal communities. Marfenina (2000) reported the diversity of fungi in arctic cities resembled those of southern fungal species; with artic cities containing more species able to grow in >37°C and more potentially pathogenic micro-fungal species. The concentration of exotic plant, insect and animal species in our cities and the removal and fragmentation of native communities infer soil microbial communities are also likely to differ in both diversity and species structure from natural soils. Higher soil temperatures, build-up of thatch (undecomposed dead grass due to lower biological activity) and exudates from fungi can also result in localised development of water repellency (hydrophobicity) and surface run-off.

New Zealand soils are typically acidic. However, urban soils often have elevated pH from calcium-containing building materials such as concrete, mortar and plaster. Heavy metal concentrations (zinc, copper and lead) also tend to be higher in soils near busy roads due to road dust deposition; along with nitrogen and sulphur levels (from car exhaust).

New Zealand urban soils differ from those in northern Europe and North America in being largely unaffected by salt and other substances used to de-ice roads. Likewise, as coal is not a major source of energy for heating homes in most New Zealand cities, our soils tend to have low levels of coal ash. However, in Reefton or Christchurch where coal fires are prevalent, such ashes can create a wide C:N ratio that does not reflect the quality of the humic substances (Bretzel & Hitchmough 2000; Schleuss et al. 2000). "Cultural" layers in New Zealand soils are generally shallow or absent. In contrast, St Petersburg's "culture layer" extends to 2 m depth, and is even deeper in cities dating back to the Bronze Age or earlier, as in some Chinese cities. Soils in European cities affected by bombing in the Second World War can contain high proportions of rubble, for example, brick makes up over 80 per cent of the volume of an urban Berlin soil (Sukopp et al. 1979).

In the past, the absence of large earth-moving machinery meant drastic land recontouring was minimised. Instead, piles were used to establish building platforms for villas and bungalows. In such subdivisions, the hydrology is not so disconnected, trees have large rooting volumes, and in some cases large native earthworms have persisted in subsoil. The impacts of modern cut/fill urbanisation are particularly detrimental because they are large and essentially permanent changes. Natural amelioration is even slower than in non-urban sites due to traffic vibrations and low organic matter inputs.

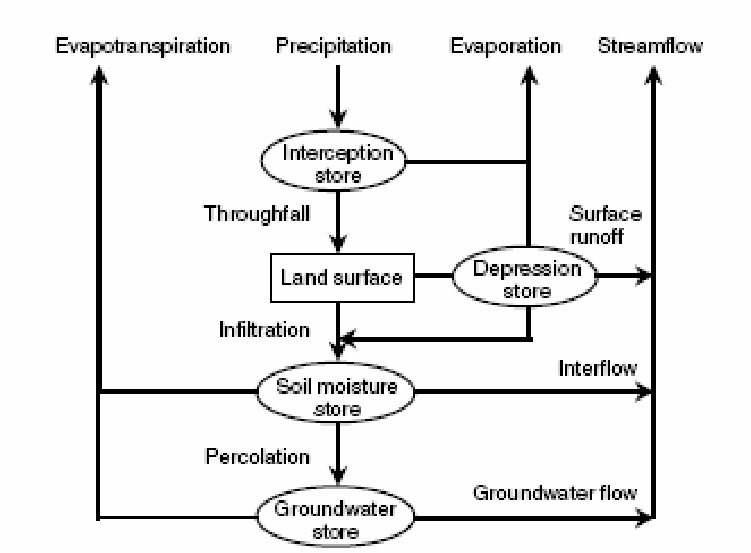
3.3 Urbanisation, compaction and the hydrological cycle

Many overseas studies identify four main drivers of hydrological changes in cities. The first driver is an increase in impermeable or largely impermeable surfaces, ie roads, footpaths, houses (roofs), carparks, and driveways (Figure 3). Rain hitting these surfaces runs off quickly, although evaporation from and infiltration to some surfaces can be significant, especially for small summer events (Mansell & Rollet 2006). However, recent research suggests the most important driver of hydrological change is the proportion of impervious surface directly connected to watercourses with pipes

(Walsh et al. 2005), as a high, hydraulically efficient connectivity means even small rainfall events (1–2 mm) can produce sufficient surface run-off to degrade watercourses. A third driver of hydrological change and increased run-off is removal of wetlands, as these can be key water storage buffers (Kaufman & Marsh 1997). Auckland has been affected in this way. The isthmus was historically characterised by many swamps where water was trapped between lava flows – most of these wetlands were filled or drained as the city expanded, eg large swamps and ponds lay around Eden Park, and across Khyber Pass west of Newmarket; the latter were filled in with rock quarried from Mount Eden (Esler 2004). The fourth driver of hydrological change and increased run-off in cities is loss of vegetation, especially when the prior vegetation was forest. The greater Auckland region was densely forested before European colonisation. The Auckland isthmus, however, was largely converted to fern during Maori occupation; William Colenso writing in 1842 "there are not any forests in this locality; the eye wanders over a succession of low volcanic hills bearing nothing but monotonous brown fern and here and there a shrub [of tutu] rising a few feet" (Esler 2004). In this section the features of a general hydrological cycle are described, first at a point-scale and then at a catchment or sub-catchment scale. Urbanisation affects all of the components of the hydrological cycle shown in Figure 3.

Water that falls onto a city in a storm event may never reach soil for three reasons. First, it may fall on an impermeable surface, where it either evaporates or runs into a piped stormwater infrastructure and direct to pond, watercourse or harbour. Second, rain may be intercepted by vegetation. Trees can intercept a significant proportion of rainfall that is then evaporated from leaves and stems. Even groundcovers and long grass can hold significant volumes, eg cup-shaped plants can hold several litres of water per square metre within their foliage. Third, rain may be retained in organic mulches or fibres above the soil surface. Composts can hold more than 100 per cent of their weight in moisture (litres of water per square metre). In all cases the interception is most significant in summer, low-intensity events with dry antecedent conditions.

Figure 3
Simplified model of water flows. Urbanisation affects every part of the hydrological cycle (from Liu et al. 2006).



Rain that reaches the soil surface can infiltrate, run off or evaporate. Infiltration rates are highest for soils with a large volume of air-filled[4], interconnected pores that are open to the surface. The more continuous the pores, the further and faster water flows down into a soil profile. Auckland soils derived from volcanic materials (Granular, Melanic, Allophanic and some Brown Soils) and sands naturally have high volumes of air-filled pores (c. 15–30 per cent v/v). Conversely, most Ultic Soils typically overlying Waitemata Sandstone have low volumes of large pores in both topsoil and subsoil (5–15 per cent v/v). In areas with surface-casting earthworms, infiltration rates can be an order of magnitude higher in spring and autumn when (worms are most active). If large pores are not open to the surface, water cannot enter the soil rapidly (Figure 4), which is why a thin skin or capping of eroded clay, silt or washings from cut concrete can prevent infiltration to an otherwise highly permeable soil. When the pores in a soil are water-filled, no more water can enter the soil, and surface run-off or ponding occurs until water drains from the base of the soil profile. This is why subsoil permeability is important. In truncated soils with no artificial drainage, infiltration from summer storms may initially be rapid but comes to a sudden stop when the topsoil is saturated (Figure 4). Water then ponds on the compacted subsoil, even though this subsoil may be relatively dry.

Plant transpiration and drainage remove water from the soil, increasing the rate pores become air-filled after rain. Biological activity and subsoiling or ripping generally increase the total volume and continuity of air-filled pores. Many Ultic Soils naturally crack in summer as they dry out – most run-off from late summer storms flows down these cracks (referred to as bypass flow) until they close up as the soil rewets in autumn. In undisturbed forest, decayed plant roots also form channels down which

[4] Air-filled pores are often referred to as macropores, and defined as pores >0.6 mm diameter, the volume of pores drained at 10 kPa tension.

water quickly infiltrate. In Auckland, lava tubes are the "ultimate" pore, transmitting very large volumes of run-off.

