20 YEARS OF WATERCOURSE ASSESSMENTS - RESURVEY IMPLICATIONS FOR FRESHWATER MANAGEMENT

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ABSTRACT (500 WORDS MAXIMUM)

Watercourse Assessment (WA) surveys in the Auckland region were first undertaken on the North Shore in 2002. WA surveys provide a baseline condition assessment of watercourses including ecological function and habitat, the state of stormwater infrastructure in the watercourse corridor and conveyance capacity. With robust field survey methodology and data quality assurance processes, information collected informs the effective management at a catchment scale. To date, over 1,400 km of streams have been surveyed, mostly from urban streams but expanding considerably into rural areas where future growth is predicted.

The WA Methodology (WAM) is now 20-years old. Despite this, many of the parameters measured remain the same or very similar to the original method. This consistency in methodology permits the assessment of change in WA indicators over the two decades since original baseline surveys through a resurvey.

To date, four catchments have been resurveyed using the WA methodology, each of these with differing urban growth and stormwater infrastructure changes. Of these, Kahika was almost fully developed when originally surveyed in 2002 with stormwater infrastructure focused on conveyance only, with limited stormwater treatment. Oteha Valley was originally surveyed in 2003 immediately following large-scale greenfield development, with stormwater network designs following Auckland Council's TP-10 guidelines. Lignite, initially surveyed in 2002 has continued to develop over the last 20 years with an increase in residential land use, much of it following TP-10 guidance. The fourth catchment resurveyed is Long Bay (Vaughan's Stream), originally surveyed in 2002 and this catchment has experienced by far the greatest land use change over the last two decades (e.g., shifting from 71% rural to 63% residential). Development of Long Bay was undertaken under a structure plan.

This paper provides an overview of key changes observed after two decades as assessed through the WA, and how our streams continue to respond to differing land use pressures and management. Management of Freshwater health is a key regulatory requirement of Auckland Council and the WA offers insights on the responses of streams at a catchment scale to management decisions. Our talk will summarise 20 years of changes in bank stability, riparian condition, and the effectiveness of stormwater infrastructure, most notably stormwater outlets.

Improving our understanding of freshwater responses to land use change as well as development rules, under varying stormwater management provides valuable insights to future planning of our urban and urbanising catchments. Regulators and Entities alike are now obliged under Te Mana/Mauri o te Wai, to prioritise and deliver outcomes for the health and wellbeing of freshwater above all other considerations (National Policy Statement for Freshwater Management 2020, Resource Management Act 1991, Water Services Bill 2). Long-term datasets and the ability to repeat measures incorporating stream health at 10 to 20 year intervals provides a meaningful measure of waterway health trajectories. The WA programme provides a powerful means of assessing and demonstrating improving delivery of statutory functions, outcomes from stormwater network users and investment and decision-making at catchment scales.

KEYWORDS

Watercourse Assessment Resurvey, Geomorphology, Stream Management, Erosion, Stormwater Infrastructure Condition, Operation and Maintenance; Land Use Change, Monitoring.

NOMENCLATURE

Abbreviation	Definition
WA	Watercourse Assessment
WAR	Watercourse Assessment Report
WMP	Watercourse Management Plan
WAM	Watercourse Assessment Methodology

PRESENTER PROFILE

Adray Minh Quang Nguyen (Auckland Council)

Adray has a background in aquatic ecology and environmental science. They are passionate about using environmental science, geographic information systems, and community awareness to address environmental issues. They are currently managing the Watercourse Assessment programme and Rural GIS Enterprise for Auckland Council.

Andrew Rossaak (Morphum)

Andrew has 25 years ecological and environmental experience in diverse landscapes, and is passionate about wetlands and watercourses. Andrew has been involved in Watercourse Assessments for the last 5 years. He is collaboratively working to improve ecological outcomes and the sustainable provision of ecosystem services through innovative and practical processes.

Elizabeth Morrison (4Sight – Part of SLR)

Elizabeth's key area of expertise is restoration ecology. She has worked on projects in various ecosystems from native bush, wetlands, streams and riparian environments from project concept through to implementation. Her projects often involve collaborating with multiple technical experts and stakeholders to ensure desired ecological outcomes are achieved.

1 INTRODUCTION

Freshwater is essential to life and one of our most precious taonga. Clean water and healthy waterways are essential to our lives and the ecosystems they support. It is vital to our environment, our economy and our survival. Although water is widely regarded as one of the world's most important taonga, freshwater ecosystems are constantly threatened by human activities, both directly from activities such as habitat loss, flow alteration, abstraction, and pollution; and indirectly through changing land cover, urbanisation and increasing demands for food supply and other natural materials, and a poor understanding of their natural habitat values. More recently, introduced species and climate change are also placing additional pressure on our resources.

A major challenge for natural waterway professionals in protecting and restoring waterways is the overall complexity of freshwater systems and how they respond to human activities. This is because waterways evolve and change in ways that are often unexpected, they are dynamic ecosystems, not static ones. Unlike many human-mediated causes and effects which occur over short time frames, waterways adjustment and evolution is often a very slow cumulative process. The cumulative effects of degradation may only become apparent many decades after their initiation, but the recent change is often blamed for the degradation rather than the cumulative effect. This can be particularly challenging in urbanised environments with ongoing development and intensification.

Significant efforts and investments are currently being made to improve drainage to natural waterways in urban areas via built stormwater networks and in rural areas via drainage networks. However, very little effort has traditionally been provided to determine what effects these investments and associated altered hydrology have on the natural channel systems themselves. Urban water management of these systems often defaults to proxy measures associated with peak flow management through infiltration and retention/detention systems. These are modelled via hydrology and are mostly focused on flood risk management. In rural areas, altered hydrology is rarely, if ever assessed at all. More direct measurement of effects are available however and greater uptake of these methods will become more necessary to meet policy requirements and public demands associated with the quality of our freshwater habitats.

Implementing Te Mauri o te Wai requires a change in approach to meet our commitment to protecting and restoring freshwater ecosystems. We need to approach natural watercourse management with much more detail and investment than has been seen in the past, and with greater certainty about the outcomes of the investments. Therefore, we need to survey and record the condition of our watercourses to inform our work. In the Auckland region, this process began around 2002 when the first whole-of-catchment watercourse assessment methodology (then referred to as Streamwalks) was developed and implemented.

The Streamwalk Survey concept began at North Shore City Council to support the "Effects Assessment" components of the North Shore City Stormwater and Wastewater Network Consent applications. The Streamwalk survey methodology was subsequently formalised and introduced as Watercourse Assessment Methodology (WAM): Infrastructure and Ecology (Version 2.0) in 2016 (Lowe et al., 2016). This assessment methodology has been applied to many catchments across the region and more recently, in other regions.

Whilst the geographic range of WA’s continues to expand to new catchment areas, we have also started re-surveying catchments. The purpose of the resurveys is to assess the current watercourse state and to evaluate the extent of change since the initial surveys. The original Long Bay, Kahika, and Lignite catchments were surveyed in 2002, while Oteha Valley was surveyed in 2003. These catchments were at different stages of urban growth and followed different stormwater infrastructure decisions. Starting with Kahika and Lignite in 2019 and Long Bay and Oteha Valley in 2021, re-survey data is now available that allows us to much more quantitatively assess how urban streams change over time and how well existing stormwater network infrastructure performs in the context of receiving environment effects and from overall asset management perspectives.

This paper provides an overview of the key changes of some of the data collected in WA over two decades and how our streams have responded to different development pressures and management practices, with the hope of highlighting the potential of WA resurvey data to inform future stormwater planning, guidance, and investment decision-making.

