AUCKLAND’S APPROACH TO THE STREAM EROSION PROBLEM

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ABSTRACT (500 WORDS MAXIMUM)

Auckland’s population is projected to grow by 800,000 (50% increase) in the next 30 years and the increase is predicted to make up over 50% of NZ’s population growth in that time. Stream bank erosion is a growing concern in the region, due to development and changes in catchment hydrology. With widespread future growth and associated impervious surfaces, stream erosion is set to become an important issue affecting water quality, infrastructure, properties, ecosystem health and public safety.

Better land management is required to ensure stream erosion is minimised or prevented and waterways remain healthy. In urban areas, assets and buildings are commonly adjacent to streams and erosion of the banks are threatening their structural integrity. Sediment is a key ‘matter’ to take into account as part of the National Policy Statement for Freshwater Management (NPSFM). Regional targets, of which sediment is expected to be one, will be set and will need to be met to ensure improved freshwater quality. In the Auckland region, turbidity and sediment are major issues with significant impacts on estuaries and harbours that also require improved management as part of the New Zealand Coastal Policy Statement (NZCPS).

This paper outlines the direction Auckland Council is embarking on to proactively identify existing and future stream erosion risk and to gain an improved understanding of baseline sediment and erosion levels across the region. Identification of the erosion risk can be incorporated into future planning and development frameworks in a similar manner to floodplains and overland flow paths. It will provide an additional tool for the assessment of site suitability for land use change and for any requirements associated with managing erosion as a natural hazard. With an improved understanding of the erosion risk at the early stages of land use change, mitigation strategies can be developed and tested to understand their effectiveness for maintaining stream bank integrity and improving freshwater and coastal water quality. Modelling and monitoring of sediment delivery from stream bank erosion processes can also be undertaken to comply with the NPSFM. The paper will outline how the previous paper, titled ‘Continuous Simulation Modelling To Support Healthy Waterways’, and the following GIS stream erosion assessment work fit into Auckland Council’s wider stream erosion management framework.

The paper also outlines the development of a GIS-based stream erosion assessment screening tool, that can be applied at a region scale to efficiently identify streams that might be prone to stream erosion (due to hydraulic forces). The assessment uses data on stream gradient, channel cross-section and an estimate of the critical shear stress of the soils. The assessment has been undertaken for eight catchments in the Auckland region calculating unique channel characteristics for over 800 cross-sections extracted from LiDAR data. The study analysed and presented which parameters stream erosion (using boundary shear stress) is most sensitive to. It also determined the validity of using LiDAR derived cross-sections for the calculation of stream channel parameters and in the prediction of stream erosion. The assessment has identified specific reaches where erosion is likely to currently be occurring and validated these against site-specific assessments. Output from

the erosion assessment can then be used to assist with decision making associated with future development and land use change. Further catchment or reach specific analysis can then be undertaken as appropriate to facilitate future growth and measures developed to mitigate the potential for stream erosion in these areas.

KEYWORDS

Streambank erosion, boundary shear stress, cohesive soils, sediment, GIS, LiDAR, surveyed cross-sections

PRESENTER PROFILE

Josh Irvine is a Chartered Professional Engineer and a Senior Water Resources Engineer at WSP Opus, with over 10 years of experience in water resources and stormwater management. He has experience in a wide variety of areas including hydrological and hydraulic modelling, stormwater design, project management, construction monitoring and watercourse assessments.

1 INTRODUCTION

1.1 THE PROBLEM

Auckland's population is projected to grow by 800,000 (50% increase) in the next 30 years and the increase is predicted to make up over 50% of NZ's population growth in that time. As a result of historic development, many streams in the region are currently eroding as a result of land-use changes in their drainage catchments. With widespread future growth and an associated increase in impervious surfaces, stream erosion is set to continue being an increasing issue affecting water quality, infrastructure, properties, ecosystem health and public safety.

Figure 1: Collapsed retaining wall and walkway caused by streambank erosion occurring at Oakley Creek

Better land management is required to ensure stream erosion is minimised or prevented and waterways remain healthy. In urban areas, infrastructure like piped assets, walkways and buildings are commonly adjacent to streams and erosion of the banks are threatening their structural integrity. Sediment is a key 'matter' to take into account as part of the National Policy Statement for Freshwater Management (NPSFM). Regional targets, of which sediment is expected to be one, will be set and will need to be met to ensure improved freshwater quality. In the Auckland region, turbidity and suspended sediment are major issues with significant impacts on estuaries and harbours that also require improved management as part of the New Zealand Coastal Policy Statement (NZCPS).

Streambank erosion is a natural geomorphological process (Leopold et al, 1964). However, historic agricultural activities and urban development have increased streambank erosion, affecting property, assets and infrastructure and the freshwater and marine environments.

It is estimated that there are over 20,000km of permanent and intermittent streams in the Auckland region and only 19% of these pass through native forest (ARC, 2001). It is therefore likely that up to 16,000km of streams are experiencing higher than natural flows and stream erosion. Typically, the streams are located on private property, complicating their management.

Stream bank erosion is one of the primary sources of sediment delivery to aquatic and estuarine coastal systems. With the volume of sediment transported to marine and freshwater environments in the Auckland region considered a major issue affecting ecosystem health, improved management of factors resulting in bank erosion are needed to reduce environmental effects. For example, an estimated 32,800 tonnes of sediment is delivered to the Kaipara Harbour from the Hoteo River catchment each year, with an estimated 72% of the load generated from streambank erosion processes (Cardno, 2016). The long-term increase in sediment delivery to the Kaipara Harbour from its contributing stream systems is smothering and reducing the extent of sea grass habitat critical to snapper and shellfish fisheries. This can have follow-on social and commercial effects, with the snapper fishery nursery grounds located in the Kaipara Harbour supporting as much as 98% of the North Island west coast snapper fishery (NIWA, 2009). In streams, excess sediment decreases water clarity affecting the ability of fish to feed, damages fish gills, smothers invertebrate habitat, amongst other negative impacts (NIWA, 2016).

1.2 NATIONAL LEGISLATION CONTEXT

The management of streambank erosion in the Auckland region is ultimately governed by the Resource Management Act 1991 (RMA), as outlined in Figure 2.

The National Policy Statement for Freshwater Management (NPSFM) 2014 amended in 2017 (MfE, 2017) and the New Zealand Coastal Policy Statement (NZCPS) 2010 (DoC, 2010) are two key national policy statements under the Resource Management Act.

The NPSFM identifies *high sediment levels* and *deposited sediment* as matters for the compulsory national values *of Ecosystem health* and *Human health for recreation* to consider respectively. It also identifies the natural movement of sediment as a matter contributing to the *Natural form and character* of a freshwater management unit, in other national values.

The NZCPS policies, under the Sedimentation Policy 22 section related to the management of stream erosion are:

> *(1) Assess and monitor sedimentation levels and impacts on the coastal environment.*
>
> *(2) Require that subdivision, use, or development will not result in a significant increase in sedimentation in the coastal marine area, or other coastal water.*
>
> *(3) Control the impacts of vegetation removal on sedimentation including the impacts of harvesting plantation forestry.*

> *(4) Reduce sediment loadings in runoff and in stormwater systems through controls on land use activities.*

The Enhancement of water quality Policy 21 also sets out relevant policies for the management of stream erosion.

The RMA defines a natural hazard as *"any atmospheric or earth or water related occurrence (including earthquake, tsunami, erosion, volcanic and geothermal activity, landslip, subsidence, sedimentation, wind, drought, fire, or flooding) the action of which adversely affects or may adversely affect human life, property, or other aspects of the environment." Erosion*, sedimentation and subsidence are all identified natural hazards that relate to streambank erosion. Although it is clear the effects from a one-off stream erosion event is not comparable to the potential destruction caused by other natural hazards like earthquakes, volcanic activities and flooding, considering the greater likelihood of stream erosion related hazards the risk of these hazards can be significant.

Other related guiding policy for the management of streambank erosion include the Soil Conservation and Rivers Control Act 1941 and the Local Government Act 2002.