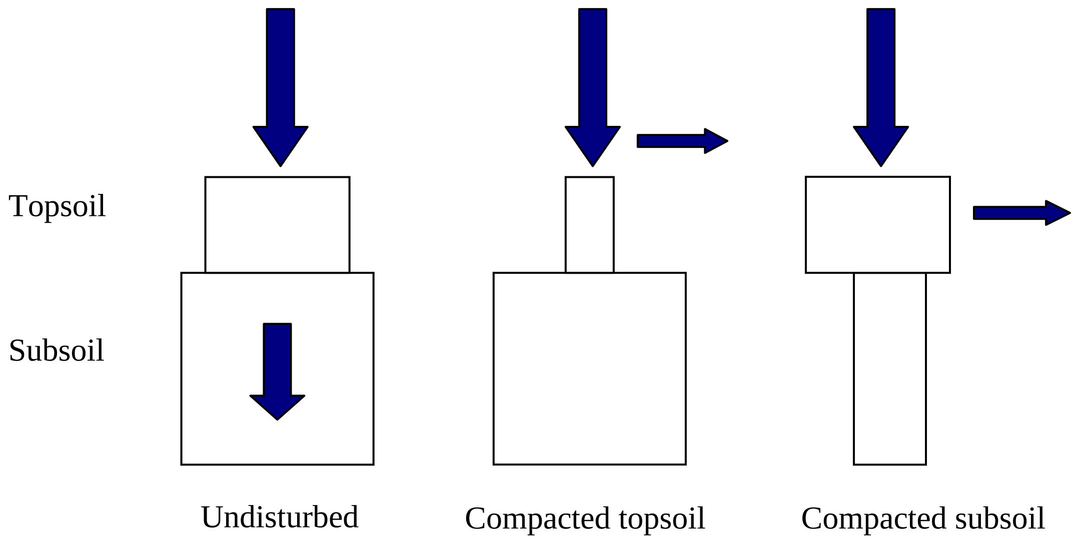
Water repellency can be a feature of excessively dry patches of soil, thatch build-up on grassed surfaces, sands, burned soils, and where there are high levels of soil fungi. Water repellency reduces infiltration rates, with the severity of the repellency dependent on antecedent rainfall; however, in Auckland repellency has only been observed in Recent Sands (eg in Woodhill Forest) and on some grassed areas, eg golf and bowling greens.

Run-off occurs when:

- rainfall intensity exceeds the rate water infiltrates into the soil;
- an area receives additional water from adjacent slopes, impermeable surfaces or tree trunks (trees can concentrate flows down their trunks);
- soil is saturated to the surface and rainfall intensity exceeds the permeability of the least permeable layer in the soil profile; and
- surface detention volume is full. Surface detention is usually highest on relatively flat, rough surfaces with thick organic mulches and dense vegetation.

New subdivisions and closely mown lawns often have smooth surfaces with minimal detention capacities compared with forests or pasture. Forests usually have a "dimpled" topography and in pasture stock treading and grass clumps create surface detention.

Figure 4
Both water storage capacity and infiltration rate need to be considered when looking at soils as a sink for stormwater. Each of the above "flasks" represents a soil where water flows into the top during rainfall. The flask of undisturbed soil on the far left has a wide neck, so can receive water at high-flow rates, and a large body which stores a large volume of water. The centre flask represents a site with compacted or sealed topsoil but loose subsoils. The narrow neck only allows water to enter at a slow rate – the rest of the water flows away as "run-off" and the storage capacity is not utilised. The flask on the far right represents a soil on a cut/fill site with heavily compacted subsoil. Replaced topsoil allows water to flow into the soil at a moderate rate, but the storage volume and permeability of the subsoil is reduced by compaction so water flows laterally over the replaced subsoil (as occurs in natural soils with a perched water table).



Subdivision activities usually reduce interception (vegetation is removed), surface detention, and stormwater infiltration. The main driver of change is compaction due to earthworks associated with subdivisions, particularly where the majority of the area is treated to structural support requirements (not just driveways, roads and house footprints). The greater the degree and extent of compaction, the greater the reduction in pore volume and the more run-off is generated. Severe compaction makes even highly pervious volcanic soils behave more like impervious surfaces. A second cause of reduced infiltration rates is the development of a thin crust of silt that seals the openings of pores. This is particularly common for soils without a cover of mulch or plants. Water storage capacity (the maximum depth of water that can potentially be stored in the soil profile) can be reduced by both compaction and truncation of the soil profile. Also, this storage capacity may never be reached if the infiltration rate (ie the rate at which water gets into the soil) is the limiting factor. In this case most water flows over the soil surface (Figure 4), so the soil does not become saturated.

Water infiltration and storage can be increased by changing any or all the above features. The following section identifies to what extent current subdivision activities have affected infiltration and soil moisture storage, while the final section identifies ways to manipulate infiltration and storage at different stages of subdivision – from avoiding earthworking areas (before subdivision) to retrofitting actions after houses have been built such as loosening soils.

Figure 5

Increase in impervious surface and decrease in tree canopy associated with urban subdivision is marked in this recent aerial photograph of South Auckland.

4 Infiltration and Permeability of Urbanised Soils in New Zealand

This section summarises New Zealand literature and case studies on the infiltration and permeability of urban soils. It focuses on the impact of compaction on soils not covered with buildings or roads – the residual, "pervious" and fragmented skin.

It is often assumed that infiltration rates of coarse soils, eg sands, are not greatly affected by urban development due to high bearing pressure and free drainage. However, United States data from Florida (Gregory et al. 2006) and Alabama (Pitt & Lantrip 1999) and New Zealand unpublished data for Taupo Pumice Soils and Recent Sands show these soils can be severely affected. Gregory et al. (2006) quantified the effect of various levels of compaction on a soil (92 per cent sand, <2 per cent clay) and concluded construction activity decreased the infiltration rate and increased the potential for run-off (Table 1), and the ground pressure of the equipment was not as important as whether compaction had occurred at all.

Pitt and Lantrip (1999) reported some sandy urban soils had low infiltration rates and therefore did not conform to established models. They found these soils in high-traffic areas such as school playing fields (due to compaction) and areas receiving sediment, such as swales. Pitt and Lantrip (1999) also found infiltration increased over time; an effect that may indicate natural amelioration where initial compaction levels were high – this rebound through the biological activity of a grass sward has been measured in New Zealand in earthworked sites, in paddocks pugged by animal treading, and in pasture leys following cropping.

Table 1

Effect of compacting a raw sand in Florida (Gregory et al. 2006).

Type of site	Average infiltration rate (mm/h)	
	Non-compacted sites	Compacted sites
Natural forest	377–634	8–175
Planted forest	637–652	160–188
Pasture	225	23

New Zealand data generally support the findings of overseas studies. Individual studies are reported below, including unpublished Auckland soil data collected by Landcare Research from 1997 to 2003 in NIWA and Landcare Research PGSF programmes. The former assessed the physical and chemical properties of grassed swales adjacent to the Northern Motorway near Silverdale; the latter compared soils under contrasting land uses, using pasture and/or native forest as an undisturbed "control" and road verges or urban sections as "urbanised". These data, those from Bennett (2000) for Albany, and a riparian reforestation trial in Waitakere City looked at Ultic Soils[5] and fine-

[5] Highly weathered, clay-rich soils that have low iron oxide content and are structurally weak.

textured Recent Soils developed on Waitemata Group materials. These are the common soils in the rolling hills and valleys of North Shore and Waitakere cities and parts of Auckland and Manukau Cities. Data presented on infiltration and run-off from Granular Soils of Pukekohe are associated with compaction created by market gardening, not urbanisation. Other data for impacts on free-draining, well-structured and/or coarse-textured soils are sourced from Hamilton (Allophanic Soils from weathered volcanic ash) and Taupo (Pumice Soils) in the absence of Auckland data.