2 WATERCOURSE ASSESSMENT METHODOLOGY: HISTORY AND PREPARING FOR TOMORROW

The WA field surveys provide a snapshot of the catchment watercourses and associated stormwater infrastructure at a given time. Watercourse Assessment Reports (WAR) provide baseline information on the existing condition of watercourses that can be used to inform decisions on stream health, improve degraded streams and address specific stormwater issues (asset condition and conveyance) while considering development pressures and the essential role of urban streams in conveying stormwater (Lowe et al., 2016). WARs also identify erosion hotspots, engineering issues and propose Enhancement Opportunities, and thus significant multifactorial benefits can be achieved across the catchment within the operational, environmental, economic and social constraints (Lindgreen, Turner and Ansen; 2016).

The WAM rationalises and improves on the previous specification the Stream Assessment Survey and Watercourse Management Plan Specification – version 1.4 in 2012. The methodology has also been developed with consideration of the Stormwater Asset Data Standard (July 2014). Where possible, the GIS data (pick/selection lists in Watercourse Assessment Geodatabase) matches the Auckland Council asset data standard (e.g. material types and dissipation structures) allowing better alignment with the Auckland Council strategic direction and management of the natural asset (Lowe et al., 2016).

The data collected as part of a WAR provides information for identifying projects that may be included in Asset Management Plans. WARs provide recommendations on management zones as well as offer enhancement opportunities within the catchment. In addition, all the data collected as part of the geodatabase is designed to be integrated into AC's GIS data systems and used as a raw data source for interrogation and analysis for a number of outcomes (Lowe et al., 2016).

The process and workflow for undertaking a WA are depicted in Figure 1

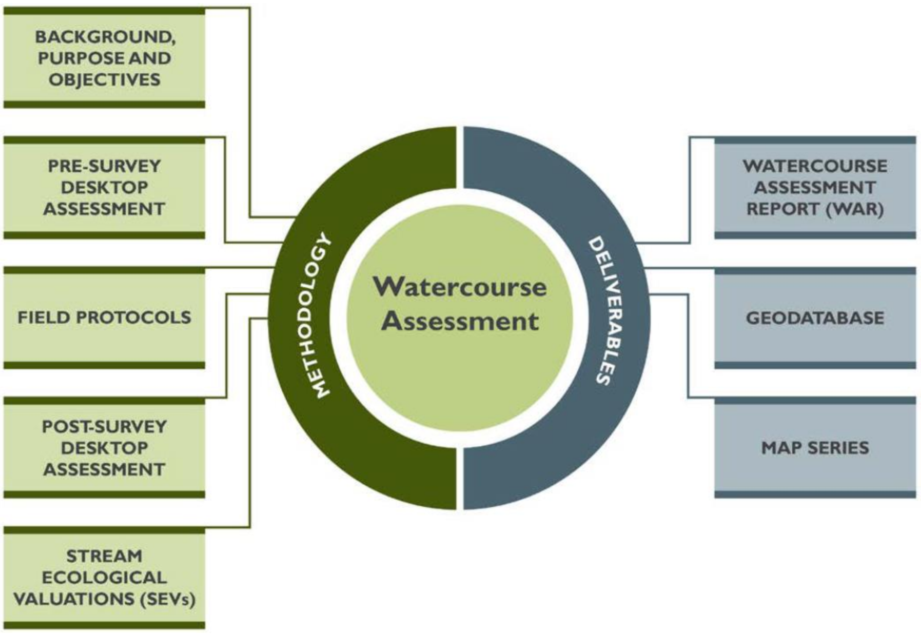


Figure 1: Overview of the Watercourse Assessment Methodology (WAM, Lowe et al., 2016)

The WA and its deliverables are an essential resource for watercourse management in the Auckland region. Given the robust methodology and well-established database, the reassessment provides a useful understanding of how our watercourses and stormwater infrastructure have responded to land-use change and growth pressures within each catchment. The outputs of WAR resurveys provide AC with information on where watercourses have been modified, how natural streams and built infrastructure have changed over time and supply AC with the data needed to improve the management of urban watercourses and stormwater infrastructure by identifying issues and opportunities for network renewals and stream restoration activities.

The resurvey methodology follows the existing WAM 2.0, however, it primarily focuses on data comparison to highlight changes over time with the intention that a full analysis of the WAR data can still be obtained from the resurvey data. The resurvey analysis is, however, limited to the parameters assessed in the original surveys. The resurveys have been whole-of-catchment based, including the original survey extent, where possible. There are some instances where watercourses had been piped and where it was appropriate to survey additional watercourse reaches (however analysis in the resurvey has been restricted to the same streams as the original survey). The data gathered can identify vulnerable reaches of the watercourse, assess the effectiveness of previous remediation and mitigation works, and inform catchment wide management decisions regarding the effectiveness of the stormwater network and future development applications.

3 CATCHMENT LAND USE CHANGE

Land use change and the way these changes occur play a critical role in the health and well-being of ecosystems. For example, it is well-known how changes in impervious levels can dramatically change peak flow velocities and durations within receiving environments. This can make streams more erosive and degrade overall ecosystem health and water quality. The levels of protection for streams have also changed over time with most recent policies aiming to limit the loss of stream habitat and protect riparian margins compared to more historical approaches.

Depending on when a catchment was developed, the stormwater management approach used to address these hydrological effects ranges from no controls to the most recent implementation of retention/detention controls. When assessing changes in WA data over time, it is important to place the observed changes in some form of developmental context to support the interpretation of the data and gauge the effectiveness of stormwater management controls for stream health management. This section assesses land use changes in each of the four assessed catchments and relates developmental timeframes to the context of stormwater management requirements needed to support urban growth.

The four resurveyed catchments have experienced different characteristics of land use change since their original survey. This section summarises and compares these land-use changes over time in each catchment (Figures 2, 3, 4 and 5).

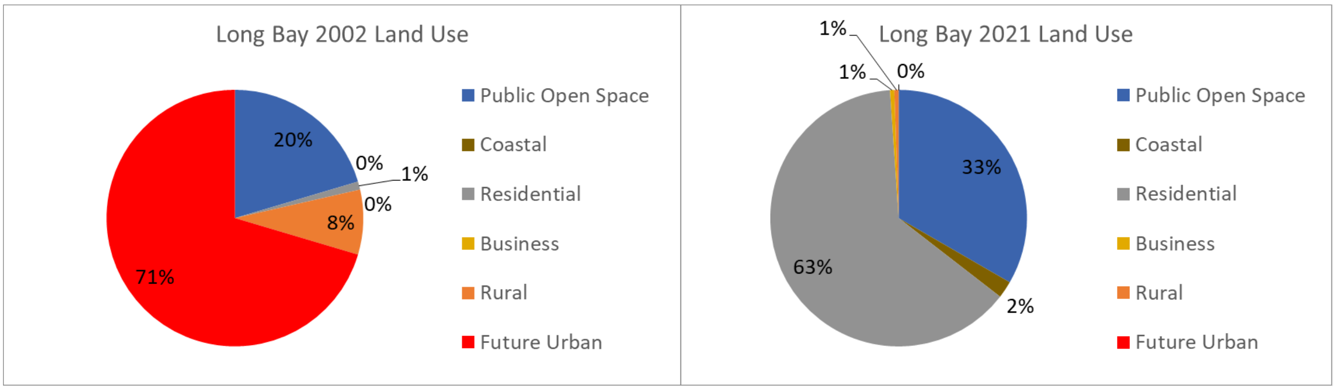


Figure 2: Long Bay Land-use changes between the WA surveys

Of the four catchments, Long Bay had the least urban development at the time of the original survey in 2002. Since 2002, the catchment has undergone increased urbanisation with a 59% increase in residential land-use (Figure 2, Davis et al., 2022).

Public open space has increased since the original survey inclusion of farmland into Long Bay Regional Park in 2008 (Davis et al., 2022). This represents more of a zone designation change rather than actual land-use change though, with much of the new "public open space" still in rural use. The resurvey also found that the upper western catchment land-use is a mixture of medium to large lot lifestyle properties bordered by steep gullies, while in the lower eastern areas the land-use is mostly recently developed residential housing areas incorporating newer stormwater infrastructure (Davis et al., 2022). Long Bay has been developed under its own Structure Plan, with stormwater management through methods and policies very similar to the current Auckland Unitary Plan incorporating more on-site retention and detention systems including rain tanks, bioretention and larger communal ponds and wetlands.