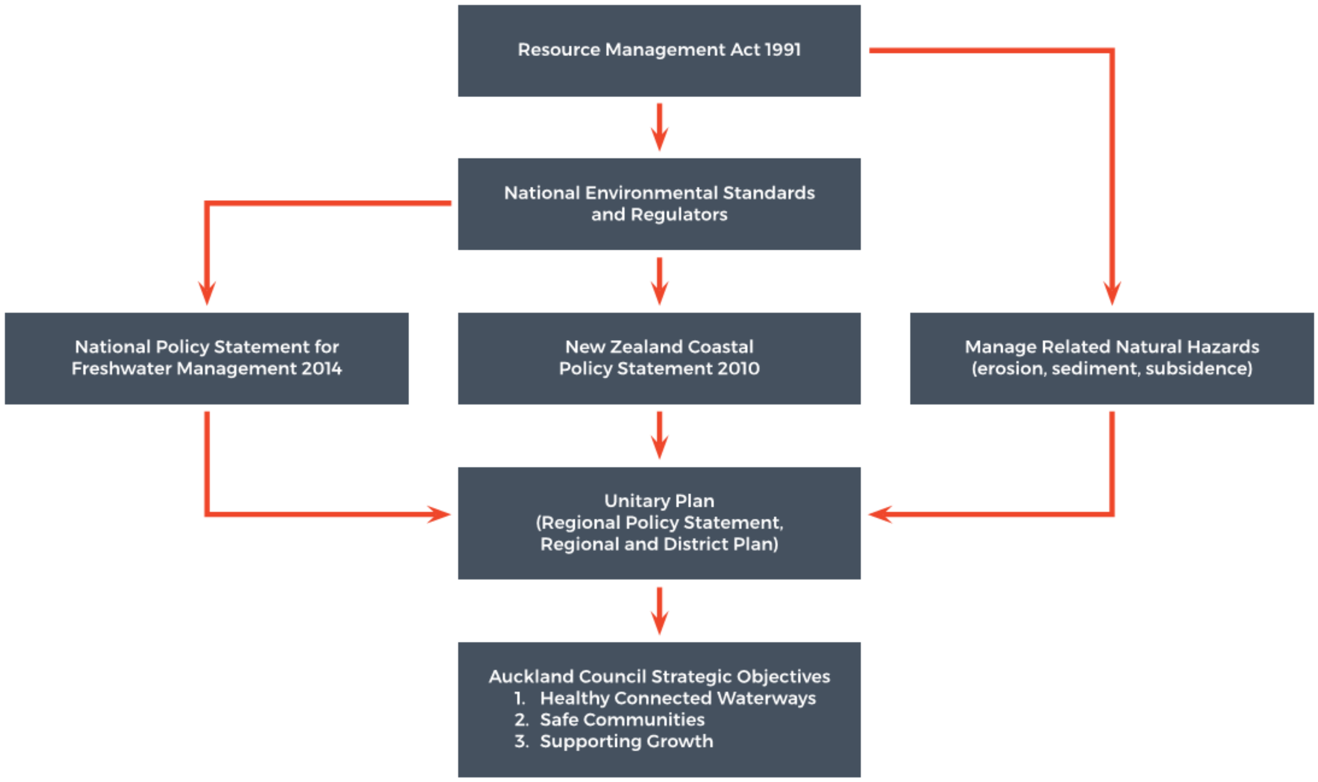

Figure 2: Context of Auckland Council's Streambank Erosion Management

1.3 AUCKLAND CONTEXT

The Auckland Unitary Plan sets out the planning rules to give effect to the Resource Management Act. There are a number of rules and provisions, in the Unitary Plan, that are related to managing the effects of land-use changes and development on the stream environment. The Auckland Plan, Auckland's 30 year spatial plan, considers how Auckland will address its key challenges of high population growth, shared prosperity and environmental degradation (AC, 2017).

Auckland Council's Healthy Waters Department, who manage stormwater and its effect on the environment, have three key strategic objectives aligned with delivering the benefits that support the Auckland Plan outcomes (AC, 2018). These include:

- Safe Communities: Risk to our communities, including people, property and infrastructure is reduced.
- Supporting Growth: Growth through water sensitive development and provision of quality stormwater infrastructure is enabled.
- Healthy and Connected Waterways: Stream, groundwater and coastal water values are maintained and enhanced, and communities are connected with them.

All of Healthy Waters strategic objectives relate to the management of streambank erosion, due to its threat to people, property and infrastructure, managing the effect of land use changes and development on streams, and ensuring healthy and connected streams in the region.

A large proportion of the Auckland region contains cohesive clayey soils, typically Waitemata clays. Although highly variable, these clays are generally not very erodible, have high critical shear stresses (Jowett & Elliot, 2009; Cardno, 2017) and can withstand some undercutting of the streambanks and relatively high bank heights. These properties mean the streams in Auckland could take decades to adjust to changes in the catchment.

However, despite their relative erosion resistance, a local study of the Hoteo River concluded that approximately 72% of the sediment entering the marine environment is sourced from streambank erosion (Cardno, 2016).

Figure 3: Hoteo River outlet to the Kaipara Harbour taken in March 2011

Approximately 80% of streams (stream length) in the Auckland region have contributing catchments of less than 100ha and at low flow are generally less than a few metres wide. The majority of streams are located in private property, complicating their management. The historic development in close proximity to stream channels provides the stream corridor with often little or no room to naturally adjust to increased flows. Coupled with the high population growth anticipated in Auckland, which is likely to exacerbate existing issues, stream erosion is likely to have growing significance and provide unique challenges in the Auckland environment.

1.4 HISTORIC AND CURRENT MANAGEMENT

Management of increased streams flow and runoff, from development, in the Auckland region was introduced through the provision of extended detention as outlined in TP10 in 1992 and 2003 (ARC, 1992; ARC, 2003). Extended detention sought to temporarily store the runoff from a 34.5mm rainfall event and releasing this over 24hrs, to minimise the potential for stream channel erosion (ARC, 2003).

The Unitary Plan introduced rules to prevent and minimise adverse effects and enhance freshwater systems. Stormwater Management Areas for Flow Control (SMAF) were incorporated in the Unitary Plan in 2017. The intention of SMAF areas are to protect the high-quality streams in the Auckland region, susceptible to increased flows from impervious development or changes in land-use. The primary indicators for the identification of these areas included the Macroinvertebrate Community Index score, bed slope and catchment imperviousness (Kettle et al, 2013). SMAF 1 and 2 areas are required *to provide detention (temporary storage) and a drain down period of 24hrs for the difference between the pre-development and post-development runoff volumes from the 95th and 90th percentile 24hr rainfall event respectively minus the 5mm retention volume, over the impervious area for which hydrology mitigation is required* (AC, 2016). All greenfield areas are also required to meet the SMAF requirements. The SMAF rules may not be going far enough to adequately manage the potential effects of land use changes and development on streams, especially for urban streams not covered by a SMAF area.

The application of water sensitive design to land use planning and land development has also been implemented in Auckland with guidance from Auckland Council's Stormwater Management Devices in the Auckland Region (GD01) and Auckland Council's Guideline Document (GD04) Water Sensitive Design for Stormwater (AC, 2017; AC, 2015). This will aid in ensuring a more natural flow regime in streams.

2 OVERALL APPROACH

2.1 AUCKLAND COUNCIL'S APPROACH

Auckland Council is seeking to proactively identify existing and future stream erosion risk in the region and to understand baseline sediment and erosion levels.

In the Auckland Region the majority of sediment within freshwater and marine receiving environments comes from stream erosion. Whilst models exist to estimate the contribution of sediment from different land uses, models of stream erosion processes require specific information for each stream reach.

Identification of the stream erosion risk needs to be incorporated into future planning and development frameworks in a similar manner to floodplains and overland flow paths. Identified erosion risk will provide an additional tool for the assessment of site suitability for land use change and for any requirements associated with managing erosion as a natural hazard. With an improved understanding of the erosion risk at the early stages of land use change, mitigation strategies can be developed and tested to understand their effectiveness for improving freshwater and coastal water quality. Monitoring of sediment levels can also be undertaken to comply with the NPSFM.

There are many benefits to better management of stream erosion. Figure 4 outlines key benefits of healthy stable streams, including streams being valued, improved water quality, reduction in erosion risk and improved ecosystem health.