4.1 Silverdale anthropic and grey soils

This research quantified the physical properties of swales adjacent to the Northern Motorway near Silverdale. Swales were created as part of large earthworks similar to those used on subdivisions: topsoil was removed; the site graded using cut/fill, compacted to support a roadbed, and 50–100 mm of stockpiled topsoil (often mixed with subsoils) spread over the surface before a grass sward was established and maintained by mowing. While the topsoil had adequate mean infiltration rates (saturated hydraulic conductivity in Table 2), many sites had a compacted, blocky soil surface in which a few large cracks transported most of the water to the subsoil. Subsoils had low permeability (Table 2), with one-third of the cores having saturated hydraulic conductivity rates less than 0.4 mm/h and half the cores less than 5 mm/h. Low permeability limits the capacity of swale soils to treat and store road run-off, as infiltration has been shown to reduce pollutant loads significantly. These shallow soils also tend to pond rapidly (preventing further infiltration). Unsaturated hydraulic conductivity (Table 2) is a measure of water flow into the soil when rainfall does not pond on the soil surface and removes the influence of large pores such as cracks that typically form in summer when these compacted Ultic Soils dry. Unsaturated hydraulic conductivities were also significantly reduced in swales compared with an adjacent pasture site.

Table 2

Hydraulic conductivity of four swales on the Northern Motorway near Silverdale and in grazed pasture adjacent to each swale sampling point. Topsoil cores were taken from 0 to 75 mm depth, subsoil cores from 100 to 175 mm depth. Values are medians; the number of samples is given in parentheses.

Measured soil parameter	Swale		Pasture control	
	Topsoil	Subsoil	Topsoil	Subsoil
Saturated hydraulic conductivity (mm/h)	157 (n = 45)	5.1 (n = 37)	76 (n = 24)	41 (n = 12)
Unsaturated hydraulic conductivity (mm/h)	3.0 (n = 44)	1.0 (n = 31)	10 (n = 24)	10 (n = 12)

4.2 Waitakere Ultic and recent soils

This study quantified the effect of urbanisation by sampling the same soil, as classified using the New Zealand Soil Classification[6] (Hewitt 1998), under forest, grazed pasture and earthworked urban areas (a road verge or graded subdivision). Soils were sampled in winter, to avoid natural surface cracking, down to the lesser of a root-limiting or slowly permeable layer on which water would pond in winter and which would prevent deep percolation. Saturated conductivity of each soil horizon was measured on four, 100 mm hand-carved cores. Results are shown in the following three graphs (Figures 6, 7 and 8).

Mottled Yellow Ultic Soils (eg Whangaripo Series) are imperfectly drained, clay-rich soils typical of gently rolling landscapes in North Shore, Waitakere and Flat Bush (Manukau). Topsoil hydraulic conductivity was highly variable and therefore not significantly different between the three land uses (Figure 6). This probably also reflects the sensitivity of these soils to compaction by machinery and animals (under pasture). Subsoil conductivity was markedly lower than topsoil conductivity in all land uses – a feature of this soil group. However, mean conductivity and its variability were reduced by almost an order of magnitude at the urban sites (Figure 7). This implies:

- There are few pathways for water to drain into urban subsoil compared with forested or pasture sites.
- Stormwater run-off from urban cut/fill sites will be higher than in pasture sites when topsoils become saturated.
- Amelioration at urban cut/fill sites should aim to increase subsoil permeability or soil water storage because infiltration rates (ie topsoil conductivity) are adequate.

A similar pattern is shown for the imperfectly to poorly drained Mottled Albic Ultic Soil (Mahurangi Series) in Figure 8.

[6] Ultic soils are mostly yellow brown earths in the New Zealand Genetic Classification.

Figure 6

Saturated hydraulic conductivity (Ksat) of Mottled Yellow Ultic Soils' topsoils (green squares) and subsoils (red squares) under long-term forest, pasture and urban land uses. Two sites in each land use were sampled. Vertical bars represent standard deviation.

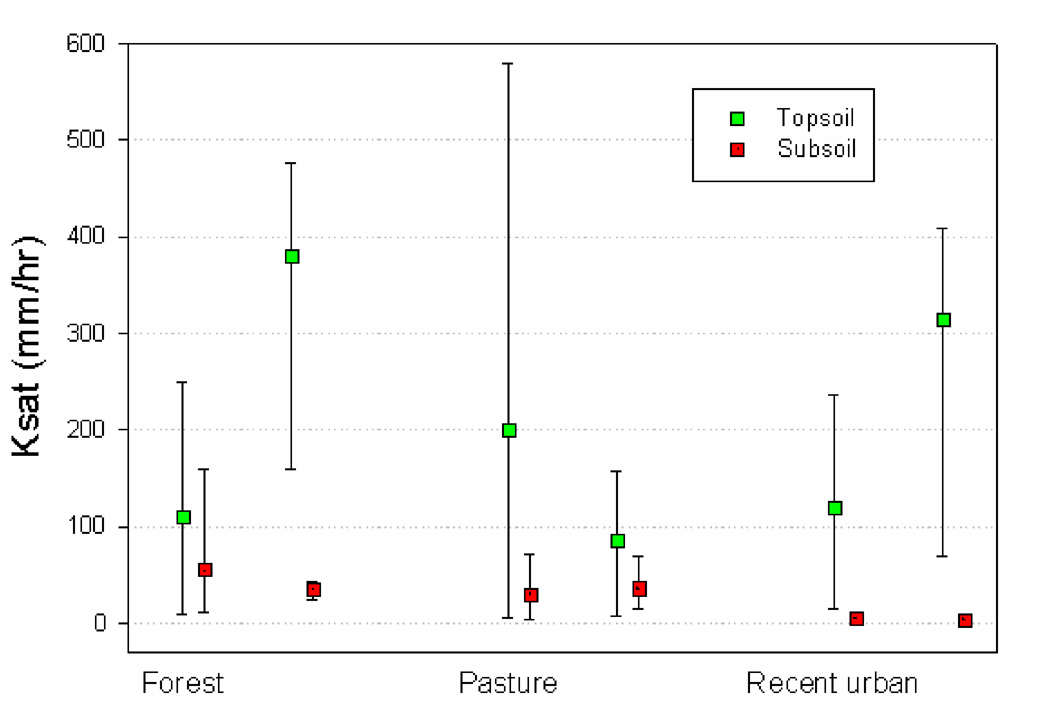


Figure 7
Subsoil saturated hydraulic conductivity (Ksat) under long-term forest, pasture and urban land use of Mottled Yellow Ultic Soils. Vertical bars represent standard deviation.

