CULVERT, THE CHOKING POINT OF NETWORK RESILIENCE

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ABSTRACT

The current population of New Zealand is around 5 million, with approximately 86% inhabiting cities. With this urbanisation, the hydrological cycle is increasingly impacted. Urbanisation impacts the nature of catchments by altering land cover and other hydrology conditions which affects the flow characteristics and conveyance in catchments. Further to this, the climate is also changing. As stated in the Climate Change Projections for New Zealand, moderately extreme rainfall is likely to increase in most areas, and very extreme rainfall is likely to increase in all areas, with increases more pronounced for shorter duration events (NIWA, IPCC 5th Assessment, 2nd edition). In the year 2023 alone, severe events brought with them record rainfalls and slips, which caused extensive damage to the infrastructure and loss of life.

This paper reviews culvert modelling, which is an essential component of drainage systems, allowing flows to be conveyed underneath roads and relieving roadside channels. They are crucial in managing runoff build-up during extreme events and require robust design considerations. Even under normal operational conditions, culverts are occasionally blocked by debris, sediment, and other obstructions, significantly affecting their hydraulic performance.

Traditionally, tools such as nominal charts or software like HEC-RAS 1D and HY8, have been used to design and analyse culverts in one-dimensional (1D) flow scenarios. The limitations of 1D assessments are well recognised in that the approach lacks the ability to capture intricacies of complex flows and is limited to standard culvert shapes. Additionally, it does not provide a comprehensive visual representation of a wide range of flow scenarios. To gain a holistic understanding of culvert performance and flood hazards on individuals, vehicles, and structures, 2D assessments are better suited.

By modelling culverts in 2D, it is possible to gain a better understanding of how flow behaves around them, including backwater effects and energy losses. This understanding becomes particularly crucial when designing culverts to ensure their capability to handle expected flow conditions. 2D hydrodynamic models enable the design of culverts with non-standard shapes, which can be advantageous in situations where the traditional box or circular culverts are not feasible or efficient. These models provide a graphical representation of the flood pattern and, more importantly, assess flood risk. The results obtained from the model can be utilised for detailed hazard assessments, supporting master planning and decision-making. Additionally, they play a crucial role in modelling climate change and resilience in design structures. This information is valuable for comprehending the resilience of stormwater systems and developing appropriate mitigation measures.

This paper further discusses how using a 2D hydrodynamic model could assist engineering design and decision-making and assess flood hazards and risks focused on the Auckland region (using various tools such as Auckland Council Stormwater Flood Modelling

Specification and Australian Rainfall Runoff Guidelines). Case studies in Auckland urban areas are used as examples to illustrate these benefits of 2D hydrodynamic modelling and how the model results can be used to facilitate engineering design practices to adapt to the changing climate and build more resilient communities.

KEYWORDS

Culverts, Decision-making, Resilience

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1 INTRODUCTION

Culverts are one of the most critical components of stormwater conveyance systems used under accessways at channel crossings. As inground infrastructure that is generally obscured from view, the danger they pose due to design flaws and or insufficient maintenance is not often fully appreciated. During the Auckland Anniversary event 2023, two men were found dead in separate incidents in Wairau Valley on Auckland's North Shore with one of them found in a flooded culvert (Stuff - January 28, 2023).

As engineers, we are tasked with design and analysis of culverts where we have long relied on traditional methods using first principles and software tailored to one-dimensional (1D) flow scenarios. As developments expand and the field progresses, the need for accurate and comprehensive assessments progressively becomes apparent, a shift towards two-dimensional (2D) assessments is emerging as an ideal approach.

In this paper, we explore these aspects of culvert modelling against the backdrop of increasing population and urbanisation as well as changing climate and how these can be exploited in assessing risk.

2 BACKGROUND

The current population of New Zealand stands at approximately 5 million, with a record net migration gain of 110,200 in August 2023, according to provisional estimates released by Stats NZ today. With more people arriving and living in the country, there is pressure to provide healthy and affordable accommodation. In closing this gap, policies for fast tracking projects and intensification have become common place. This rapid urbanisation has significant repercussions on the hydrological cycle.

It alters the natural landscape and other hydrological conditions, affecting flow characteristics and conveyance systems within those catchments and beyond. Furthermore, with the looming spectre of climate change, there is high likelihood that these challenges will be exacerbated. According to the Climate Change Projections for New Zealand, it is predicted that moderately extreme rainfall is likely to increase across most regions and very extreme rainfall in all areas. According to Mihu-Pintilie et al (2019), in reference to numerous other researchers, many natural disaster patterns have diversified and modified under the pressure of climate change among which is the intensification of the hydrological cycle which has made an unprecedented impact on the magnitude, spatial extent, duration and frequency of hydro-meteorological disaster events. In local context, the consequences of these climatic shifts became evident in 2023, when severe weather events unleashed record-breaking rainfall and triggered landslides, wreaking havoc on infrastructure and claiming lives across the country.