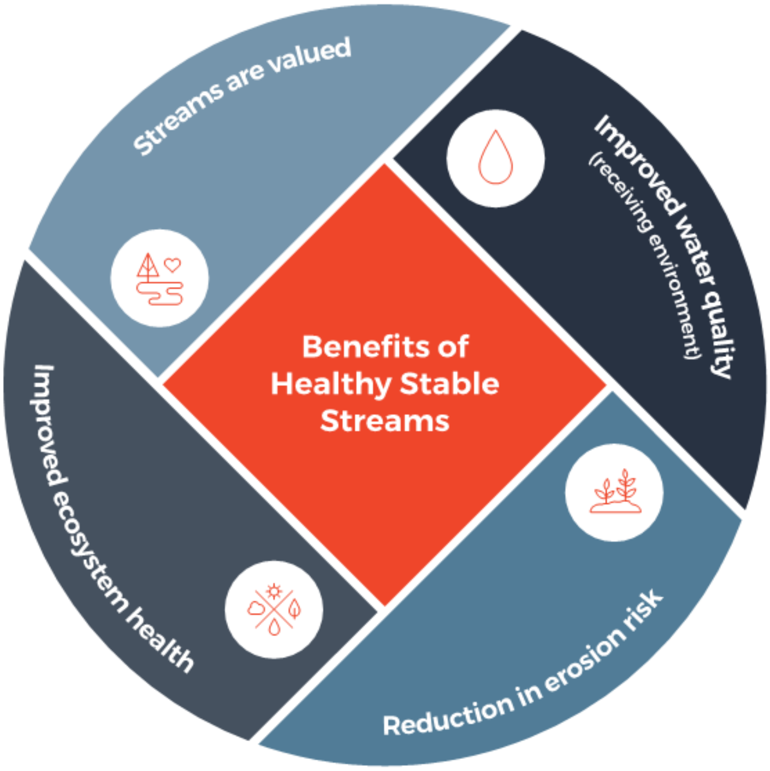

Figure 4: Benefits of Healthy Stable Streams

Auckland Council want to recognise streams as an asset and as a key part of the stormwater network, providing a conveyance function as well as many ecological, social and cultural benefits. As with pipes, the intention is to identify what streams are, or will be, under capacity considering existing and future development. Stream condition may need to be managed in a similar manner to built assets, in terms of structural integrity, capacity and risk of failure. Renewing/restoring streams if their condition is degraded, daylighting streams and protecting our most valued and pristine streams can all benefit from improved understanding of erosion processes. Stream erosion assessments and modelling will become a necessary tool to manage historic and future effects of development and land use changes on streams and will supplement the existing watercourse assessments programme.

Details of the possible future work to be implemented is outlined in the programme of works in section 2.3.

2.2 THEORY

Channels evolve over time to convey a certain level of flow commonly referred to as the "channel forming flow" or "bankfull discharge", which generally ranges from recurrence intervals of between 1 to 2.5 years (Leopold, 1994). Streams will adjust and further evolve when flows are altered as a result of land use changes, development in the catchment, or other mechanisms. Higher discharge rates can result in erosive processes leading to channel widening and increases in channel cross-sectional area, while lower discharge rates will result in sedimentation and accretion, resulting in channel infilling and a reduction in channel cross-sectional area. Higher flows and erosion are the most dominant responses to hydrologic change in the Auckland region.

Auckland Council is focusing on the prediction of whether streams are stable or not using shear stress. Boundary shear stress is the driving force behind the flow and is considered more appropriate for Auckland, given the cohesive nature of the soils in the region (Yang, 2006).

For small slopes, the average boundary shear stress can be approximated to:

$$\tau_o = \gamma_w R_H S \qquad (1)$$

Where,

τ_o is the average boundary shear stress (Pa)
γ_w is the specific weight of water (Nm^{-3})
R_H is the hydraulic radius (m)
S is the slope (m/m)

This is often called hydraulic erosion, caused by the flow of the water across the stream boundary surface. The slope in the formula is the energy grade line but is often approximated as the water surface slope or the channel bed slope. For wide channels, the hydraulic radius can be approximated as the average flow depth.

The boundary shear stress can be compared to the critical shear stress of the soils that make up the bank and bed of stream channels to provide an indication of the potential for erosion. This metric is favoured over stream power as stream power does not typically have the ability to account for the cohesion of the soils and their associated resisting forces. Cohesion is the force that binds particles in the structure of a soil. Cohesion is generally larger in soils with higher clay content and with cohesive soils it increases the smaller the particle size.

Understanding the likelihood of whether streams are susceptible to hydraulic erosion will also help to understand whether channel incision and undercutting of the streambank is likely to occur, which could lead to increased risk of lateral bank failure and mass wasting (geotechnical erosion) processes.

2.3 PROGRAMME OF WORKS

Considerable effort will be required to better understand the total stream erosion risk in Auckland, to reliably identify existing and future issues, to better value and protect streams, develop guidance for stream erosion mitigation works, and to develop better funding methods for the mitigation of increased flows from development.

A programme of works was developed for the better management of streambank erosion in Auckland. The programme of works, outlined in Table 1 summaries the main challenges facing Auckland Council. The main challenges are typically due to gaps in understanding and information around the stream erosion issue and are often specific to a paucity of physical data associated with Auckland soil types and the natural materials lining the streams. Tools or actions have been recommended to mitigate the identified challenges and the list has been categorized and prioritised based on the pieces of work that are most important and urgent. The highest priority tasks are in the pale orange colour, followed by pale yellow and the lowest priority in pale green. The programme of works will be refined and remain a 'live' document. Some of these identified tasks have already been initiated including continuous simulation modelling (Islam et al, 2018) and the stream erosion GIS assessment, outlined in section 3 of this paper.

Table 1: Stream erosion management programme of works

Key Challenges	Possible Tasks or Actions
Risk	
Understanding of existing and future stream erosion issues	• Regional GIS based assessment identifying what streambanks are likely to erode due to hydraulic erosion. • Regional GIS based assessment identifying what streams banks are likely to erode due to geotechnical erosion. • Rapid geomorphic assessments (RGA) to identify stream erosion issues on a catchment scale. • Stream erosion modelling to predict what streams are stable on a catchment scale (in conjunction with flood modelling). • Utilise tools like BSTEM to predict existing erosion rate and effectiveness of mitigation options on a reach scale.
Understanding the scale of the stream erosion hazard/risk	• High-level quantitative assessment of the potential impact of stream erosion using key GIS layers.
Compliance with NPSFM	• Set freshwater objectives and limits through consultation (sediment). • Develop a tool to predict sediment levels in the freshwater environment (informed by monitoring data). • Establish baseline erosion rates.
A programme to proactively manage under capacity and degraded streams from erosion	• Identify what streams are under capacity, based on the upstream catchment and flows. • Develop a renewal programme for the restoration of degraded streams.
Understanding the delay of stream erosion effects following land use changes	• Develop a methodology to confirm the likely period for rural streams to adjust when bush is replaced by pasture and when rural land is converted to urban. Use this, in conjunction with an understanding of historic land-use change and soil properties, to identify what streams have adjusted to the increased flows and what streams need to adjust.
Climate change will likely adversely affect stream flows and subsequently increase stream erosion	• Source climate change rainfall time series, run a continuous simulation model, define the annual maxima event, determine the amount of erosion due to climate change and the period over which the stream will be affected.
Community	
Understanding community expectations and aspirations for streams	• Consult with general public, māna whenua, local community.
Reporting of stream erosion issues from residents/public	• Develop a system to spatially record reported stream erosion issues and stream erosion condition (combined with watercourse assessment information).
Financial	
‘Funding streams’ for stream erosion mitigation	• Develop a system to quantify the value that streams provide and quantify the effect of development on the streams.
Quantifying the benefits of stream erosion mitigation options	• Tasks to be developed.