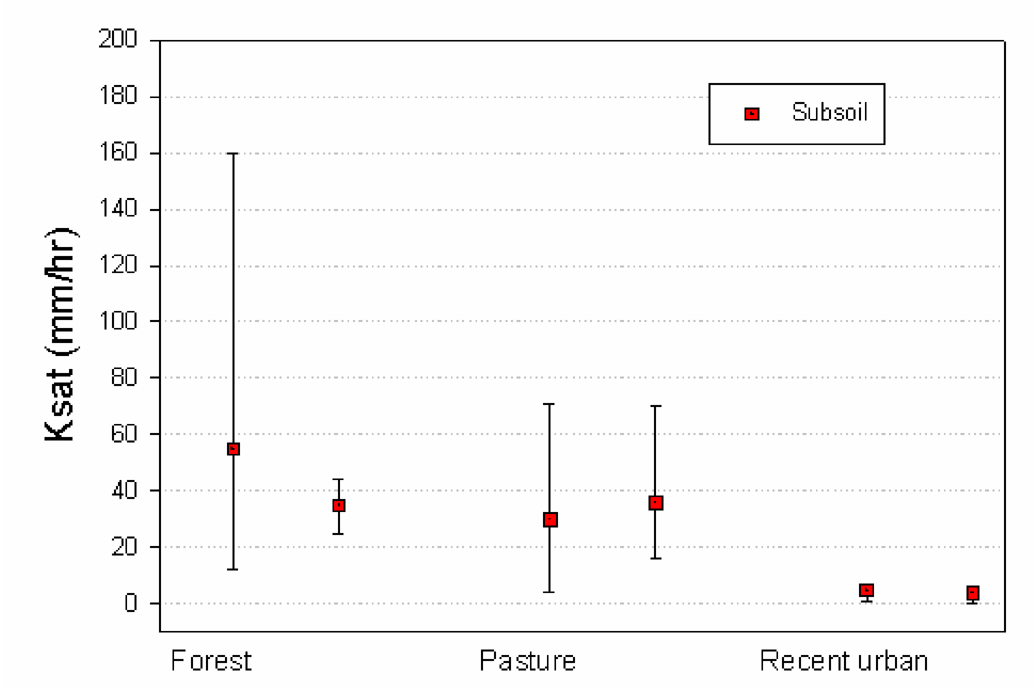
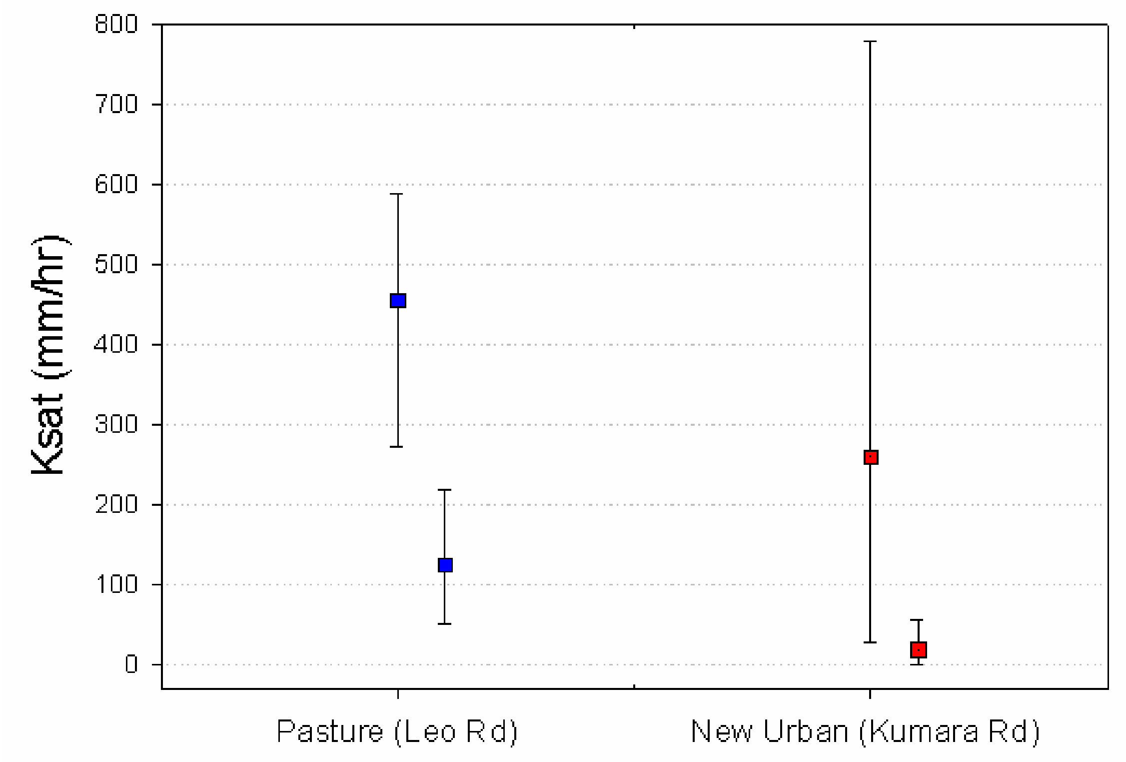


Figure 8
Albic Ultic Soils' saturated hydraulic conductivity (Ksat) under long-term pasture (blue squares) and urban (red squares) land use. In each colour, the left-hand bar is topsoil Ksat and the right-hand bar is subsoil Ksat. Vertical bars represent standard deviation.



Forested and urban areas on Mottled Fluvial Recent Soils (Whakapara Series) were also measured. In their natural state under remnant forest, these imperfectly drained soils had mean topsoil and subsoil permeability in excess of 50 mm/h and up to 95 mm/h, contrasting with the low subsoil permeability of the nearby Albic Ultic, Yellow Ultic and Orthic Brown Soils (Appendix 2). At the single cut/fill site found on Recent Soils, structural degradation had lowered permeability to a mean 14 mm/h. In this case achieving pre-urban run-off characteristics would require increasing topsoil permeability.

Topsoil permeability was also reduced in an urbanised Orthic Brown Soil. However, high spatial variability and a moderate mean permeability of 50 mm/h would be unlikely to result in surface run-off unless soils were above field capacity or there were very high intensity rainstorm events (Appendix 2).

4.3 North Shore Ultic Soils

Bennett (2000) reported run-off from earthworked Ultic Soils with a range of surface substrates, including topsoil sourced from a nearby stockpile, subsoil, mulch, and grass. The imperfectly drained soils were typical of Ultic Soils in the Auckland region, being 28–30 per cent clay on mixed subsoil fill of Waitemata Group mudstone and sandstones[7]. Bennett (2000) noted that the topsoil was compacted, regarding this as "a normal result of placement on an earthwork site". He measured the infiltration rates of each surface treatment, using the field double-ring method (Table 3), and run-off from 12 rainfall events from July through October 1999 that ranged from 2.7 to 47.1 mm, and with 6-min intensities up to 41.6 mm/h.

Run-off was greatest from plots with the lowest infiltration rates, with mulch and grass slowing run-off but increasing its variability, compared with subsoil plots, which showed a linear relationship between run-off and rainfall ($r^2 = 0.86$). The grassed plots had lower run-off than mulched plots; Bennett hypothesised this was due to grass roots increasing the size (and stability) of macropores over time (and hence infiltration). He noted that topsoil absorbed a significant volume of rainfall, but, because it overlaid low-permeability (earthworked) subsoils, water was prevented from moving down into the soil profile. In larger events, therefore, the soil became saturated and generated run-off, ie under winter conditions when evapotranspiration is low, large volumes of run-off can be expected from these soils. Bennett considered the low infiltration rate of subsoils might be exacerbated by surface sealing from clogging by finer soil particles.

Table 3

Infiltration rate (mm/h) and bulk density of earthworked soils, Albany (Bennett 2000).

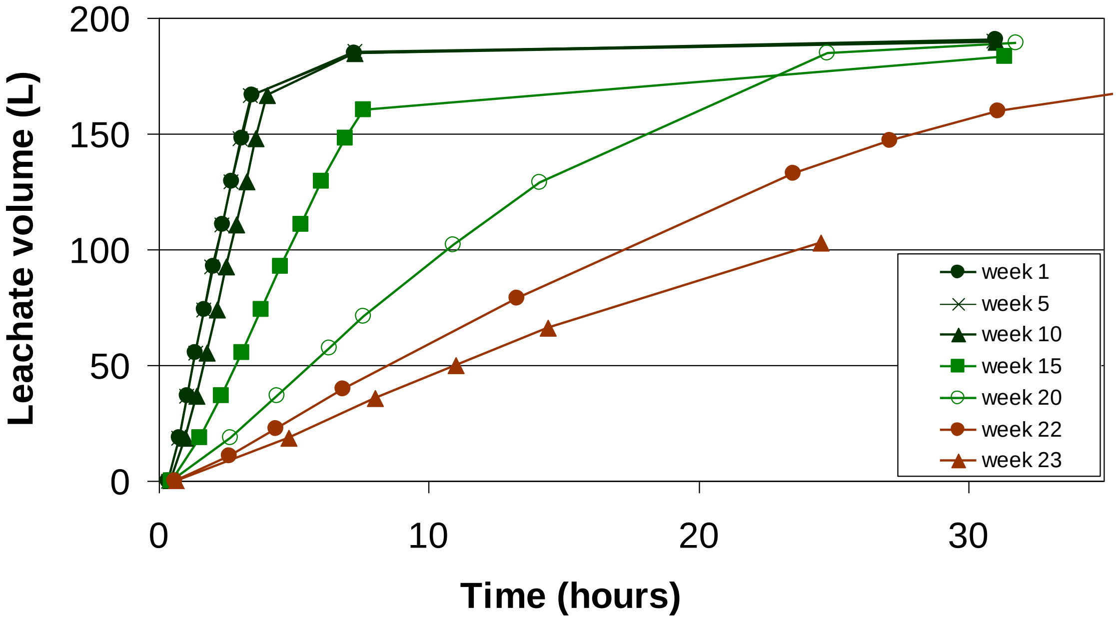
Surface substrate	Infiltration rate mm/h (mean + SD)	Bulk density Tm^{-3} (mean + SD)
Bare subsoil	6 ± 5	1.16 ± 0.04
Bare topsoil	74 ± 19	1.13 ± 0.06
Grassed subsoil	16 ± 7	1.06 ± 0.02