2.1 URBANIZATION

Figure 1, plates A through F, show aerial photos of a section of Pomaria Road in Henderson, Auckland, where it intersects with Lincoln Stream over a period of 77 years. Over this time, the area changed from predominately farming land to a relatively intense urban setting. Based on the information from Auckland Council GeoMaps, the existing impervious coverage of the subcatchment (taken at the spill point of the subcatchment i.e., where Lincoln Stream crosses Universal Drive and referred to in this paper as Lincoln Stream Subcatchment) within which this area is shown is 57%. Based on the Auckland Unitary Plan, Operative in Part (AUP OP 2016), the area is mainly zoned as Mixed Housing urban Zone (MHU) interspersed with Terraced Housing and Apartment Buildings Zones (THAB), general business zone as well as open spaces-informal recreation zone whose imperviousness coverages vary from 10 to 100% which for this subcatchment aggregates to approximately 71% i.e., the maximum probable development coverage. This intensification by itself contributes to a notable increase in the amount of runoff generated by the subcatchment.

Figure 1: Aerial photography of Pomaria Road (Lincoln Stream Sub-catchment)

2.2 CLIMATE CHANGE

Within the context of Auckland, the Stormwater Code of Practice V3 (AC SW CoP 2022) recommends that a climate change uplift factor of 2.1°C should be applied to existing rainfall depth in the design of stormwater infrastructure (for the 100-year annual recurrence interval [ARI] this corresponds to a 16.8% adjustment). With the release of Version 4 (March 2024) of the AC SW CoP, a 3.8°C uplift factor (corresponding to 32.7% for the 100-year ARI) has been proposed to be applied for the secondary system.

In addition to these changes, revised rainfall distributions with higher peaking factors have also been introduced. To illustrate this point, Table 1 indicates various 24-hour rainfall depths for the Lincoln Stream Sub-catchment for the existing and future rainfall for various events. The temporal intensities that such rainfall depths are distributed by are summarised in Figure 2 (original distribution as shown in the Guidelines for stormwater runoff modelling in the Auckland Region - TP108 [1999]). Short duration rainfall extremes are intensifying as a result of these climatic changes resulting in increased flood risk (Fowler et al 2021). Researchers and other professionals working in this space are tasked with find ways to manage this increased risk and needing to better understand magnitude/severity of these changes.

Table 1: Rainfall depths for Lincoln Sub-catchment with allowance for climate change

ARI	Existing (mm)	2.1°C (mm)	3.8°C (mm)
2-year	82	89	104
10-year	135	153	177
100-year	200	234	265