Key Challenges	Possible Tasks or Actions
Geomorphology	
Stream erosion is dependent on a number of site-specific factors which could be very costly to capture	• Site specific soil testing for different soil types to infer soil properties across the region, based on a general understanding of soil type and geology. • Investigate the potential to use LiDAR derived information to get an understanding of stream channel geometry, vegetation and meanders. • Understand what parameters streambank erosion is most sensitive to. Focus on establishing accurate methods for the capture of these parameters for the prediction of stable streams for regional scale assessments. • Develop an erosion assessment hierarchy that establishes a process for erosion assessment at different spatial scales.
Understanding of localised erosion (scour)	Tasks to be developed.
Flows	
Flow information to be used for stream erosion assessments	• Develop a continuous simulation modelling methodology to be able to predict stream flows in ungauged catchments so that a prediction of the potential of stream erosion over time can be made. • Develop stream erosion modelling guidance.
Groundwater and infiltration information for stream flow modelling	Tasks to be developed.
Interventions	
Understanding the effectiveness of the current and historic controls related to stream erosion	• Evaluate the theoretical effectiveness of current and historic hydrological controls i.e. TP10, GD01, SMAF rules. • Assess whether additional or an update to the existing controls would be beneficial. • Develop additional controls or update to existing controls. • Policy changes (regional policy statement, Unitary Plan).
Understanding what native vegetation are appropriate for riparian planting and where in the riparian margin the vegetation is best placed	• Assessment of what native vegetation will provide significant benefits to support stream banks. • Develop guidance on streambank planting.
Implementing appropriate stream erosion mitigation options	• Monitor effectiveness of stream erosion mitigation options. • Develop guidance on suitable stream erosion mitigation works. • Update standards and guidelines (e.g. technical notes, stormwater code of practice). • Work closely with regulatory to develop guidance on working in and around streams to minimise effects.
Local research to support management approach	Tasks to be developed.

3 STREAM EROSION GIS ASSESSMENT PILOT STUDY

3.1 OBJECTIVE

One of the identified key pieces of work to better manage stream erosion is a regional stream erosion GIS assessment. The assessment would be used as a screening tool to better understand the scale of the issue and to help prioritise areas for more detailed investigation of erosion risk.

A pilot study was initiated in 2018 by WSP Opus, to efficiently identify streams that are currently eroding (due to hydraulic forces only) and those potentially prone to stream erosion from land use change and additional impervious surfaces. This study confirms the feasibility and the accuracy of such an approach before undertaking a regionwide analysis.

The assessment is predominantly GIS based, using stream gradient, channel cross-sections and an estimate of the critical shear stress of the soils. The study's aims to identify whether the stream banks are likely to start eroding from erosive flows. It does not consider other erosion processes like bank slumping (geotechnical erosion). All onsite specific soil data can feedback into this regional tool to improve the assessment over time.

Following the high-level regional GIS assessment has identified reaches with an erosion potential, further catchment or reach specific analysis can be undertaken and measures developed to mitigate the potential for stream erosion.

The study also assessed the sensitivity of the key parameters used to measure stream erosion risk, the challenges of such an approach and the validity of using LiDAR information for defining channel geometry.

3.2 OVERVIEW

The pilot study included a mix of eight rural and urban catchments. The catchments were selected based on the amount of information Auckland Council holds on stream erosion hotspots and erosion issues identified from previous watercourse assessments, and detailed stream erosion analysis undertaken by Cardno. The study catchments made up approximately 2.5% of the Auckland region.

The methodology aims to assess the stability of stream channels during a 2yr ARI peak flow. The 2yr ARI peak flow was chosen as an indicator of bank forming flows and is similar in magnitude to the mean annual flood (MAF). High resolution LiDAR data flown in 2016 was used for the assessment. A 1m DEM, produced from the LiDAR data, was used as the basis for the work and channel geometry. An overview of the methodology undertaken for this work includes:

- Produce a stream layer
- Divide the stream layer into stream reaches
- Calculate the bed slope for each stream reach
- Estimate the 2yr ARI flow for each stream reach
- Calculate the associated hydraulic radius
- Calculate the associated boundary shear stress
- Calculate the excess shear stress for each stream reach
- Symbolise the stream layer based on the excess shear stress.

Further explanation of these steps is outlined below.

3.3 METHODOLOGY

The stream layer was created from the existing Auckland Council overland flow path layer, produced using GIS tools (Irvine & Brown, 2013). Overland flow paths with a catchment area of >20ha formed the stream layer and piped streams were removed from the dataset.

For the eight catchments in this study the stream layer was split into 819 reaches, considering confluences, with lengths ranging from 8.5-895m with an average length of 190m. Over 90% of the stream reaches were less than 400m in length and over 158km of stream length was assessed.

The average bed slope, as an approximation of the total energy slope, was calculated by dividing the elevation difference between the start and end of each stream reach by the length of the stream reach. Due to LiDAR limitations, a few stream reaches had very low or negative gradients. These stream reaches (less than 0.2% gradient) were set at 0.2% slope to ensure Manning's capacity calculations were more realistic and to approximate the assumed energy grade line slope. Similarly, 25 of 829 (3%) stream sections had very high slopes; greater than 5%. These were manually checked for their validity. Stream reaches that were erroneous were removed from the dataset. These were typically where the mapped stream alignment was offset from the stream channel because of either using a 'filled' DEM or heavy vegetation cover above the streams.

The 2yr ARI flow was calculated for 7 locations of varying catchment size and shape, and slope, for three of the catchments (Rangitopuni, Awaruku and Omaru) using the TP108 (ARC, 1999) method. A relationship between the 2yr ARI flow and catchment area was generated by fitting a curve to the 7 locations. The formulas from the curves (example provided in Equation 2) were then used to estimate the 2yr ARI flow for each stream reach as a function of the catchment area. Flows were calculated for the 2yr ARI event considering existing and future land use development. Climate change was not considered in this pilot study. Curve Numbers (CN) of 74 and 98 were used for the pervious and impervious components respectively for all catchments. The existing development for rural and urban catchments were assumed to be 0 and 50% impervious respectively and the future development were assumed to be 60% impervious. Comparison with flows calculated using the TP108 graphical method shows the flows were generally within ±15%. Equation 2 was used to estimate the 2yr ARI flow considering future development for each stream reach.

$$Q_{2yr}=0.139A^{0.814} \qquad (2)$$

Where,

Q_{2yr} is the 2yr ARI peak flow (m^3/s)

A is the catchment area (ha)

The hydraulic radius was calculated using a combination of GIS, programming and hydraulic modelling tools. A stream cross-section was extracted at the mid-point of each stream reach, perpendicular to the direction of the flow. The extent of the stream cross-sections varied with catchment area. The elevation data was imported into MIKE 11 to calculate the hydraulic radius and cross-sectional area for various levels/stages. The hydraulic radius corresponding to the 2yr ARI flood level was found, linearly interpolated if required, and attributed to each stream reach.

The average boundary shear stress was calculated for each stream reach, considering existing and future development, using Equation 1. The boundary shear stress, based on flow depth rather than the hydraulic radius, was also calculated. This gives a more conservative indication of the maximum boundary shear stress, acting on stream bed and toe of the bank.

In the absence of onsite data, a global critical shear stress value of 20Pa was used for this study. This is considered low and conservative for a cohesive soil with a high clay content. The intention is that the critical shear stress will be spatially varied once more site-specific data is captured. Cardno has shown critical shear stress values ranging from 6-183Pa from onsite testing in the Omaru Creek catchment (Cardno, 2017) and critical shear stress values of 5-99Pa from the Awaruku catchment (Cardno, 2015).

The excess shear stress gives an indication of the potential for the stream banks to erode. The excess shear stress was calculated for the existing and future development scenarios, using the Equation 3.

$$\tau_e = \frac{\tau_o}{\tau_c} \qquad (3)$$

Where,

τ_e is the excess shear stress

τ_o is the average boundary shear stress in Pa

τ_c is the critical shear stress in Pa

The excess shear stress for each catchment was categorised and displayed in 4 colour categories, as shown in Figure 5, for easy visualisation of erosion potential. A stream reach with an excess shear stress of between 0-1 is predicted to be stable, between 1-2 there is considered a potential for some erosion to occur, between 2-10 erosion is predicted to be occurring, and with an excess shear stress of >10 significant and widespread erosion is predicted (Cardno, 2017).