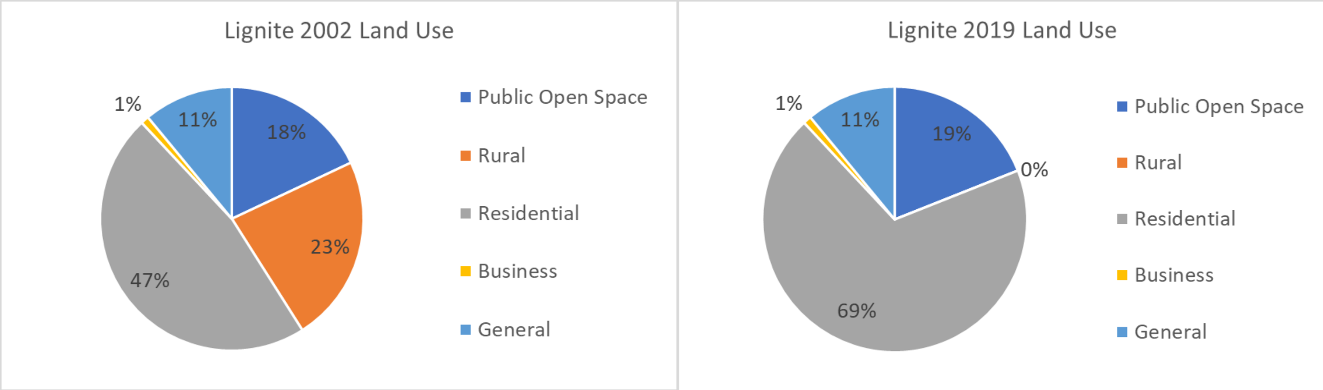


Figure 3: Lignite Land-use changes between the WA surveys

Lignite has experienced residential development since the 1970s, having been predominantly rural in the 1950s (Brockerhoff et al., 2021). The resurvey shows that while the land-use areas of Lignite' Business, General and Public Open Space have remained relatively unchanged, the catchment continued to experience urban development since the original survey, most notably with all Rural areas converted into Residential land-use (22% increase) (Figure 3). This is the greatest land-use change since 2002 in the catchment as it developed from low-density to higher-density housing through greenfield development and densification, resulting in an 11% increase in impervious surfaces (Brockerhoff et al., 2021).

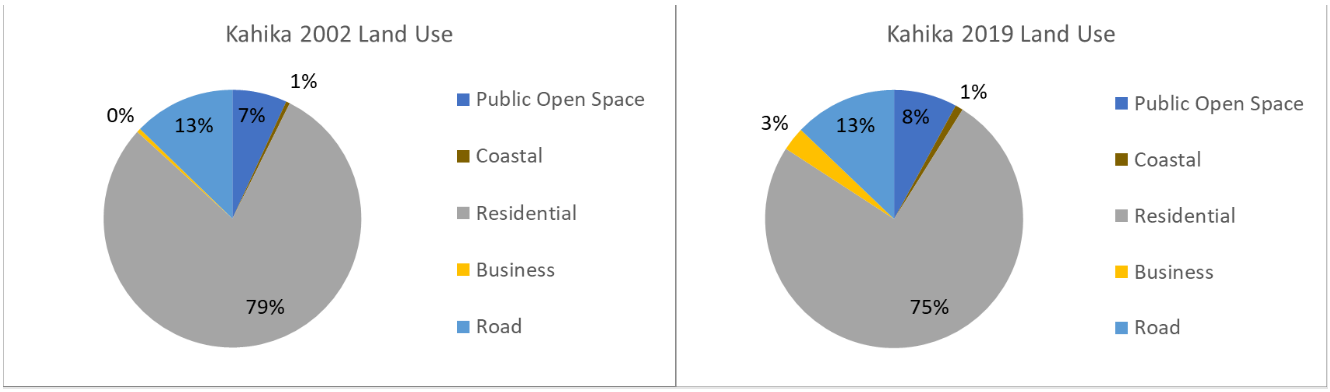


Figure 4: Kahika Land-use changes between the WA surveys

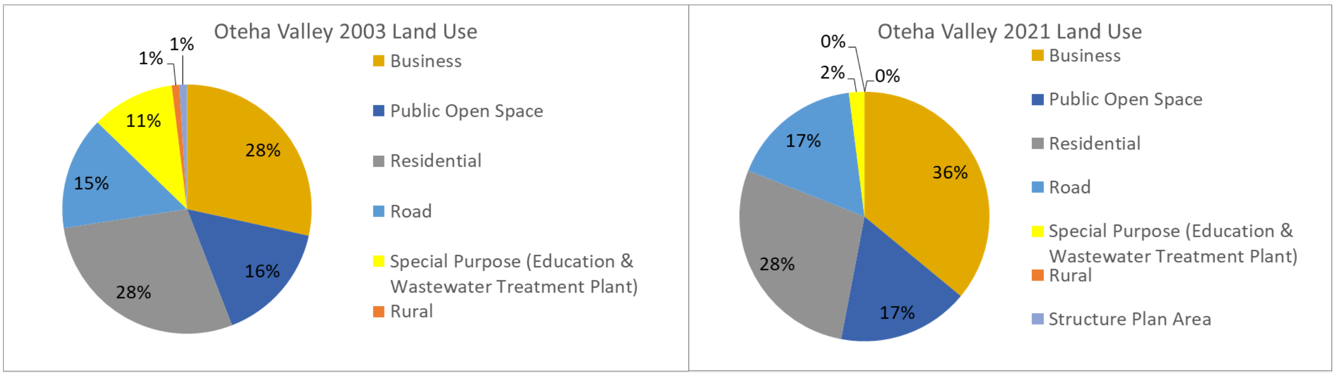


Figure 5: Oteha Valley Land-use changes between the WA surveys

The land-use composition in Kahika and Oteha Valley is very similar to those reported in the original surveys, suggesting much less urban development within these catchments (Figures 4 and 5). Kahika had the lowest land-use change out of the four catchments, with Business land-use growing by 2% and Residential land-use declining by 5% (Figure 4). This means that Kahika was almost fully developed at the time of the original survey with nearly 80% of the catchment in Residential land use, and impervious roads at 13% in 2002 (Brockerhoff et al., 2020). The resurvey also found that impervious surfaces in Kahika increased by 13% since 2002 indicating an intensification of the existing residential and business land use through infill housing and subdivision (Brockerhoff et al., 2020).

The original study of the Oteha Valley was conducted immediately after the catchment's large-scale greenfield development. Thus, the resurvey has continued to show some level of continuous development since the original survey with Business land-use area increased by 5% and Roads by 1%. Oteha Valley Special Purpose land use decreased by 9% from 11% in 2003 to approximately 2% in 2021 (Figure 5). This change is mainly the result of the Rosedale Wastewater Treatment Plant zoning change from Special Purpose in the North Shore City Council Zoning Plan to Business (Light Industrial) in the Auckland Unitary Plan (Brockerhoff et al, 2022). Added to this was the continuation of the industrial development of pasture grassland since the original survey in 2003 (Brockerhoff et al, 2022).

Development within both Oteha Valley and Lignite would have been undertaken under a TP_10 based stormwater management approach which encouraged the uptake of water quality and quantity management to reduce the effects of freshwater-receiving environments. This often resulted in the construction of larger communal pond and wetland devices within catchments to manage water quality and/or peak flows through extended detention strategies. More value was also placed on stream habitat and riparian margins at this time which emphasised a reduction in loss of stream habitat by piping or culverting and protection and planting of riparian margins around existing watercourses.