To remedy the low natural permeabilities typical of Ultic Soils so they could be used in rain gardens, sand was added to an Ultic Soil from the North Shore to create a medium with the sandy loam texture specified in ARC (2003). The amended substrate was placed in a large lysimeter, mulched, planted, and irrigated once a week for about six months. Results showed adding sand is likely to be ineffective as the poorly structured clays consolidate in a relatively short time leading to permeability decreasing over time, ie the hours taken to leach each irrigation event increased over time (Figure 9). Further, the amended Ultic Soil cracked on drying, allowing stormwater to bypass the soil matrix.

[7] The study site was located between the North Harbour Stadium and Otehi Valley Road exit from the Northern Motorway.

Figure 9

Cumulative leachate flow for a 70 mm depth of Ultic Soil mixed with sand and irrigated with a standard volume of water once a week for 23 weeks.

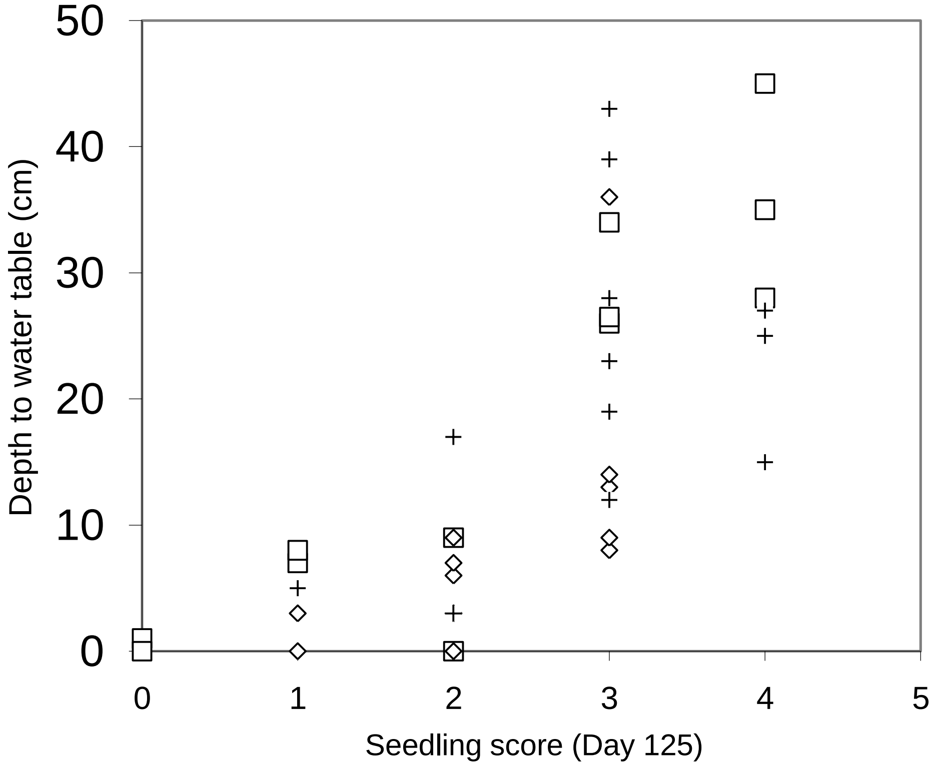


Soils with low soil permeability and/or perched water tables have traditionally been ameliorated in the forestry industry by physical cultivation treatments. A study in Riverhead Forest examined the effects of compaction and cultivation on Mottled Yellow Ultic Soils typical of Hydrologic Class C on Waitamata formation soils, and pine seedling growth and survival. Half of a 10-hectare harvested block was cultivated to 0.6 to 0.7 m depth with a single-winged tine followed by four discs. This cultivation improved seedling survival and growth over four years by increasing the depth to water table (Figure 10), macropore volume and oxygen diffusion rate. Cultivated areas were not only more permeable but water moved deeper into the soil.

An outcome of the trial is that nearly all areas harvested by ground-based logging in forests on similar soils are now routinely cultivated, irrespective of soil type. This is because of the complex soil pattern, the difficulty of predicting where compaction has occurred, and the cost of inadequate establishment when seedlings are planted at 550 to 650 stems per ha. Extensive site-prep by ripping and bedding has, however, been superseded by spot cultivation using a hydraulic excavator, which can access soils with low-bearing strength and consistently creates a favourable planting site; if bedding is shallow, ripping can create water-filled channels with no outlet for the water.

Figure 10

Pine seedling health plotted against water table depth for day 125 (December 1997) and day 195 (February 1998). □ Control; ◊ Compacted; + site-cultivation. Seedling score: 0 (dead), 1 (50 per cent dead needles), 2 (healthy but not actively growing), 3 (healthy and actively growing), 4 (growing vigorously).



4.4 Waitakere recent and anthropic soils

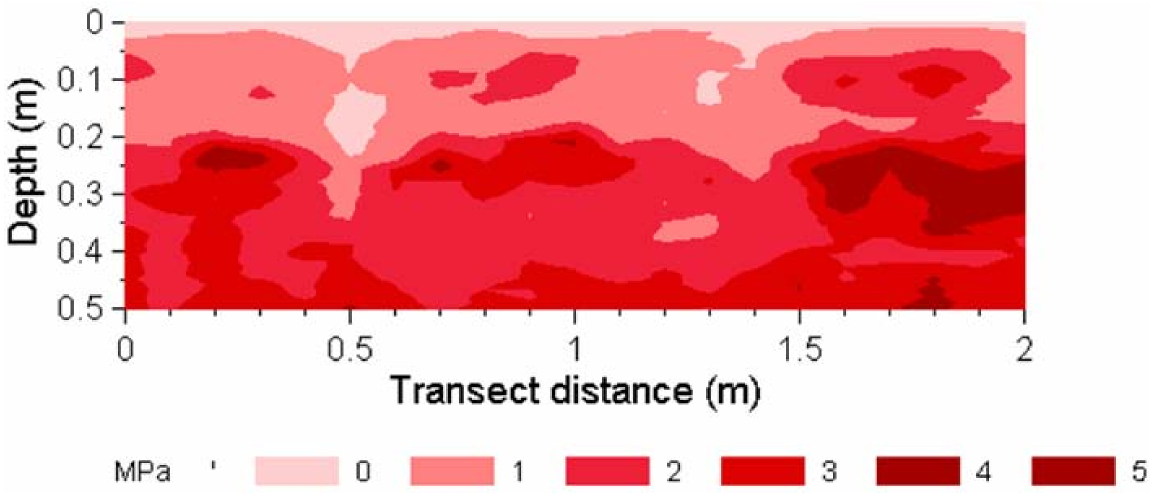
Soil quality and soil variability were characterised in four native revegetation trials along the banks of the Opanuku Stream in Waitakere City. All sites had imperfectly drained Mottled Fluvial Recent Soils (Whakapara Series clay and silt loams) before earthworks.

The main changes were caused by fill. About 100 mm of imported Ultic topsoils and variable depths of imported Ultic subsoils were placed over the original surface. This created a characteristic soil strength profile that has a peak at the bottom of each imported layer caused by vehicle compaction (Figure 11). Water and root movement was often blocked in these compacted, high-strength layers. This was visible as gleyed soils (grey colours) and absence of roots, with roots confined to the topsoil, ie reduced from >500 mm to 100 mm depth. Although the new topsoils generally had adequate macroporosity, most plants died, as water ponded in winter on flat areas – only cabbage trees, tolerant of temporarily waterlogged conditions, survived.