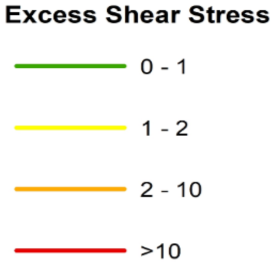

Figure 5: Excess shear stress categories

A map of the excess shear stress results for each stream reach combined with the watercourse assessment data was created for each catchment. The watercourse assessment data included the erosion hotspots and the percentage of the stream reach that was actively eroding at the time of the assessment, for both the true left and the true right streambank (displayed either side of the excess shear stress). Figure 7 shows part of the Omaru catchment with the excess shear stress and watercourse assessment data displayed.

3.4 RESULTS

Statistical analysis of the 819 stream reaches is outlined in Table 2. It shows the average calculated velocity was 1.2m/s and the average boundary shear stress was 48Pa, for the existing development scenario. It also demonstrates the potential effect of development on the parameters that affect shear stress.

Table 2: Statistics from the analysed 819 stream reaches

Parameter	Unit	5th percentile	95th percentile	50th percentile
Slope	%	0.2	3.1	1.5
Reach Length	m	64	712	193
Existing Development				
Average Boundary Shear Stress	Pa	12	136	48
Excess Shear Stress (ratio)		0.6	6.8	2.4
Flow (2yr ARI)	m^3/s	1.0	79	3.2
Velocity	m/s	0.6	2.2	1.2
Hydraulic Radius	m	0.14	1.8	0.40
Maximum Probable Development				
Average Boundary Shear Stress	Pa	14	176	59
Excess Shear Stress (ratio)		0.7	8.8	2.9
Flow (2yr ARI)	m^3/s	1.7	145	5.6
Velocity	m/s	0.65	2.7	1.4
Hydraulic Radius	m	0.17	2.2	0.48

3.5 VALIDATION

The work was validated with a detailed stream erosion study for the Omaru catchment and onsite stream erosion observations from watercourse assessments.

The Omaru catchment erosion study included onsite testing of the soils and surveyed stream cross-sections (Cardno, 2017). The average boundary shear stress provided a reasonable match to the results from the GIS assessment, as shown in Figure 6. Major differences occurred at two locations, due to the difference in the calculation of bed slope and differences in the length of the reach assessed. The calculation of the slope has been identified as a critical parameter for further analysis to reduce uncertainties.

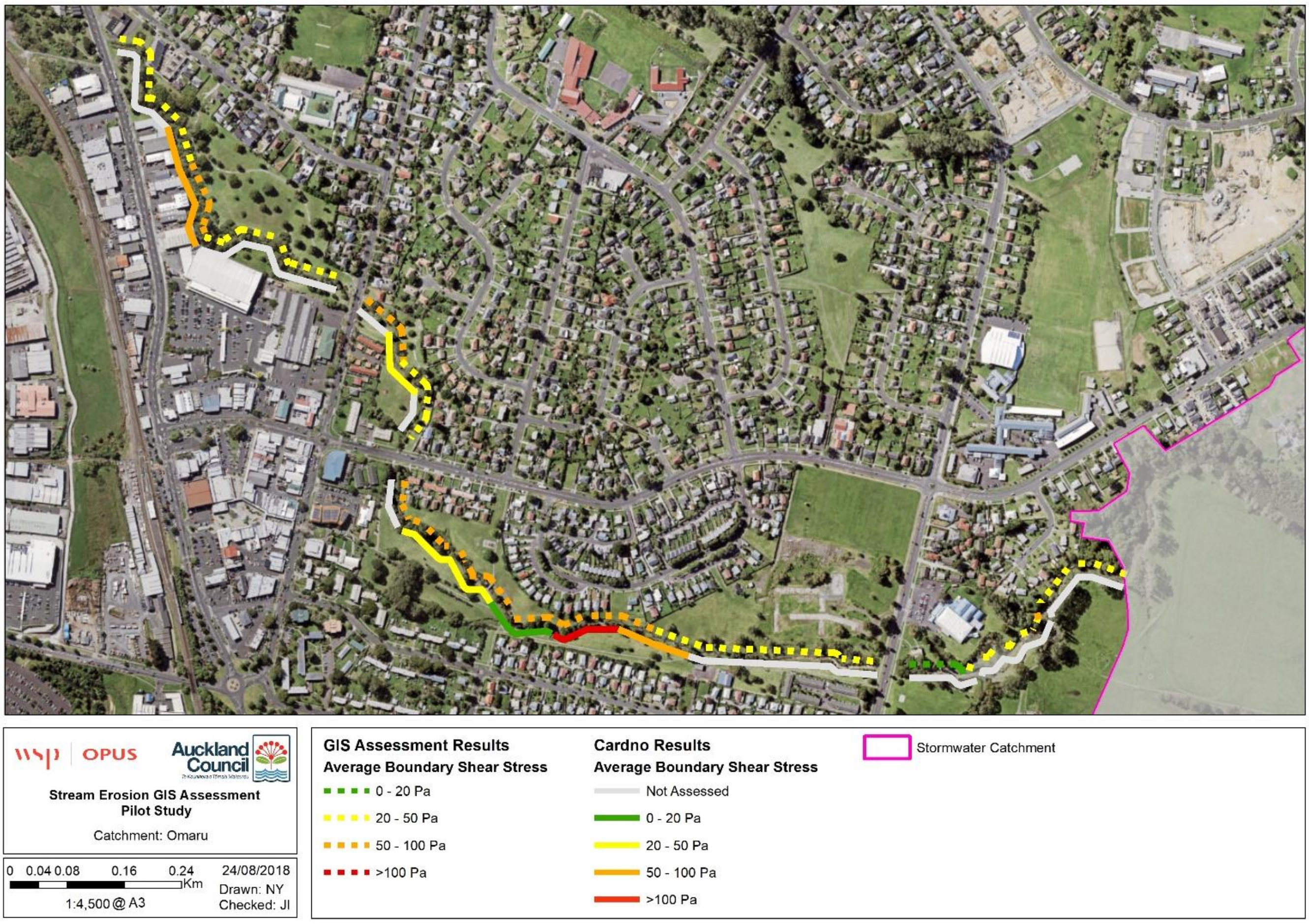

Figure 6: Comparison of the average boundary shear stress results with onsite data for the Omaru catchment

Figure 7 shows the results of the GIS assessment for the Omaru catchment, validated with the erosion specific information captured during the watercourse assessment. The excess shear results are shown as the centerline of the stream. The watercourse assessment data included the erosion hotspots and the percentage of the stream reach that was actively eroding at the time of the assessment, for both the true left and the true right stream bank (displayed either side of the excess shear stress). The results (including the other catchments) generally show a good qualitative match between modelled and observational datasets for most reaches but an inadequate match in some. This is likely predominantly due to having a limited understanding of the resisting forces of these reaches. It is considered that the boundary shear stress calculation is representative, but there are limitations in implying an excess shear stress without onsite testing of the critical shear stress of the soils. Additional onsite testing of soils from around the region is planned to more accurately account for critical shear stress from different stream bank material types and conditions.

Further validation will be undertaken when data from these additional studies and onsite testing become available.