Kahika catchment was developed at a time when stormwater management was focused primarily on conveyance and moving water to the coast through pipes and outlets. These stormwater systems typically incorporate little water of stormwater treatment systems aimed at managing water quality or peak flow. While there were fewer controls in place to protect streams from piping during the main phase of greenfield development in Kahika, the very steep nature of the existing topography protected streams from direct development to a large extent, along with their surrounding riparian margins.

The land-use data captured in the watercourse resurveys highlight some valuable information about how our urban catchments change over time. An added benefit is that development and redevelopment cover a range of different stormwater management frameworks from, virtually all conveyance focussed network development (Kahika) to more recent retention/detention-based network development and more restrictive developmental controls during earthworks phases (Long Bay). Most importantly, the changes in land use highlight that urban development within a catchment is not static, but continues to evolve and, in most instances, further intensifies after the main greenfield development period is completed.

Continued intensification can have very important ramifications for stormwater management and freshwater resource health depending on how existing stormwater infrastructure is performing under the loads it was originally designed for combined with the additional loading from intensification that may not have been fully designed for as part of the original development. Therefore, The WA data can therefore provide valuable information associated with the effects of future densification strategies promoted through policies like the National Policy Statement for Urban Development which promotes growth and how they might impact other strategies like Te Mana/Mauri o te Wai which promotes the health and wellbeing of freshwaters. Can these policies operate together and achieve the outcomes sought by both at the same time? Or will concessions or modifications to policies, the way we develop and intensify, or the way we manage our urban stream environments?

4 RIPARIAN VEGETATION

Riparian vegetation provides a range of ecological services from habitat provision, filtration of overland flow, stream shading, water temperature control, and bank stability (Hughes 2016, Marden et al., 2005, Riis et al. 2020). As such riparian vegetation enhancement is a mainstay in stream and catchment management and is one of the key assessment criteria of the WA methodology. The successional stage of riparian vegetation is recorded, as well as the longitudinal and latitudinal extent (buffer width), dominance of native or exotic species, and level of stream shading provided.

In a similar manner to stormwater infrastructure development, the ways in which riparian margins are managed has changed over time. The general trend has been increased protection and enhancement of the riparian zone through the years in association with the increased protection of natural stream channels. Along with increased protection, another trend has been an increase in riparian widths over time, with widths typically increasing from 2 – 5 m if topography was favourable to urban development, through to 10 m in many urban zones and as much as 20 m or more in less intensively developing areas.

The resurvey catchments showed a pattern over time of increased riparian cover, even in catchments with intensive urbanisation such as Long Bay (Davis et al., 2022) and Lignite (Brockerhoff et al., 2021). In the Long Bay catchment, the shift in land use from rural into mixed residential housing improved overhead cover in places, especially in the lower catchment, as riparian planting programmes are triggered by subdivision of land parcels. The Lignite and Kahika catchments had large existing riparian buffers at the time of the original surveys, and the increase in riparian cover was likely due to natural regeneration and canopy infilling (Brockerhoff et al., 2002, Brockerhoff et al., 2021). Although the Oteha Valley catchment has been heavily modified, the main watercourses in the catchment have retained riparian vegetation buffers. Similar to Long Bay, the largest change in stream shading in the Oteha Valley catchment was in the smaller streams where riparian planting programs had more recently been completed and were now successfully established (Brockerhoff et al., 2023). The observed intactness of riparian margins in the Lignite, Long Bay and Oteha catchments is likely the result of improved protection given to these habitats during early development phases as a result of improved guidance and policy changes aimed at improved protection. However, the intactness of these margins in the Kahika catchment is more likely a result of topography constraining the original development, with the steep sided nature of the gullies being unsuitable for urban development at that time.

Riparian planting and management is by far the most common method implemented to manage stream bank erosion in urban streams, most notably within greenfields development areas. However, despite the riparian cover increases observed during our watercourse re-assessments, erosion susceptibility appears to have increased over time in the Long Bay (Davis et al., 2022), Lignite (Brockerhoff et al., 2021), and Kahika (Brockerhoff et al., 2021) catchments. In the Lignite and Kahika catchments, lower bank erosion was found to increase even in streams with diverse mature native forest communities. This suggests that although appropriate riparian vegetation provides some bank stabilisation qualities (Marden et al., 2005), the capacity of existing vegetation to mitigate erosion completely is not being achieved in an urban stormwater context. The prevalence of exotic ground cover vegetation was also found to increase in all re-survey catchments. This is reflective of the continued spread of pest species such as tradescantia (*Tradescantia fluminensis*), bindweed (*Convulvulus spp.*), and wild ginger (*Hedychium spp.*). Exotic groundcover pest species (*Tradescantia* in particular) propagate and spread down watercourses rapidly and form dense carpets when established which out compete native plants. These exotic species are opportunistic and species such as tradescantia have poor root systems so do not stabilise or filter overland flow as well as suitable native plants.

There were little to no changes observed in understory and canopy vegetation communities, with riparian vegetation generally maintaining the mixed or native dominated communities recorded in the original surveys (Brockerhoff et al., 2020, Brockerhoff et al., 2021, Brockerhoff et al., 2022, Davis et al., 2022). Changes in understory and canopy community composition are slower than that of groundcover vegetation, due to longer life cycles of the trees comprising these sections. It is however noted, that populations of invasive climbing pest species (such as jasmine *Jasminum polyanthum* and madeira vine *Anredera cordifolia*) were also recorded. The prevelance of pest species may drive changes in understory and canopy vegetation communities if not managed appropriately.

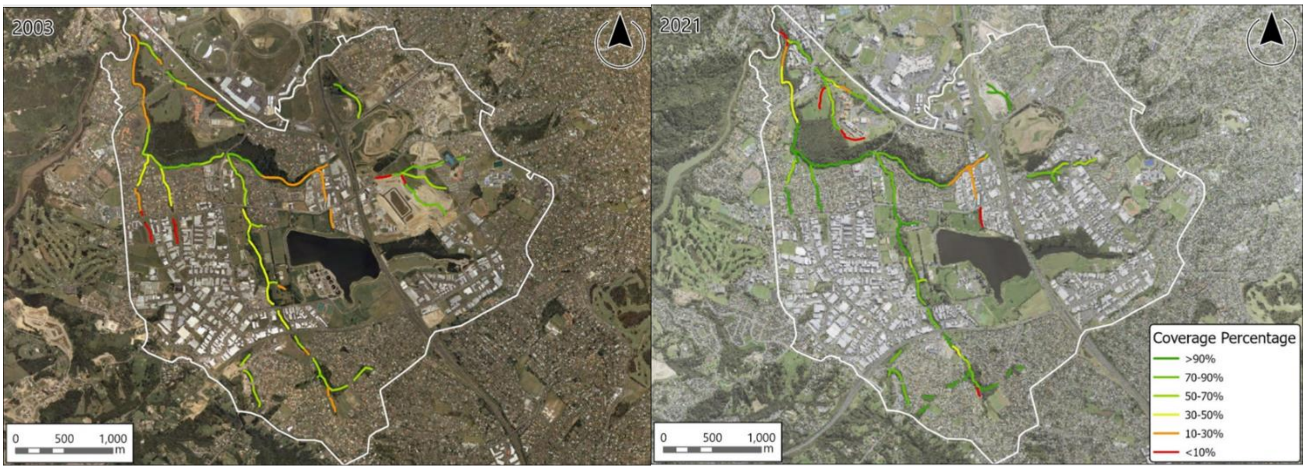


Figure 6: Overhead cover in the Oteha Valley Catchment in 2003 (left) and 2021 (right). Some reaches are absent from the 2021 map as they have been reclaimed or recorded as wetlands.

Figure 7: Agricultural land use dominated the Long Bay catchment area in 2002 (left, photo from Kokopu Connection, 2005) and newly planted riparian vegetation in 2022 (Davis et al., 2022, right).