The soils were ripped in an attempt to ameliorate the inadequate soil depth and to increase permeability. Ripping was effective where the fill was less than 20–30 cm, as it allowed roots to reach buried, uncompacted topsoils. However, ripping had to be aligned so that rainwater flowed out of the rip lines, otherwise water ponded because there was no outlet from the rip lines and there was no benefit. The wide variation in subsoil water content, depth of fill, multiple compacted zones, and uneven contour made effective ripping difficult to achieve. A second ameliorative treatment was spreading a thick (100–150 mm) layer of woodchip mulch. Over 12 to 36 months the mulch decomposed and was incorporated into the underlying topsoil by earthworms, creating a deeper, aerated soil.

Figure 11

Soil strength in a slice of soil 1.2 m wide and 50 cm deep showing bands of compacted soil at about 10 and 20 cm depth. Pale colours (<3 MPa) show favourable conditions for roots. The upper 20 cm of pale material is fill – the original ground surface was compacted before fill was added. Dark areas show compacted zones. The soils was ripped at 40–50 cm depth and 1.3 m along the transect, indicated by pale zones reaching to about 35 cm depth. Water would infiltrate rapidly into these zones.



4.5 Pukekohe granular soils

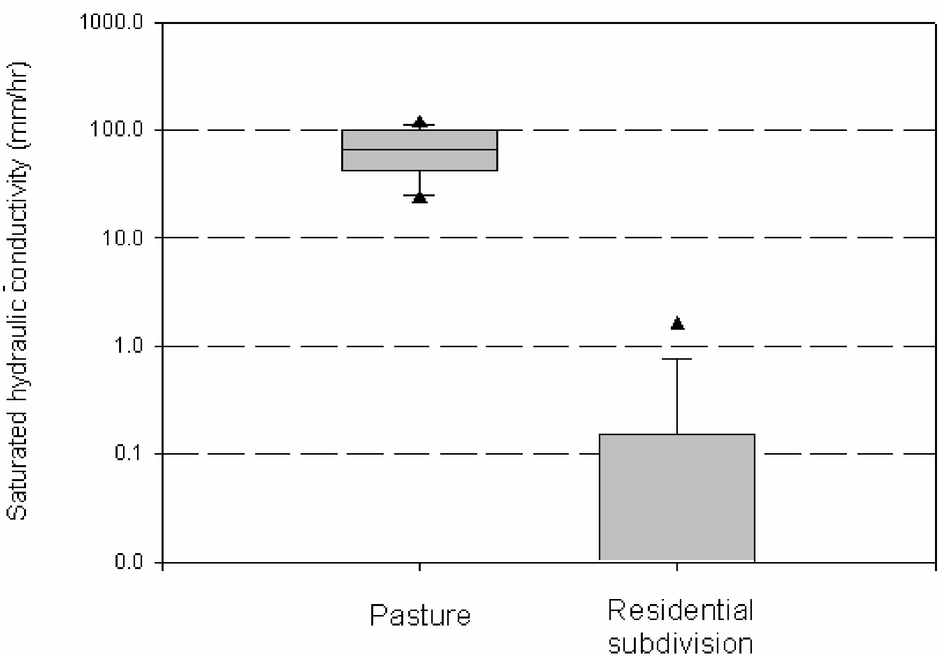
Narrow horticultural tractor-tyre traffic has a dramatic and very significant effect on Pukekohe soils, decreasing their infiltration rates by orders of magnitude, causing water to channel and flow down wheel tracks during storm events (Basher et al. 1999; Basher & Ross 2001). Basher et al. (1999) measured mean infiltration rates in wheel tracks of 0.7 and 3.5 mm/h compared with 450 and 360 mm/h in ripped tracks. Basher and Ross (2001) reported mean infiltration rates between June and January in uncultivated wheel tracks of 0.5–77 mm/h compared with 8580–60310 mm/h in ripped tracks and 410–910 mm/h in cultivated onion beds. Because compaction is applied from the surface, ripping restores infiltration in these soils – where compaction is multi-layered and deep seated as in cut/fill subdivisions, such effective amelioration is unlikely to be achieved on earthworked sites.

4.6 Hamilson Brown and gley soils

The Hamilton study followed the same format as the Waitakere study, contrasting physical properties of soils in paired urban subdivisions and long-term pastures. Topsoil was not significantly degraded at either urbanised site. Further, the potential for run-off at the subdivision on gley soils had been decreased by increasing the depth of replaced topsoils compared with its natural state (to c. 200 mm) (Zanders et al. 2001). Conversely, the well-drained Orthic Brown Soil (Kainui series) was substantially degraded (Figure 12), primarily due to cut-and-fill operations truncating the original soil profile. The natural permeable B horizon (c. 100 mm/h conductivity) was removed and replaced with a consolidated C horizon of compacted, near-impermeable clay (c. 0.1 mm/h conductivity). Although the topsoil was generally not significantly degraded, the absence of a permeable B horizon to 40 cm depth indicates a significant decrease in water storage and minimal drainage to groundwater, and hence an increase in surface ponding and stormwater run-off in winter conditions.

Figure 12

Saturated hydraulic conductivity measured for subsoil (B horizon) of Kainui soil series (Orthic Brown Soil) under pasture and residential subdivision. The grey boxes encompass the mean and standard deviation and the bars the 95 percentile values (Zanders et al. 2001). Note the logarithmic scale.



4.7 Taupo pumice soils

The impact of earthworks associated with urban subdivisions on infiltration rates was quantified for Pumice Soils in Taupo. Earthworks reduced infiltration rates by 50–100 per cent compared with non-earthworked, infrequently mown or grazed sites. Mean infiltration rates dropped from 330 mm/h to <10 mm/h at Wharewaka (Figure 13); from 290 mm/h to 10 mm/h at Brentwood; and from 220 mm/h to 30 and 40 mm/h at two earthworked sites in the Acacia Heights catchment. The response of these brittle, well-drained Pumice Soils mirrors the sensitivity of sandy soils in Florida reported by Gregory et al. (2006).

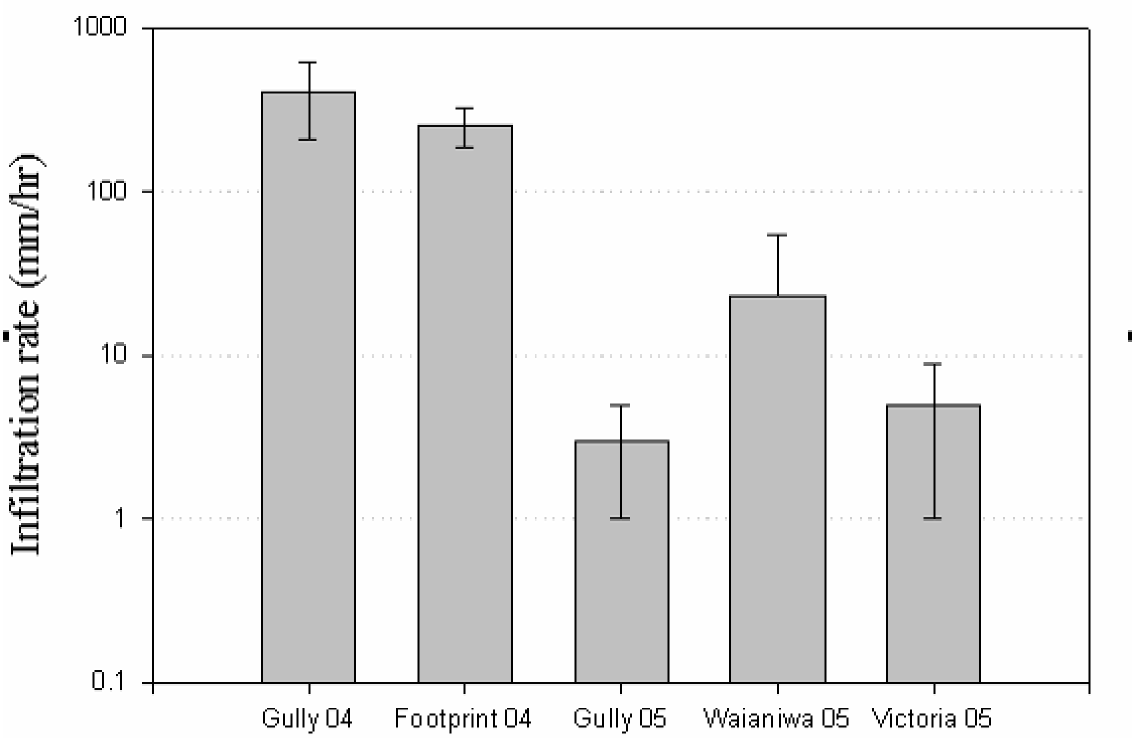
The impacts of cut/fill and earthworking on infiltration of Pumice Soils were not dissimilar to those of converting forest or scrub to pasture reported by Selby (1971), who measured infiltration of pumice soils under different land uses and antecedent conditions. Selby concluded:

- Stormwater run-off was greater from grazed pasture than scrub and ungrazed pasture.
- Increased run-off is associated with compaction caused by animals and vehicles.
- Run-off was greatest when soil moisture content was low due to hydrophobicity.

Selby recommended that valley floors be used for infiltration, with animals and vehicles excluded to prevent soil compaction. This exclusion strategy could be adopted in Auckland to protect vulnerable soils in areas identified as stormwater infiltration zones.

Figure 13

Mean infiltration rates at a subdivision on Pumice Soils measured before and after earthworks (04 = spring 2004, 05 = spring 2005). Note the log scale. "Gully" refers to the overland flow path; "Waianiwa" and "Victoria" refer to sites within the subdivision; the comparable undisturbed pre-earthworks site is "footprint".



5 Conclusions

Urban soils, particularly those created during cut/fill subdivisions, have common characteristics that usually decrease their capacity to mitigate the increased stormwater run-off generated by creating impervious surfaces (roofs and roads). Topsoil is removed and subsoils deliberately highly compacted to create stable surfaces to support slab-on-grade house and road foundations. Compaction, topsoil degradation and truncation[8] combine to reduce infiltration, subsoil permeability, water storage volume, and rooting depth. Where topsoil is replaced, infiltration rates may be unaffected but drainage impediments from compacted (impermeable) subsoils remain. Very sharp changes in texture and density between topsoil and subsoil exacerbate reduction in the permeability and ability of plants to exploit subsoils. Where topsoil depth and/or topsoil quality are reduced and subsoils compacted, the impacts of cut/fill are long lasting, as natural amelioration (via plant and soil organism activity) is slow.

While the impacts of urbanisation on soils are easily identified, it is harder to quantify this increase in run-off and translate these changes to changed run-off coefficients or curve numbers. DeFries and Eshleman (2004) suggest the consequences of anthropogenic land use change for hydrologic processes, including altered infiltration, groundwater recharge and run-off, are major research needs but have received little attention. Antecedent conditions are critical in assessing run-off from contoured sites generated by relatively small rainfall events, as soil moisture storage may be minimal in winter due to water perching on top of a low-permeability, compacted subsoil – run-off cannot infiltrate saturated soils.

There are a wide variety of strategies to mitigate increased run-off in urban subdivisions and achieve the overall goal of urban subdivision that has similar stream flows compared with the prior land use (pasture and/or forest). Strategies should both minimise or avoid degradation (by minimising trafficked footprints) and remedy degraded soils. Because topsoil permeability appears to be adequate in most sites, remedies that focus on increasing soil profile depth, moisture storage volume[9] and subsoil permeability are likely to be effective. This includes increasing the depth of replaced topsoil and its organic matter content. Other remedies include manipulating tree height, canopy cover, and canopy density to maximise interception, evapotranspiration and soil structure. Road verges and parks could be much more effectively used to retain and treat stormwater. The greatest benefits are likely to be achieved by protecting and ameliorating the most permeable soils.

However, the most effective methods of achieving hydrologic neutrality must also focus on the impermeable areas, ie:

[8] A soil profile is truncated when the (usually more permeable) upper soil layers are removed. The impact of truncation is greatest when the new subsoils have substantially lower permeability and are close to the surface as shown in Figure 2.
[9] Soil volume can be increased by increasing depth and/or area (by extending under relatively impervious surfaces such as footpaths and driveways). Aim for depths above water tables of at least 300 mm and preferably 1000 mm to support trees.

- Minimise the area of impermeable surface. This can be achieved through cluster housing, decreasing road widths, and replacing impermeable surfaces such as driveways, footpaths and roofs with permeable surfaces such as permeable paving and green roofs respectively.
- Disconnect impervious surfaces from pipes, and uncouple pipes from streams to avoid hydraulically efficient connections. Instead, direct run-off to areas that infiltrate and/or temporarily store run-off (Figures 14 and 15).

Figure 14

Two methods of decoupling impervious surfaces and pipes at Waitakere Civic Centre. A: Run-off from carparks and footpaths enter rain gardens. B: Permeable paving around a tree protects the soil surface from compaction while maximising area for pedestrians, and receiving run-off from the adjacent area.

A

B

Figure 15

This development in Auckland City uses a rain garden (basin on left), grassed swales and carparks with grassed permeable paving to detain and treat stormwater.

6 Recommendations

Recommendations are clustered into four groups. General recommendations are followed by options that **avoid** or minimise soil degradation, options that **remedy** or ameliorate degraded soils, and finally, options to **mitigate** for degraded soils. The key options for avoiding, remedying and mitigating soil degradation and increasing run-off in urban areas should be ranked by probable effectiveness and likelihood of uptake. Probable effectiveness can be quantified for each hydrologic class by assessing the likely "per cent affected area" and magnitude of run-off reduction. The likelihood of uptake can be assessed by discussing the options with developers to identify probable costs and practicality. A reduced set of preferred options should be demonstrated and tested on suitable subdivisions before general adoption.

General

- **Monitor run-off.** Run-off from urbanised cut/fill sites should be quantified by monitoring stream flow in sub-catchments undergoing conversion from rural to housing subdivision (allowing before-after comparison), and existing urban areas undergoing intensification. Sites should include sub-catchments with Hydrologic Soil classes A and C. Installing flow-recorders on the outlets of detention ponds that drain discrete subdivisions within each sub-catchment is likely to provide very useful data over several years when combined with rainfall data to allow targeting of events with high antecedent rainfall (when soils would be expected to be near or at field capacity).

- **Identify soil permeability and run-off hot-spots.** Identify hot-spots within catchments, where maintaining/improving permeability has high benefits. These include soils with high permeability (Hydrologic Class A), high storage (wetlands and "mullock" areas), deep soil profiles, and areas at the top of catchments receiving point stormwater loads (eg impermeable surfaces near ridgelines). In particular, identify areas within Class C soils – those derived from Waitemata sandstone and siltstone – with moderate to high permeability, and ensure these are utilised for mitigating stormwater run-off where practical, by fencing, and not earthworking or trafficking these areas. A pamphlet could be produced to identify the visual cues to high permeability Ultic Soils, using photographs.