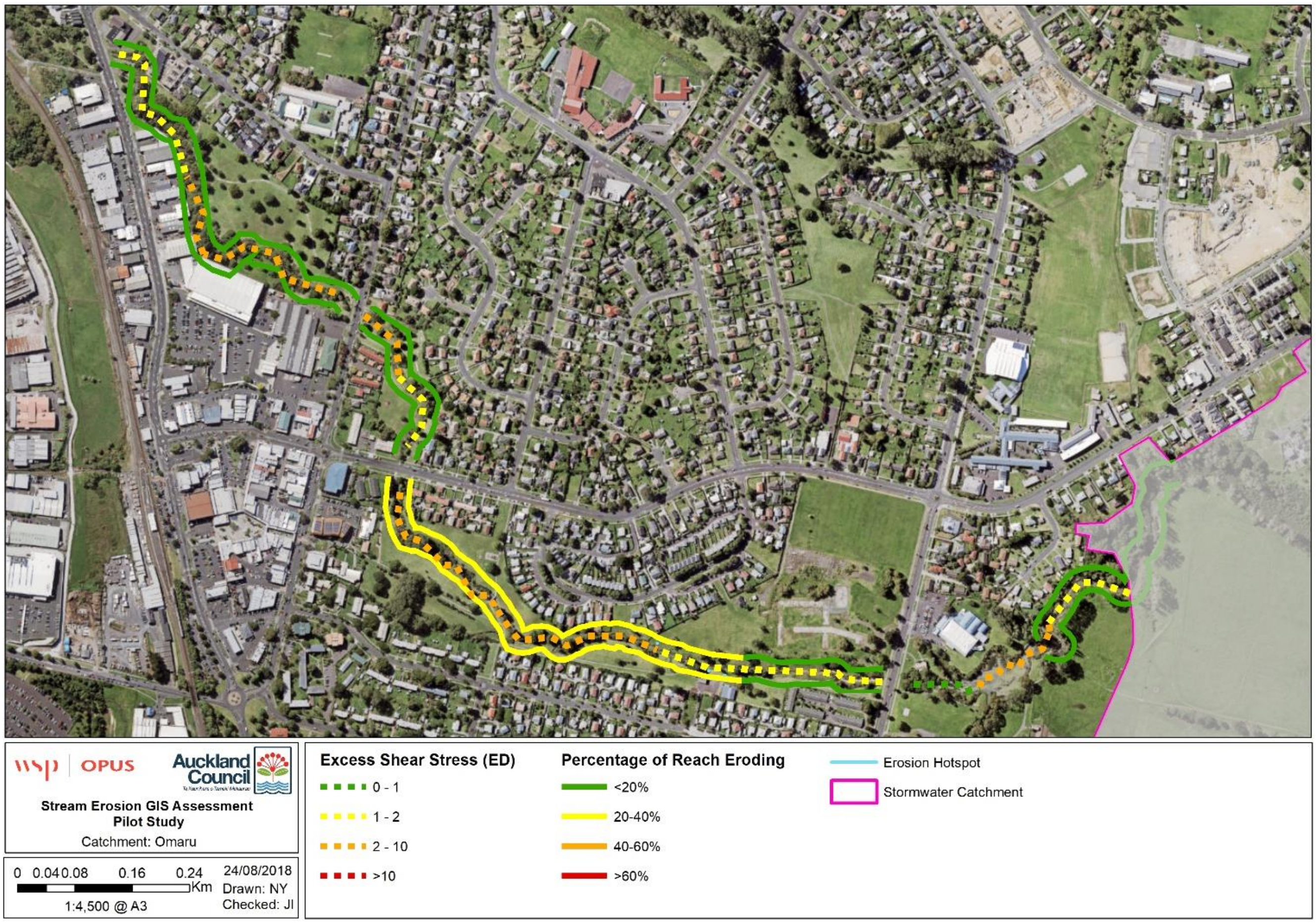

Figure 7: Comparison of the excess shear stress results with watercourse assessment data for the Omaru catchment

3.6 PARAMETER SENSITIVITY

With a high-level GIS assessment, it is possible certain parameters are not always extracted accurately. Sensitivity analysis was undertaken to better understand what parameters are critical to being accurate and what are less critical (or where assumptions or approximations could be potentially made).

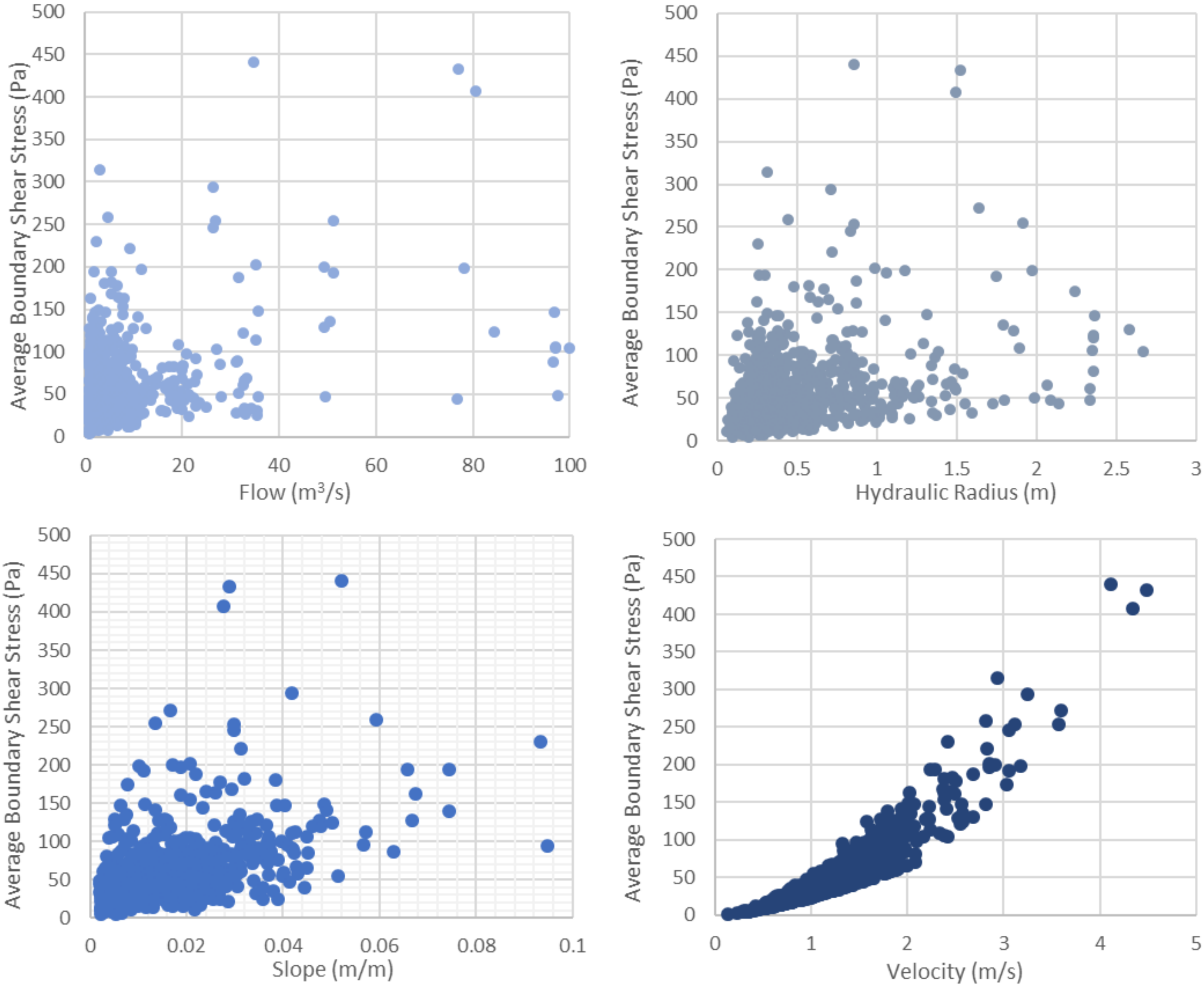

Figure 8 shows graphs of the average boundary shear stress to the input variables of flow (or catchment area), hydraulic radius, slope and velocity.