The variance in levels of protection and riparian margin widths around streams can play a critical role in overall stream health and opportunities for enhancement of ecosystem values. In older areas of urban Auckland, these margins can be highly constrained with development occurring right up to natural bank-full level and often even extending into natural channels, narrowing their widths and reducing overall capacity. Access to stream channels for operation and maintenance of infrastructure and the natural channels themselves also is an important consideration to current and future stream management. For example, where riparian margins have been protected and enhanced in recent years, accessways for operation and maintenance to infrastructure like outlets is often not incorporated into these margins, creating significant challenges and increased costs (notably consenting costs) when infrastructure requires renewal.

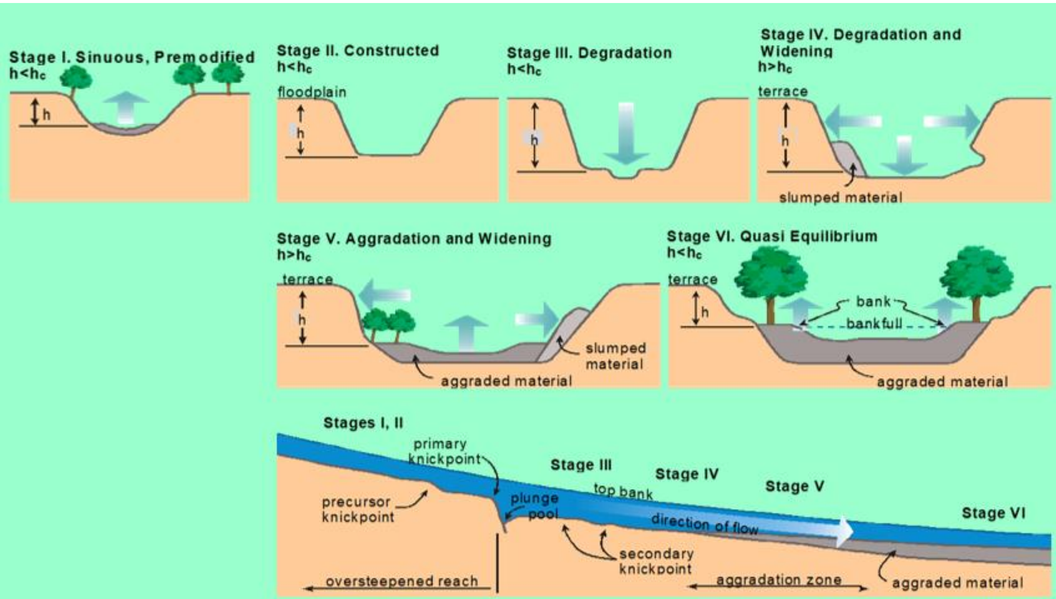
Over the last few years, AC have been undertaking research into measuring the physical benefits and additional strength riparian roots provide to stream banks to better assess benefits and likelihood of success that riparian planting can sufficiently mitigate erosive forces on stream banks. This information is also being presented at this stormwater conference (Simon et al. 2023). Benefits of riparian vegetation for erosion mitigation is measurable, but more quantifiable erosion management assessments are rarely undertaken as it is assumed that plants alone are the solution. Outcomes from these re-surveys highlight the need for more certainty around stream and overall geomorphic stability both during greenfields development phases when space is more typically available for resolving instabilities using a variety of different methods. It is also of critical importance when resolving erosion issues in brownfields areas where streams are often highly constrained by poor access. Getting erosion mitigation right first time without propagating erosion issues upstream or downstream from an existing erosion hotspot will be of critical importance for restoring streams and managing future costs necessary to improve the health and wellbeing of our urban streams.

5 BANK STABILITY & EROSION

It is often claimed that Auckland's cohesive soils are "resistant to erosion than non-cohesive streams". We are now very much aware that cohesive soils are no more resistant to erosion than non-cohesive soils, however, the way they erode and the timescales at which erosion occurs are very different. Non-cohesive streams respond rapidly to disturbance by lateral widening and rapid bank failure, whereas cohesive streams first respond with vertical incision and channel deepening before widening over much longer timescales, often multiple decades.

As our understanding of stream natural processes and how they change over time improves through the discipline of stream geomorphology, we have become much more aware of what physical processes are taking place in our natural streams – and what we can expect in the future. And the outlook is not encouraging!

The natural stream channel processes closely follows international stream channel evolution models as shown in the Figure 8 below by Simon & Rinaldi (2006). Whilst stream erosion is a natural process, a century of land use change is exacerbating the issue through altering catchment hydrology due to deforestation in rural catchments and increasing impervious surfaces in urbanising catchments. As a result, Auckland streams are becoming increasingly incised and prone to lateral bank failure.



Figures 8: Stream channel evolution models (Simon & Rinaldi, 2006)

Stages II and III represent channel incision processes of the channel evolution model which can often be overlooked and or are poorly understood as they often take place within existing stream corridors with no obvious lateral movement of stream bank margins. Because bank margins don't change apart from height, this incision is often overlooked as erosion. However, once certain bank height and soil strength thresholds are exceeded, for example "critical bank height", stream banks can no longer support their own weight, leading to bank failures and lateral widening. These geotechnical erosion processes are represented by Stages IV and V of the channel evolution model.

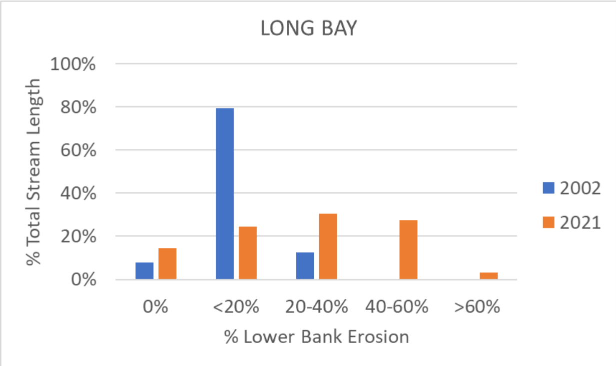
Bank failures associated with lateral widening can appear much more acute and visually dramatic as they tend to fail initially over a very short period of time. They can also much more significantly alter the path of the stream which can play havoc with built infrastructure and cause trees to fall into the channel. The high volumes of sediment generated by bank failures cause much more sediment to be mobilised and delivered to receiving environments across the region during rainfall events which is also much more visually apparent than channel incision processes.

Time is such a critical component for erosion in cohesive streams which highlights the importance of re-surveying watercourses using comparable methods to better capture these often long temporal trends. The recent re-surveys of the four catchments assessed so far show some very clear and consistent trends in erosion processes. By confirming what theoretical models show in practice, significant thought needs to be given to the future of urban stream management and how stormwater is managed to ensure benefits of infrastructure investment are realised and being made in the right areas so that the true costs of land use change are acknowledged and accounted for.

To better align the theoretical model of channel evolution with what we see in practice, we have separated the erosion information-gathering process for WA's into lower bank erosion and upper bank erosion. The lower bank has been assessed as the best measure of channel incision processes that become most notable during Stage III and IV of channel evolution – the earlier phases of channel adjust on preceding lateral widening. Upper bank stability is used to assess later phases of Channel evolution from later Stage IV and Stage V where lateral widening and bank failures have begun to occur once critical bank heights have been exceeded.

5.1 Lower Bank Erosion

Overall, the WA resurveys indicate a deteriorating trend in lower bank erosion across all four catchments (Figures 9a, b, c and d).