Avoid degradation

The strategy of avoiding degradation is suited to both larger subdivisions with permeable soils and/or wetlands and individual sites in older suburbs, particularly where houses are established on piles and there has been no cut/fill. For low-density developments, reduction of footprint alone (by cluster housing) may be sufficient to minimise changes in run-off (Brander et al. 2004):

- In sites with Hydrologic Class A and sandy Class B soils, restrict earthworks to roads and building footprints where possible, particularly in areas designated for stormwater disposal ("hydrologic reserves") and parks. Do not earthwork or traffic the whole site – to achieve this construction equipment will usually need to be physically excluded.
- Retain wetlands and wet storage areas. Work with the natural flow of water.
- Evaluate compaction and grading requirements to ensure the minimum necessary areas are graded and compacted, eg outdoor paved areas do not require the same level of compaction as building platforms. Use the lightest equipment necessary to get the job done and achieve final grades with as few passes as possible. Restrict soil stripping and replacement, especially the upper 0.3 m of subsoil and topsoil, to dry periods when soils have the highest bearing strength and are most resilient.
- In extremely sensitive areas, eg at heads of catchments on highly permeable soils, build houses on piles, rather than slab-on-grade, to avoid contouring and consequent soil degradation.
- Protect root systems of existing large trees by suspending or supporting pavement/road over soil, installing grates around tree trunks, or placing gravel or organic mulch over soil surface to reduce compaction pressures. This approach is adopted where sections are subdivided and could be expanded from tree protection to wider areas around individual trees and/or to areas receiving run-off.

Remedy or ameliorate degraded soils

Amelioration can take the following forms:

- Increase the depth of topsoil applied to road verges and/or increase the organic component of replaced soils. Identify the benefit of applying 200–300 mm of topsoil and/or compost amendment on water storage volume. Amending Ultic Soils with inorganic components such as sand is likely to be ineffective in the medium-term as these clays are poorly structured and consolidate to low permeability media in a relatively short time
- Maximise dense, actively growing and tall plant cover on road verges and public areas, with a focus on increasing grass height to 100 mm, and increasing tree canopy cover. Large trees require a substantial rooting volume – this could be achieved by ensuring road verges are increased in width and/or including structural soils under footpaths (see mitigate section below). Plants increase soil macroporosity and permeability through their root activity, by adding organic matter and favouring earthworm activity. Trees intercept rain, particularly during

low intensity events, thus minimising the rain reaching underlying impervious surfaces, and run-off. Plants also transpire, drying the soil to create increased storage capacity, primarily in warm months (not winter). Transpiration is maximised by placing trees in areas with maximum sunlight, eg on Spanish X grids (not east-west grids).

- Shape the grade of underlying compacted subsoil to promote lateral movement of water to an under-drainage or retention system to avoid long periods of saturation, thereby increasing the potential to retain the first part of a storm event.
- Increase permeability and water storage capacity of residual, permeable areas around houses by:
  - amending topsoils with specified minimum rates or ratios of compost and encouraging healthy, dense plant cover.
  - ripping and cultivating Hydrologic Class A and coarser-textured Class C soils, into the subsoils to break up the subsoil layers. Avoid sharp textural contrasts by ripping, rotovating or discing the interface between topsoil into subsoil to create a transitional layer that favours water and root movement into subsoils. Hydro jetting, deep-water jetting, and air injection have been used to fracture compacted soil in urban areas; however, the availability of this equipment in Auckland has not been assessed. Ensure drainage from rip lines. Soil moisture content is critical for all ripping procedures. If soils are too wet smearing occurs (the soil acts as plasticine); too dry, and the energy required to pull rippers through the soil is very high. Effects may only last two-to-three years if recompaction pressures are present such as foot traffic. Cultivation cannot be used where trees are present as it damages root systems, allowing disease to enter. Recently air-blasters have been used to remove contaminated soils around the roots of trees in Auckland's Victoria Park with minimal damage to trees; and
  - aerating using turf machinery (hollow 20 to 30 mm diameter tines are better than solid, fine tines which create localised compaction and smearing around the hole) and backfill with organic matter or sand. Tines usually penetrate the upper 100 to 150 mm and, if used in suitable soil conditions and forward speed, also loosen the soil. For grass, the optimum time for coring may be spring, before fertilisation, with a chain behind the corer to crumble and spread the cores.

Mitigate

- Require footpaths, driveways and paved surfaces around houses to be permeable (eg gravels, permeable paving, pavers with sand base, permeable concrete), with both minimum permeability rate and detention storage volume specified, ie by specifying the depth and coarseness of sand/gravel basecourse underlying the permeable surface.
- Use "structural soil" in the entire width under footpaths to road edge, 1–2 m into carparks and to 1 m depth to create large continuous volumes for tree root and

water storage[10]. Structural soils are based on sand/compost mixes and have high bearing strength and permeability. They have not yet been developed for widespread urban uses in New Zealand, but would be relatively straightforward to create based on standard paving mixes and United States information (eg Bassuk et al. 2005).

- Replace soil in radial trenches around existing trees in compacted road verges or parks to maximise tree root volume, evapotranspiration, health and canopy cover (interception).

[10] A drainage pipe at the base of the profile will be needed in imperfectly and poorly drained soils to ensure aeration levels are adequate during extended wet weather.

Figure 16

Three streetscapes showing reduction in run-off by reducing the area of impermeable surface (narrowing the road, centre photo) and canopy coverage achieved by mature street trees (increasing rain interception and evapotranspiration, bottom photo). An opportunity has been missed when narrowing the road to treat run-off in the verge areas by installing swales or rain gardens that receive water from the road. (Palmerston North.)

Figure 17

Road narrowing has been used to calm traffic, treat run-off in rain gardens and increase street appeal. (Auckland City.)

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9 Appendix 1

Table 9

Permeability classes, New Zealand Soil Bureau's Soil and Water Assessment and Measurement Programme 1983.

Permeability class	mm/h
7 Very rapid	>288
6 Rapid	145–288
5 Moderately rapid	73–144
4 Moderate	19–72
3 Moderately slow	5–18
2 Slow	1–4
1 Very slow	<1

Appendix 2

Table 10

Saturated hydraulic conductivity (Ksat) and field capacity of three soil groups in Waitakere City under three land uses.

Soil series	K sat of topsoil (mm/h) Mean±stdev	Field capacity of topsoil (% v/v)	Ksat subsoil	Field capacity of subsoil (% v/v)
Pallic Orthic Brown Soil (Otao soil series, imperfectly drained)				
PASTURE @ Shaw Rd (grassed road verge)	200±200 (3-400)	58±3	23±13 (8-33,293)	57±2
NEW URBAN @ Carter Rd (slab on grade, grass cover)	50±45 (7-109)	60±1		
Mottled Yellow Ultic Soil (Whangaripo & Atkinson soil series, imperfectly drained) (dominant soils on East Coast Bays formation)				
FOREST @ CWI Hall, Titirangi Rd	110±110 (9-250)	48±1	55±70 (12-160)	48±2
FOREST @ Bishop Park, Atkinson Rd	380±175 (160-477)	52±2	35±9 (25-44, 414)	50±3
PASTURE @ Sturges Rd	200±260 (5-580)	45±2	30±30 (4-71)	38±2
PASTURE @ Shaw Rd	85±75 (7-158)	63±2	36±30 (16-70, 1280)	58±1
NEW URBAN @ Puriri Rise (new road verge)	120±100 (16-237)	46±1	5±6 (1-14)	49±2
NEW URBAN @ Puriri Rise (section)	315±165 (69-409)	37±2	4±3 (0-6)	39±3
Mottled Albic Ultic Soil (Mahurangi soil series, imperfectly to poorly drained)				
PASTURE @ Leo Rd	455±135 (272-589)	46±3	125±70 (52-218)	42±1
NEW URBAN @ Kumara Rd	260±350 (29-780)	40±1	20±25 (0-56)	42±3
Mottled Fluvial Recent Soil (Whakapara soil series, imperfectly drained)				
NATIVE @ Puriri Rise	50±25 (20-71)	46±1	95±130 (3-290)	35±1
PASTURE @ Millbrook Rd (road verge)	95±70 (11-154)	61±3		
NEW URBAN @ Puriri Rise (fill)	14±8 (7-23)	46±2		

Each value is an average of four 100 mm hand-carved cores, unless otherwise specified (for some Ksat). Field capacity = Volume of water-filled pores at −10 kPa suction for each horizon above a root-limiting layer. Only the Brown, and possibly Ultic[1] soils drain to nominal field capacity, ie a point when further drainage becomes minimal – the imperfectly and poorly drained soils tend to leak continually rather than have a defined drainage point. * = Whakapara topsoil at riparian plantings, fill site had Field Capacity of 43 ± 7% v/v.