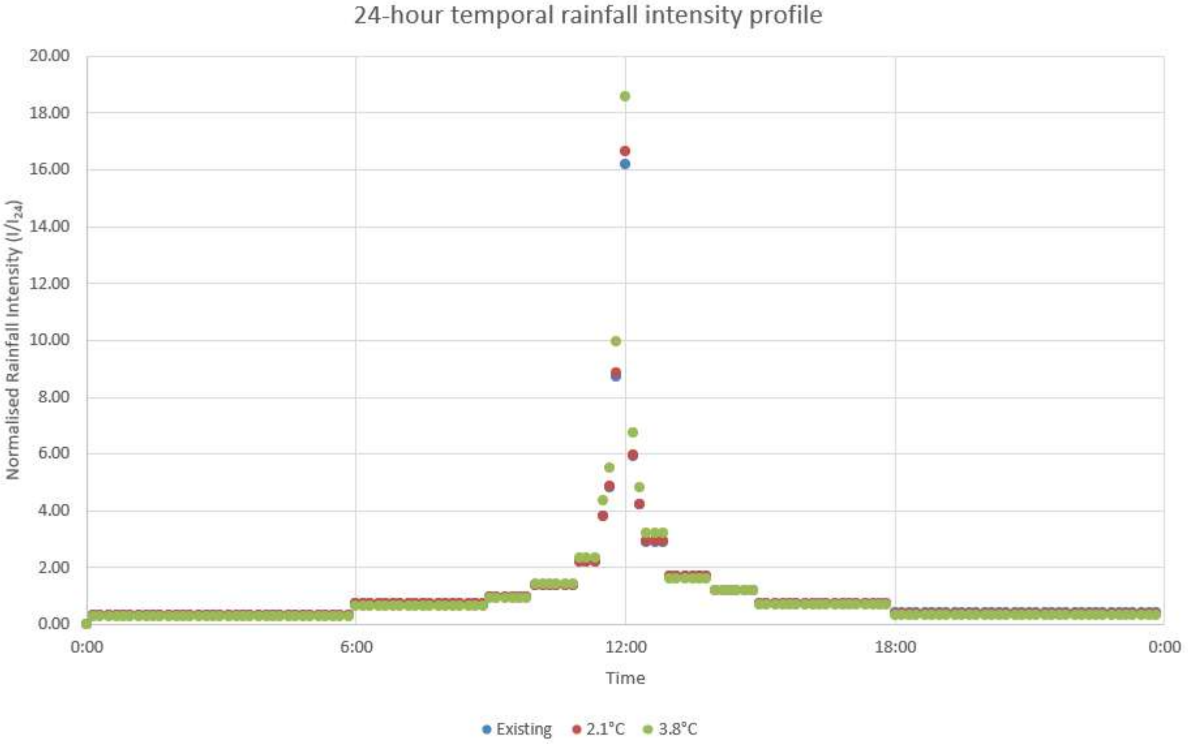


Figure 2: Normalised rainfall intensities for existing and climate change scenarios

In other regions of New Zealand, different climate change scenarios are applied, some of which are based on a set of forcing scenarios termed representative concentration pathways (RCPs) as described in the IPCC 5th assessment (NIWA 2018) and high intensity rainfall design system (currently in the 4th version – HIRDSv4) where engineers/planners/designers can extract either a depth-duration-frequency (DDF) or intensity-duration-frequency (IDF) for a particular region in the country at the specified RCP. An example of this is in Christchurch where the Waterways, Wetlands and Drainage Guide (2020) suggests an RCP 8.5 scenario for the design of permanent infrastructure and for flood hazard mapping as a conservative approach until such time as it is clear that a lower emission pathway is happening.

With urbanisation and climate, more runoff is expected to be generated from the same catchment. This puts pressure on the functionality of existing infrastructure, and it is designed to manage these flows. The following section focuses on culverts, and how modelling them fits into the wider picture and how they affect flood risk assessment.

3 CULVERT MODELLING

3.1 1D APPROACH

Engineers have long relied upon manual tools such as capacity charts and inlet/outlet control nomographs for the design and analysis of culverts (HDS #5 2012). Computer programs were developed over the years to automate these hydraulic computations, and these were generally tailored to one-dimensional (1D) flow regimes. Specialised software like HY8, HEC-RAS, Autodesk Civil 3D Hydraflow etc have been employed for faster computation and complex culvert analysis/design (Thiele et al. 2006).

While these methods have served their purpose adequately, they are not without limitations. One of the primary drawbacks of this 1D method is its inability to capture the intricacies of complex flow patterns. The approach is often limited to standard culvert arrangements, making it challenging to address scenarios involving irregular geometries or varied flow conditions. The following are some of the limitations associated with the culvert nomograph and 1D modelling methods.

Culvert nomograph Charts

- Culvert size is limited to standard sizes which requires careful interpolation,
  - For high head water depths values read from charts become less reliable
  - Large length/slope ratios exceeding chart values and requiring modifications,
  - Assumes free outfall (low tailwater depth) which is not always the case and requires modification of procedures,
- Inlet/outlet control nomographs – less direct than the capacity charts but more accurate/applicable in more situations however:
  - The process is more tedious and requires some trial and error to determine the numerous parameters necessary for adequate sizing (HEC#5 1965).

1D Modelling offers multiple benefits over manual methods as it is simple to use, provides more analysis/results and has better diagrammatic representation, but also has other limitations:

- Not suitable for complicated projects where precise stream profiles are needed i.e., surrounding terrain is not represented.
- Road's cross-sectional profile cannot be easily modelled.
- requires more input parameters and greater understanding of hydraulics.
- Assumes constant elevations across entire cross section which may not always be appropriate for understanding the study area.

The model outputs and visual representations from 1D assessment are often insufficient in gaining a comprehensive understanding of the variety of flow scenarios that culverts are subjected to. Engineers are faced with the challenge of extrapolating from limited outputs which may lead to suboptimal design decisions and increased flood risks. As much as these approaches have provided a good foundation, engineers need to look at the broader picture as the engineering landscape becomes increasingly complex. One of the ways to achieve this, is to take a two-dimensional approach. By embracing two-dimensional (2D) assessments, engineers can unlock new insights into flow dynamics, improve design accuracy, and better mitigate flood risks and reduce hazards.