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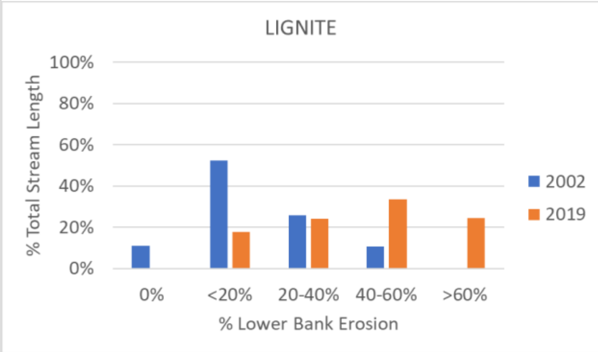

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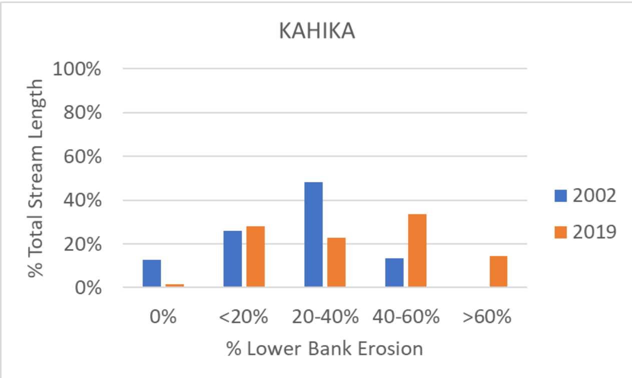

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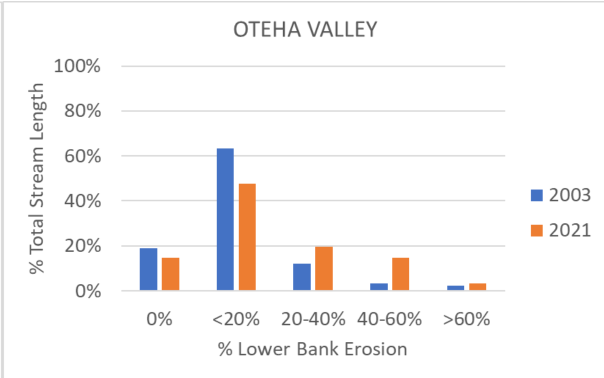


d)

Figure 9: Changes in Lower Bank Erosion percentage since the original stream survey for a) Long Bay, b) Lignite, c) Kahika and d) Oteha Valley.

There was a higher prevalence of lower bank erosion in 2022 compared to the 2002 survey (Figure 9a) for Long Bay. In 2002, bank erosion was low with most reaches characterised as "less than 20%" erosion. In 2022, scour, fluvial undercutting, and mass wasting were all common throughout the survey area (Davis et al., 2022). In urbanised rural areas where riparian planting has been installed this may be attributable to the natural process of eroding previously slumped soils as they stabilise to a more natural stream profile (Davies-Colley, 1997). Lower bank erosion was most prevalent in the upper catchment even in dry reaches, with 8% of reaches having more than 60% erosion (Davis et al., 2022). The presence of erosion in dry reaches suggests poor stormwater runoff management and it is likely that this erosion is occurring within the winter months when baseflow is higher and/or during and after rainfall (Figure 10) (Davis et al., 2022).

Figure 10: Observed changes in water clarity on the Vaughan Stream (VAUG_MAIN_8) during dry weather in summer (25/01/2022, left) and after 12 mm of rain in 24 hours (right, 31/05/2022, Awanohi Rainfall at Okura rain gauge).

Similarly to Long Bay, the Lignite resurvey found that lower bank erosion increased substantially in the period between the surveys (Brockerhoff et al., 2021). About 52% of the Lignite stream length surveyed in 2002 was “less than 20%”. At the time of the resurvey, this was greatly reduced to 18% (Figure 9b). The resurvey also shows a considerable increase of “40%-60%” lower bank erosion by 23% since 2002 (Figure 9b). There was also no record of more than 60% lower bank erosion in 2002, however, this rose to 25% in 2021 (Figure 9b). Bank undercutting and stream bed incision were more common at the time of the resurvey, particularly in areas with lower main channels adjacent to the recent subdivision works, while those with less upstream urban development adjacent had less bank erosion (Brockerhoff et al., 2021).

The percentage of Kahika lower bank with “little to no sign” of erosion decreased to about 1% in 2019, while “20%-40%” lower bank erosion has halved from 48% to 23% since the original survey (Figure 9c). At the same time, “40%-60%” lower bank erosion has more than doubled from 13% to 34% compared to data collected in 2002. Similar to Long Bay and Lignite, 14% of Kahika's lower bank was noted with “more than 60%” bank erosion 2019, while there were no records of this lower bank erosion severity in the original survey (Figure 9c). The resurvey indicates that densification and intensification of residential developments resulting in increase of impervious surfaces could have contributed to the deterioration of lower bank erosion in the catchment (Brockerhoff et al., 2020). At one site on the main Kahika Stream channel hard engineering approaches (Figure 11) led to improved lower bank erosion since the original survey (Brockerhoff et al., 2020), however this is not the preferred approach to achieve sustainable stream management.

Figure 11: Kahika channel hard engineering approaches

Unlike the other 3 catchments, Oteha Valley lower bank erosion was present across all of the % Bank erosion categories in the original survey (Figure 9d). However, the resurvey still shows a general worsening of lower bank erosion between the two surveys. Lower bank erosion of lesser severity in Oteha Valley has dropped by 4% for "little to no sign" of bank erosion and by 15% for "less than 20%" (Figure 9d) since 2003. Although the percentages of more severe lower bank erosion were relatively low compared to other resurveyed catchments, they have all increased since 2003. The "40%-60%" lower bank erosion increased sharply from 3% in 2003 to 15% in 2021. Simultaneously, "20%-40%" lower bank erosion increased by 7% to 20% and "more than 60%" increased slightly to 3% in 2021 (Figure 9d). This means that this will likely be an ongoing issue for Oteha Valley (Brockerhoff et al, 2022). The lower bank erosion is also illustrated in the stream cross sections in Oteha Valley (Figure 12) where cross sections taken in 2001 were repeated in 2019. It is worth noting that despite the improvement and construction of the Unsworth Reserve stormwater detention pond and Barbados stormwater wetland, an increase in lower bank erosion of the reaches has been observed in these areas, indicating the potential insufficiency of these devices to reduce stormwater peak flows (Brockerhoff et al, 2022).

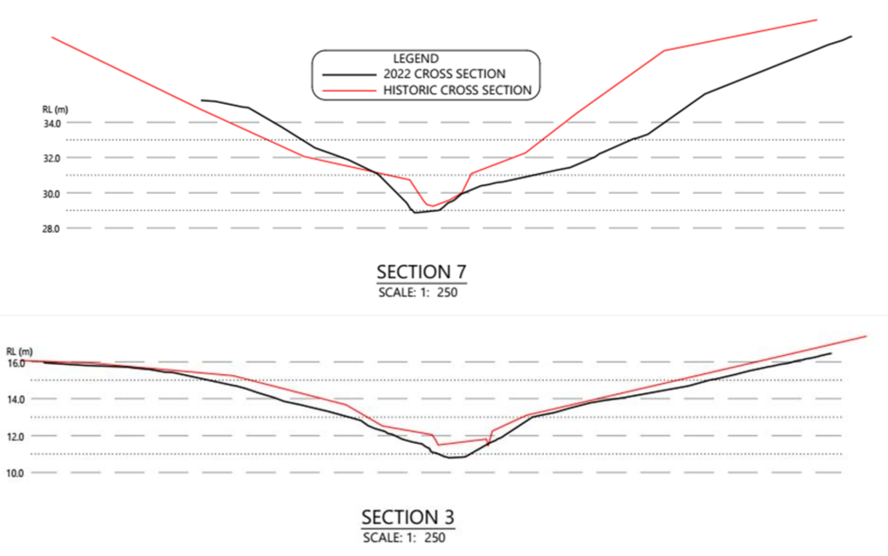


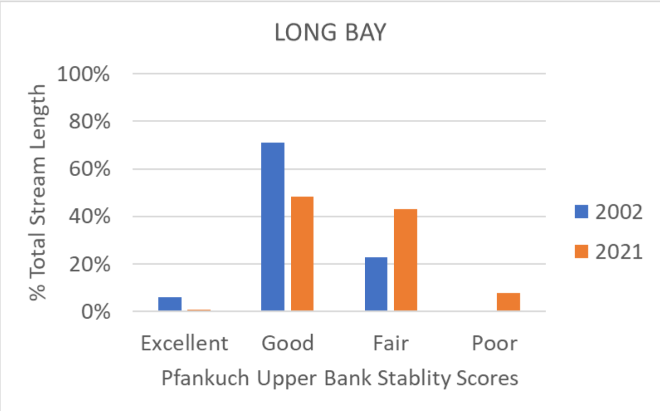
Figure 12: Oteha Valley stream cross section change since the original survey (in red)