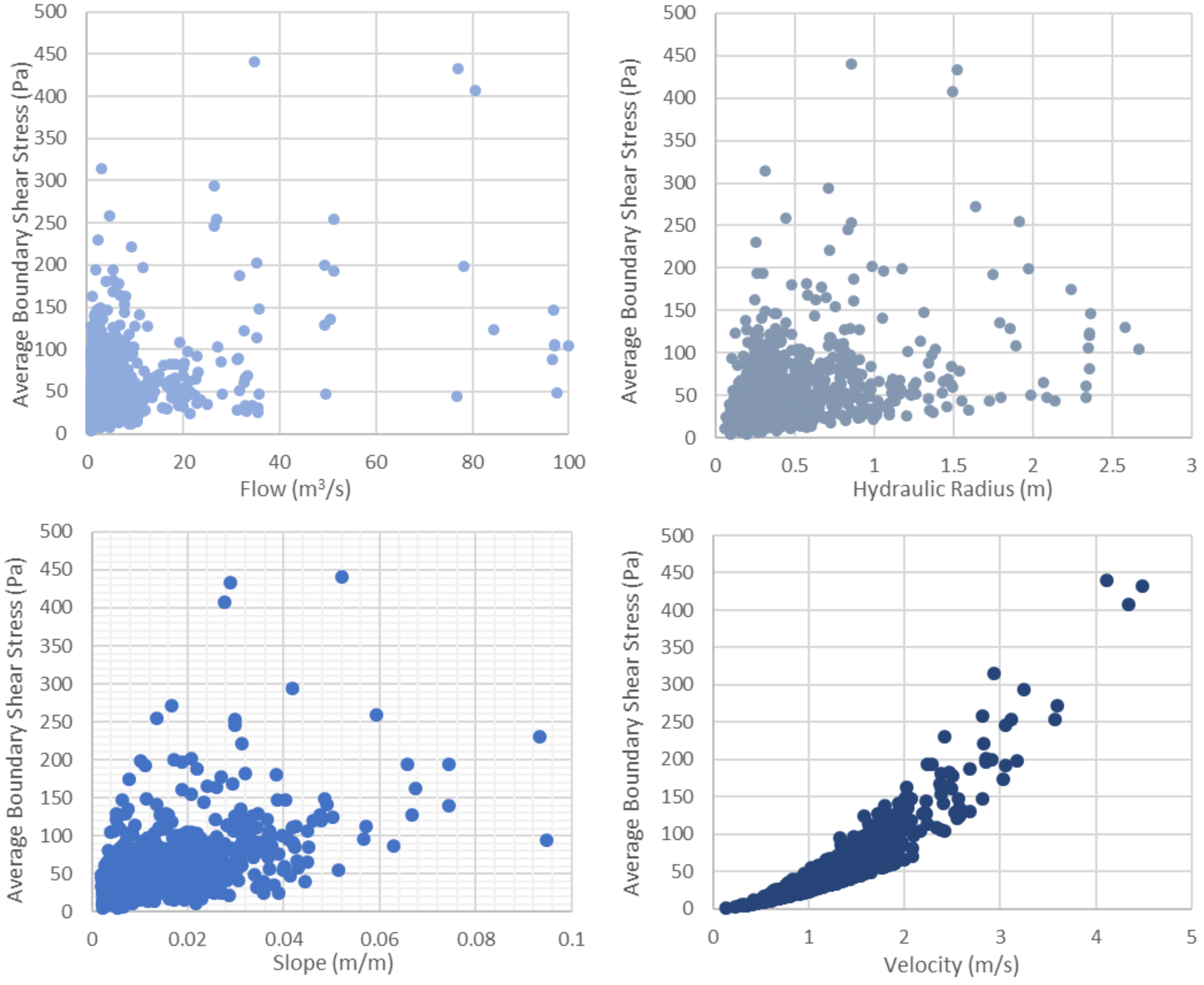

Figure 8: Graphs of average boundary shear stress and various parameters

From the graphs there appears to be:

- A weak positive relationship between the average boundary shear stress and the flow or catchment area. This indicates streams with larger catchments will experience higher average boundary shear stresses.
- A weak positive relationship between the average boundary shear stress and the hydraulic radius (or flow depth). This indicates higher flow depths increases the average boundary shear stress.
- A positive (possibly non-linear) relationship between the average boundary shear stress and the stream gradient. The indicates steeper streams will have higher average boundary shear stresses and likely a larger variability of shear stress values.
- A strong positive non-linear relationship between the average boundary shear stress and the velocity of the flow. This indicates as stream velocities increase the average boundary shear stress increases even more rapidly.

Further analysis of those parameters with the greatest potential to affect shear stress was undertaken. The parameters were increased by an arbitrary 20% and the associated increase to the boundary shear stress was quantified. Table 3 summarises the results for

812 stream reaches. On average (mean), increasing the flow, Manning’s number and cross-sectional areas by 20% increases the boundary shear stress by 6-8%. Increasing the slope by 20% resulted in on average a 16% increase in the boundary shear stress. This information is important in understanding the effects of underestimating or overestimating some of the parameters. It is unlikely the flow, Manning’s number and cross-sectional area are underestimated or overestimated by much more than 20%. However, there is a potential the slope could be out by 100 or even 200%. Given the sensitivity of boundary shear stress to slope and the difficulties with measuring or approximating the energy slope, this is the most important and critical parameter to estimate accurately.

Table 3: Sensitivity of boundary shear stress to various parameters

Input Parameters	Percentage difference in boundary shear stress			
	Min	Max	Median	Mean
Flow +20%	-10.4%	20.0%	7.9%	7.6%
Manning’s number +20%	-10.4%	20.0%	7.9%	7.6%
Cross-sectional area +20%	-22.3%	49.7%	7.9%	6.3%
Slope +20%	9.5%	33.3%	15.5%	15.7%

3.7 LIDAR CROSS-SECTION ANALYSIS

The validity of using LiDAR extracted cross-sections for the calculation of average boundary shear stress was explored, by comparing LiDAR to surveyed cross-sections at 72 locations. The locations were a selection of both urban and rural streams with varying catchment areas. Figure 9 shows the difference between the channel geometry determined from both a surveyed and LiDAR cross-section extracted from a 1m DEM. Generally, LiDAR described the stream bank geometry very well. The exception, as shown in Figure 9, was the representation of the low flow channel and its invert. This is considered primarily because LiDAR does not penetrate the water surface or vegetation cover and relies on the interpolation of points from either side of the streambank above the water surface (hydro-flattening).

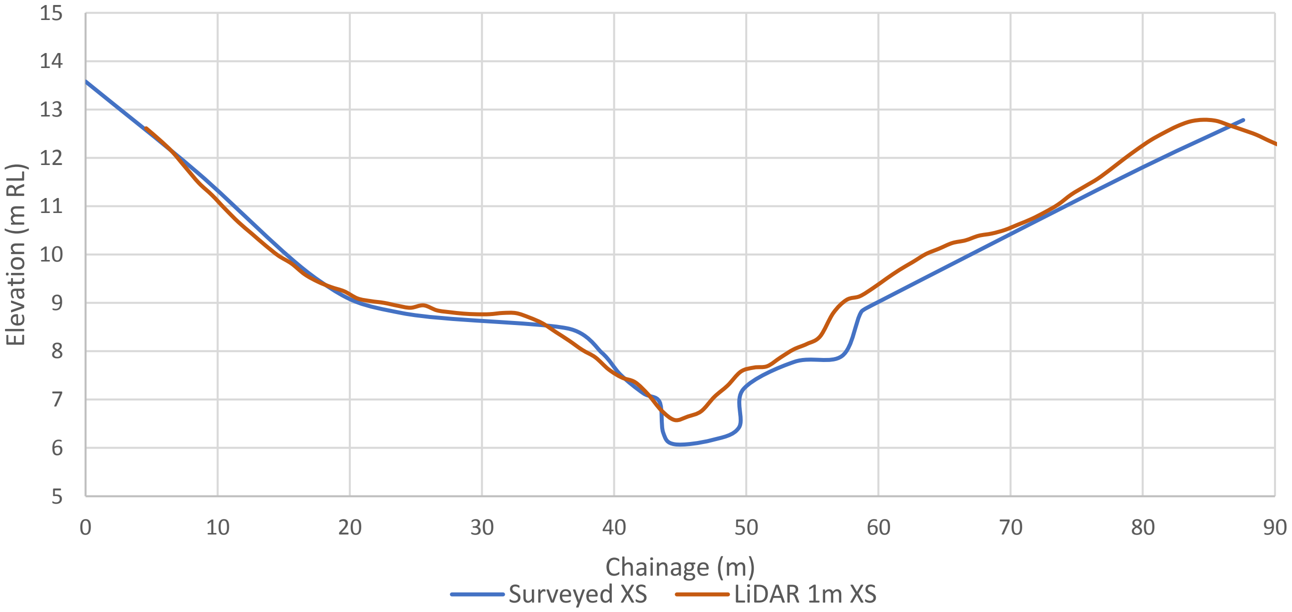

Figure 9: Comparison of the channel geometry between a surveyed and an extracted LiDAR cross-section

Table 4 outlines the numerical differences in stream channel geometry obtained from both LiDAR and surveyed stream cross-sections. LiDAR on average estimated the invert level of the stream channel to be 0.9m higher than the corresponding surveyed cross-section. Consequently, the LiDAR cross-sections overestimated the cross-sectional/flow area by an average of 14% and the flood level for a 2yr ARI event by 0.46m. The LiDAR cross-sections underestimated the flood depth by on average 0.45m and the hydraulic radius by 0.27m. The velocity remained largely unchanged. The calculated differences in these parameters resulted in only an average 12Pa difference in average boundary shear stress (Table 4). This is relatively small. The calculated average boundary shear stress derived from LiDAR data could be adjusted using a factor (like 12Pa) to minimise any underprediction in shear stress in the future.