Trends in lower bank erosion across all catchments resurveyed to date are very clear. Channel incision processes that are characteristic of advancing Stage III and IV erosion processes are continuing to advance irrespective of time since greenfields urban development was first initiation or developmental methods used to manage or reduce effects. Channel incision process are still active within Kahika catchment which is the oldest urban development measured to date and also contains the least amount of controls on stormwater infrastructure implemented to reduce erosion risk and improve water quality. Long Bay represents the most recent urban development and also has the most rigorous stormwater network management regime incorporated into the development, yet channel incision continues to advance very rapidly over only two decades. It is important to keep in mind that channel incision process occur at the earlier stages of stream channel adjustment and erosion. They are then followed by the bank failures and often larger point source, more acute bank failures that can introduce large quantities of sediment to aquatic systems over very short timeframes. With incision processes still active and likely still the dominant erosion process taking place in all four urban streams surveyed, it is likely that erosion will continue to worsen over the next two decades, resulting in significant volumes of sediment being exported to coastal areas and indicating that these streams will remain in a degraded state for many years to come without additional and more effective interventions.

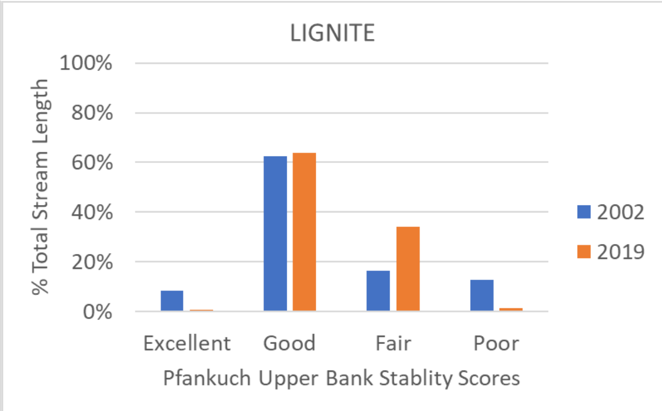
5.2 Pfankuch Upper Bank Stability

For cohesive streams, upper bank instability resulting in bank failures lateral widening of stream channels typically follows on from channel incision. Bank failures generally occur when the weight of bank material exceeds the strength of the surrounding soils. Factors that lead to these lateral failures include variables like weight of material on the banks (soils, vegetation, saturation and groundwater levels), cohesive strength and pore pressure, and overall bank height. As a simple rule of thumb, the higher the stream banks become, the more prone to failure they may become, and this can be measured by calculating indices like "critical bank height". Because bank failures and lateral widening typically follow on from channel incision, the prevalence of bank failures along a stream channel can provide an indication of how advanced the streams are along their channel evolution – their adjustment phase following disturbance.

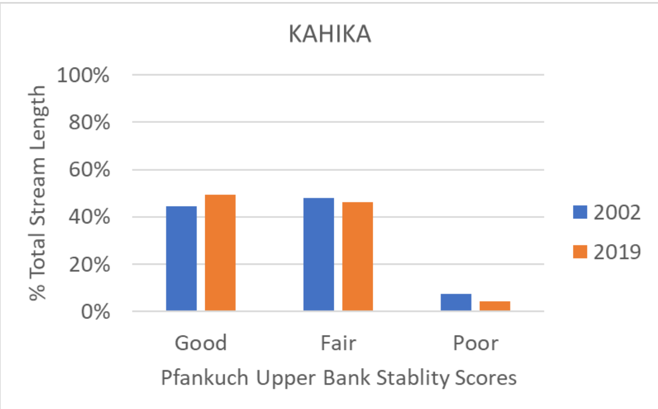
The WA utilises the Pfankuch stability index to assess the upper stream bank stability. The Pfankuch stability indices are a function of upper bank slope, mass wasting, debris jam and bank vegetation. This section compares upper bank stability indices changes over time for each catchment (Figures 13a, b, c and d).



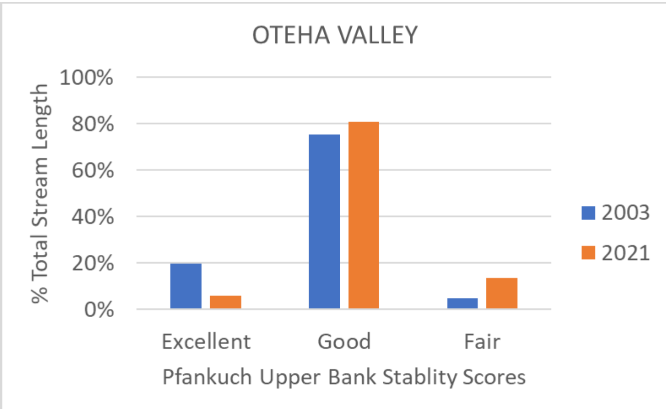
a)



b)



c)



d)

Figure 13: Pfankuch upper bank stability percentage changes since the original stream survey for a) Long Bay, b) Lignite, c) Kahika and d) Oteha Valley

The Pfankuch stability indices show a decrease in upper bank stability over time at Long Bay, changing from 71% to 48% good upper bank stability. There is also an emergence of 8% poor upper bank stability over the original study (Figure 13a). The resurvey found that despite the improvement in riparian vegetation since 2002, the overall lower upper bank stability scoring is largely due to the increases in land slope, mass wasting, and debris jams (Davis et al., 2022). It is likely that the young age of the newly planted riparian vegetation in this catchment has not established enough yet to provide the improved bank stability we would expect to see over time. Land slope has steepened over time, with 45%

having an excellent score in 2002 compared with 19% in 2022. Mass wasting and debris jams were found to have increased over time which has implications for sedimentation and the flow dynamics within the channel (Davis et al., 2022).

A similar trend can also be seen for Lignite (Figure 13b), with the exception that good upper bank stability remained relatively the same with a slight increase, while poor upper bank stability decreased significantly. In contrast to Long Bay, the Lignite resurvey found that excellent bank vegetation provides good stability in many of the reaches within the catchment (Brockerhoff et al., 2021). Serval factors responsible for the fair to poor upper bank stability have also been identified, such as the landslide-prone underlying geology, along with increased impervious surfaces and stormwater runoff from urban intensification. Mass wasting was also commonly observed in the resurvey (Brockerhoff et al., 2021). The decline in poor upper bank stability also indicates some reaches have eroded to a stable underlying rock layer (Brockerhoff et al., 2021).

Although changes in upper bank stability are similar to the lower bank erosion described above for Kahika and Oteha Valley, upper bank stability shows much less dramatic changes than lower bank erosion (Figures 13c and 13d). In fact, very slight changes in Kahika's upper bank stability have been observed. As with Lignite, extensive riparian vegetation has been found to provide good stability in the catchment (Brockerhoff et al., 2020). Mass wasting and debris jam were found to contribute to the lower upper bank stability scores. In particular, debris jams from improper vegetation clearance could possibly contribute to the emergence of 200 m of poor stability reaches (KAH_MAIN_7, KAH_TRIB4_1) (Figure 14) (Brockerhoff et al., 2020).

Figure 14: Debris jams observed in Kahika

In the Oteha Valley, a decrease in excellent and an increase in fair upper bank stability could be observed in Oteha Valley (Figure 13d). This may be due to the increase in mass wasting and debris jam, as no change in land slope and minimal change in riparian vegetation were observed since the original study (Brockerhoff et al., 2022). Interestingly, the resurvey also found that mass wasting is closely related to lower bank erosion, which showed a similar increase (Brockerhoff et al., 2022).

If we assess the information from upper bank instabilities against the standardised channel evolution model and with consideration to channel incision data, some interesting trends in catchment dynamics become apparent. Upper bank instabilities appear to be becoming more prevalent between surveys within the Lignite and Long Bay catchments, whilst in Kahika and Oteha, levels have stayed very similar between surveys. This may be indicative of the streams in these catchments being at slightly different stages of the channel evolution. Kahika and Oteha catchments are the oldest to have undergone urbanisation of the four surveyed to date. Channel incision is still very active within the streams, however upper bank failures have remained relatively similar between surveys. This may be indicative of the streams within these catchments being much better characterised by

Stage IV of the channel evolution model where both incision and lateral widening process are equally active. Because incision is still prevalent, it is unlikely that either stream have begun to accrete sediment to the bed, thus increasing bed height which is indicative of the channel reaching a stable width and is on the recovery trajectory as characterised by Stage V evolution.

Both Lignite and Long Bay catchments have experienced more recent urbanisation from their rural state during the first surveys. Both channel incision and upper bank erosion processes are active in both catchments, however unlike Kahika and Oteha, upper bank instabilities are increasing in prevalence along with incision. This may be indicative of these streams being more representative of Late Stage III or early Stage IV of their evolutionary path, thus they have a longer path to take towards recovery.

Overall, the data collected to date is indicative of urban streams becoming more prone to erosion over time, irrespective of what stormwater management methods are implemented with land use change. It may be necessary to reassess methods and approaches used to address changes in catchment hydrology that accompanies urban development to better address erosion and stream degradation. Different approaches, methods, or a combination of the two may need to be incorporated into water sensitive design approaches that better aid streams in adjusting to changes in surrounding land use and hydrology. This could include taking a closer look at riparian corridors and associated floodplains themselves to determine whether there are other options available to better approximate pre-development catchment hydrology or assisting our streams with adjusting to higher flows that can't be sufficiently accounted for during land use change.

6 STORMWATER INFRASTRUCTURE CONDITION

Piped urban stormwater networks usually discharge to urban streams. These networks can produce high flows from relatively small rain events. Outlets of stormwater assets are used to provide a transition between the reticulation network and the receiving waters. They are an integral part of the stormwater system and can affect whether the network is safe, whether treatment devices operate effectively, and whether erosion or other environmental problems occur in the receiving environments.

Outlet erosion protection and appropriate design are fundamental for preventing scour and erosion within receiving environments. Outlet design is based on the determination of stormwater volume, appropriate scour potential and protection and the receiving channel erosion susceptibility (TP10, Auckland Regional Council, 2003). Often, poor attention to design details of outlets can result in erosion, asset failure, safety concerns and operational issues (Buchanan et al., 2013).

The catchments assessed were originally developed under different decision-making systems. U

rban development of the resurvey catchments has occurred recently, particularly in Long Bay and Oteha, and so most of the stormwater assets that intersect with the streams are new and within the expected design life. However, erosion protection was the most common maintenance recommendation and with more assets requiring erosion protection when compared to the historical surveys.Table 1: Changes in recommended maintenance of stormwater assets since the original stream survey

Long Bay Recommended Maintenance	2002	2021
Does Not Apply	13	26
Erosion Protection	2	8
None		38
Patching		1
Structural		1
Total	15	74

Lignite Recommended Maintenance	2002	2019
Debris Removal		62
Does Not Apply	25	308
Erosion Protection	4	316
None	1	143
Replacement		71
Vegetation Clearance		55
Structural	1	
Total	31	955

Kahika Recommended Maintenance	2002	2019
Debris Removal	4	3
Does Not Apply	40	18
Erosion Protection	12	19
None		28
Replacement		3
Structural	10	5
Vegetation Clearance		5
Total	66	81

Oteha Valley Recommended Maintenance	2003	2021
Debris Removal	3	10
Does Not Apply	141	3
Erosion Protection	10	22
None		76
Patching		14
Replacement		10
Structural	5	10
Vegetation Clearance		20
Total	159	165

In Lignite, Kahika and Oteha catchments, assets requiring erosion protection increased from 7 to 21; 19 to 36; and 4 to 62 respectively. Long Bay had 13 assets requiring

erosion protection. These large increases are concerning as these assets are likely to be well within their design life. In addition, all four catchments had two or more assets rated as requiring replacement. Those requiring replacement in Long Bay however were located in the Regional Park in area that had not been covered by the original survey.

In Long Bay, the culverts that were installed for cattle or vehicle access across the stream on the main Vaughan Stream channel appear to have been removed so it was not possible to measure any change in previously surveyed assets over time. In 2022, most stormwater assets were new and in good condition with almost none present within the main Vaughan Stream channel.

Bank and channel lining was not a feature that was recorded in 2002. However, there appears to be an increase in the number of privately managed bank and channel lining assets, as an attempt to redirect and manage watercourse bank erosion .

The increase in assets requiring replacement or erosion protection within their design life is indicative of inadequate sustainability considerations in design. These outlets are also key contributors to the increased channel erosion noted across all the catchments. The high erosion around assets during peak stormwater flow following rain events illustrates that hydraulic energy management had not been adequately incorporated into the designs, despite guidelines being available for the past 10 years.

The stormwater management in the four catchments has been directed by different stormwater planning processes (TP10 vs structure plan vs older North Shore plans), yet despite this, all exhibit similar high asset failure rate and high asset erosion issues.

The replacement of these outlets was often with the same design, with limited attempt to remedy the underlying cause of the failure. There were assets surveyed where there was uncertainty if the asset was the original or had already been replaced within the 20 year period between surveys.

Coupled to the maintenance and replacement of assets is the challenge to access the asset. As mentioned above, the riparian vegetation in these catchments has improved and matured. This has reduced accessibility to the asset and, in some cases, a consent may even be required to remove trees in order for machinery to gain access to the failed outlet.

There is an opportunity, and a need, to revisit outlet design criteria for our stormwater network. The current stormwater outlets on urban stream banks have played a role in the degradation of these natural streams, despite intentions to the contrary. Outlet designs with low hydraulic energy, with maintenance access considerations, and with treatment need to be prioritised to reduce the erosive and contaminant loading to the urban watercourses.

Stream management across the Auckland region and throughout Aotearoa is challenging due to land-use changes adjacent to the waterways. As development and growth pressures continue to occur across the Auckland region, Auckland Council identified a need to understand how the region's watercourses, and their associated stormwater infrastructure, have been impacted by land use changes over time.

7 CONCLUSIONS

Stream management across the Auckland region and throughout Aotearoa is challenging due to land-use changes adjacent to the waterways. As development and growth pressures continue to occur across the Auckland region, Auckland Council identified a need to understand how the region's watercourses, and their associated stormwater infrastructure, have been impacted by land use changes over time.

Resurveying catchments with the Watercourse Assessment Methodology enables Auckland Council to quantify the extent of change over time across ecological condition of waterways, the geomorphic responses of streams to the altered hydraulic conditions of the catchment and stormwater infrastructure condition.

Findings from these four catchments resurvey indicate that riparian vegetation alone does not reduce the risk of erosion in a particularly effective or consistent manner. The changes in stream hydrology caused by land-use change, still often exceed the physical strength of the riparian vegetation to resist erosion. It is important to note however that streams are dynamic, and erosion is a natural process as watercourses seek to find their natural equilibrium and naturally stabilise over time.

This information will enable Council to build up a knowledge base to inform efficient and sustainable choices regarding future remediation and mitigation in regard to life cycle and cost. Only through improved understanding, identification of issues and supporting response decision in maintaining healthy waterways will stream management improve across Auckland.

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