Table 4: Differences in stream channel geometry parameters with surveyed and LiDAR extracted cross-sections

Parameter	5th percentile	95th percentile	Average (mean)
Invert Level (m)	0.20	1.7	0.91
Cross-sectional/flow area (%)	9% less	54% more	14% more
Flood level (m)	0.08 less	1.14 more	0.46 more
Flood depth (m)	-1.39 less	0.07 more	0.45 less
Hydraulic radius (m)	-0.84 less	0.03 more	0.27 less
Velocity (m/s)	0.06 less	0.00 more	0.02 less
Average boundary shear stress using $\gamma R_H S$ (Pa)	46 less	0.7 more	12 less
Average boundary shear stress using γdS (Pa)	62 less	5 more	21 less

Only small differences were found when extracting stream channel geometry using either a 1m DEM or 2m DEM.

Figure 10 shows the difference in calculated average boundary shear stress using LiDAR and a surveyed cross-section (using both shear stress calculated using $\gamma R_H S$ and γdS). Typically, LiDAR cross-sections underpredicted the boundary shear stress and the majority of the time were within 20Pa.

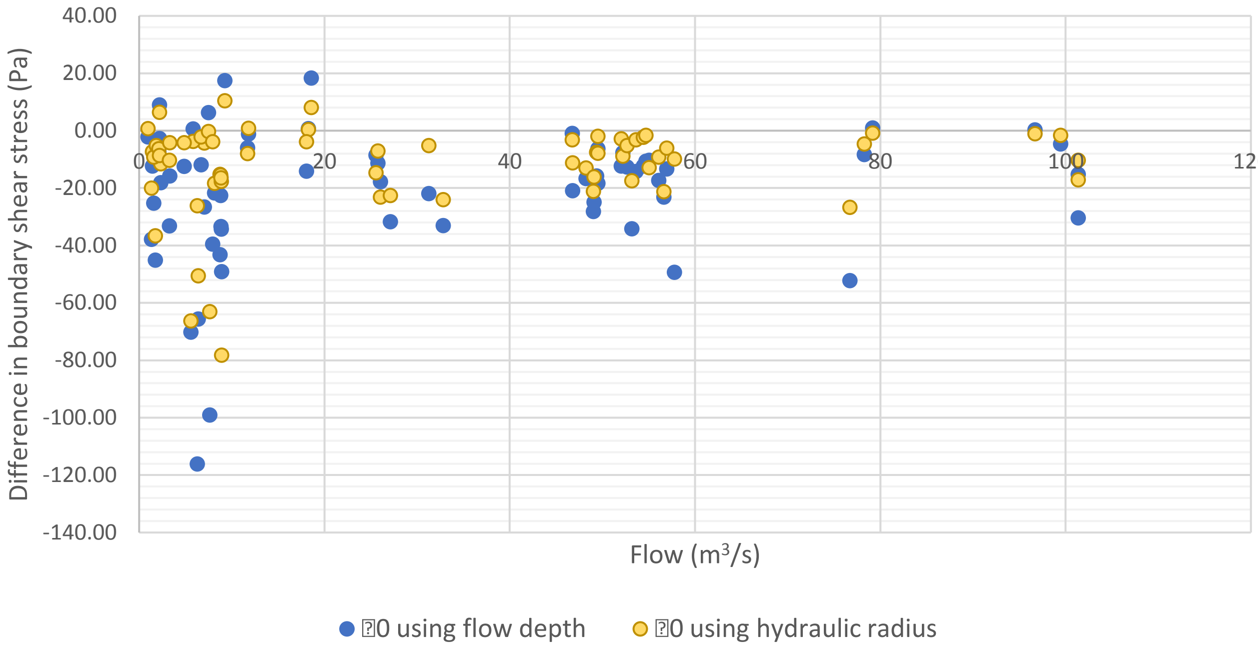

Figure 10: Difference in calculated average boundary shear stress for the 72 cross-sections

Figure 10 shows that the calculated average boundary shear stress (using $\gamma R_H S$) gives less error than γdS. This is because R_H is calculated by dividing the flow area by the wetted perimeter which are less susceptible to errors than the flow depth. Flow depth is particularly sensitive to the stream channel invert level.

3.8 LIMITATIONS AND FURTHER WORK

The following limitations have been identified from this work:

- Calculation of the stream slope using a DEM is a main limitation as:
    - The energy grade line slope was approximated using stream bed slope.
    - It is dependent on the resolution and quality of LiDAR captured points in the stream channels, and their ability to penetrate dense vegetation.
    - There were occasions where there was misalignment of the mapped stream channel, from the overland flow path layer used as the basis for the stream layer.
- Critical shear stress values may vary greatly across the region and even within a catchment because of differences in geologic and morphologic factors. This study used a global critical shear stress value of 20Pa. This will be refined once site specific data is captured.
- The 2yr ARI peak flow was calculated using a power function that best represents the relationship between catchment area and flow. Sub-catchments with very high or very low slopes will have a greater error in the predicted 2yr ARI peak flow.
- A global Mannings number for the roughness of the streams of 0.05 was used. This is to account for the bed and bank roughness and includes some sinuosity in the stream channel.

Future work will refine the parameters and mitigate the limitations to improve the reliability of the data. Improvements to the methodology could include:

- Ways to minimise potential errors within the calculation of stream slope, including smoothing distances and calculating the energy grade line.
- Undertake critical shear stress testing to better understand the variability and appropriate values across the region.

Once suitable reliability has been achieved, the next step is to produce the stream erosion GIS assessment dataset for the region.

4 CONCLUSIONS

The following conclusions can be made from this paper:

- Auckland is currently experiencing extensive stream erosion issues caused by historic development and land use changes.
- Continued development and land use changes, from high population growth, have the potential to exacerbate stream erosion issues if appropriate management actions are not implemented.
- Auckland Council is embarking on a widespread and comprehensive programme to proactively and better manage stream erosion in the region, to ensure the streams are healthy, stable and valued.
- A programme of works, to better understand and manage the stream erosion issue, has been developed, with several pieces of work already initiated (e.g. the stream erosion GIS assessment).
- The research described in this paper is focused on providing a regional scale assessment which can be incorporated into future planning decisions to better inform decision makers on future risks to streams from land-use change and identify areas for more detailed investigation of erosion risk.

The following conclusions can be made specifically from the stream erosion GIS assessment pilot study:

- It is feasible to efficiently estimate the boundary shear stress for all stream reaches in the Auckland region using LiDAR data and GIS.
- Slope and critical shear stress are the key parameters when assessing the stability of a stream. These parameters provide the most uncertainty and are inherently difficult to accurately estimate and to measure onsite.
- LiDAR can be used to extract channel properties with relatively small errors in boundary shear stress calculations. LiDAR extracted cross-sections, from 72 locations, underpredicted the stream invert levels by on average 0.9m, overestimated the cross-sectional area by 14%, and underestimated the flood depths and levels by on average 0.5m. However, the velocity remained largely unchanged and the difference in measured geometry only resulted in on average 12Pa difference in average boundary shear stress. This average difference can be factored in to the calculation of average boundary shear stress to further reduce any error with using LiDAR data.

- Average boundary shear stress (calculated using LiDAR cross-sections) using $\gamma R_H S$ provides less error than calculating boundary shear stress using γdS.

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