3.2 2D APPROACH

As computational power has steadily grown and the potential for more comprehensive and detailed analyses is realised, a shift towards two-dimensional emerges as a preferential approach. Advances in topographical survey techniques, geographical information systems (GIS) and improvements in LiDAR accuracy make for superior digital elevation models (DEM) and hydraulic design which in turn allows for greater confidence in modelling results.

As Mihu-Pintilie et al (2019) states, the availability of DEMs based on high density LiDAR data, has considerably improved the accuracy of flood parameters.

While there are inherent limitations in computer models; short of physical models, 2D modelling offers numerous advantages in the design and analysis of culverts in the urban context. By incorporating these techniques, engineers and modellers can better capture the complexities of flow dynamics including turbulence, eddies, and hydraulic jumps. This enhanced understanding enables more accurate predictions of water levels, velocities, and pressures within and around culverts, ultimately leading to safer and efficient designs.

Several commercial products are available in the market with varying degrees of affordability and user-friendliness. Within the New Zealand context, commonly used software includes, TUFLOW, XP-SWMM, InfoWorks ICM (benefits and limitations of which briefly outlined below) and DHI MIKE Urban. On the publicly available side, HEC-RAS anecdotally appears to be the most widely used and for the purpose of this paper, is used in the case study.

Benefits of the platform include an intuitive and user-friendly interface, modelling space and inbuilt mapping tools. While the recent versions have greater culvert modelling capabilities, the main drawback in the urban flood modelling context is the lack of pipe network which limits the use of the program. This is especially pronounced for small storm events which a majority of are likely to be conveyed by the pipe network, however for large events where some territorial authorities, e.g., Auckland, assume partial or total blockage of a range of pipe sizes, HEC-RAS 2D functions satisfactorily.

In the following section, we review design requirements and flood risk assessment standards within the Auckland region as a backdrop for the case studies being employed in the discussion around engineering design and decision making.

3.3 FLOOD RISK QUANTIFICATION

There are numerous tools that can be employed to quantify and assessment flood hazards. In this section we focus on some of the guidelines that are commonly applied in Auckland to help planners and engineers make decisions in urban development.

Auckland Council Technical Specification for Stormwater Flood Modelling Version 4 (2011)

The Auckland Council technical specification for stormwater flood modelling Version 4 (2011) outlines Auckland Council's requirements for the planning and management of stormwater drainage modelling. This modelling specification also provides a framework for classifying and assessing flood hazards as well as understanding their significance. Three different hazard classifications with increasing levels of associated risk are identified and summarised in Table 2.

Table 2: AC Modelling Specifications Hazard Classification (Auckland Council, 2011)

Description	Depth-velocity Criteria
Potential Hazard	0.05m < Depth < 0.1m
Minor Hazard	0.1m < Depth < 0.3m and Velocity < 2.0m/s
Significant Hazard	Depth > 0.3m and Depth > 0.1m & Velocity > 2.0m/s

Auckland Transport - Transport Design Manual (TDM) for Road Drainage Version 1.2

The Auckland Transport - Transport Design Manual (TDM) for Road Drainage Version 1.2 outlines the authority's requirements for the overland flow over roadways. The TDM sets the design requirements when considering pedestrian and vehicle safety.

Table 3: Major Event - Roadway Flow Limitations

Description	Depth-velocity Criteria
Pedestrian safety	No Obvious danger dg x V $\leq 0.6\text{m}^2/\text{s}$
	Obvious danger c $\leq 0.4\text{m}^2/\text{s}$
Vehicle safety	Maximum height of energy line 300mm above roadway surface for areas subject to transverse flow. The exception is specific floodway design and additional vehicle warning and protection, where dg x Vave $\leq 0.3\text{m}^2/\text{s}$. On street parking is not to be permitted where overland flow exceeds $0.3\text{m}^2/\text{s}$.

Australian Rainfall and Runoff Guidelines (ARR)

The Australian Rainfall and Runoff Guidelines (ARR) serve as a widely embraced national document in New Zealand, offering a framework for estimating design flood characteristics. Flood hazard assessment involves the consideration of velocity and depth, which are combined to delineate various levels of risk for people, vehicles, and structures.

The flood vulnerability curves, and hazard definitions outlined in the ARR provide a comprehensive understanding of these risks concerning human safety, transportation, and infrastructure. With a focus on the effects on people, vehicles, and structures, the ARR categorizes hazards into six distinct vulnerability classifications (H1 – H6), each representing increasing levels of associated flood risk, as detailed in Figure 3.

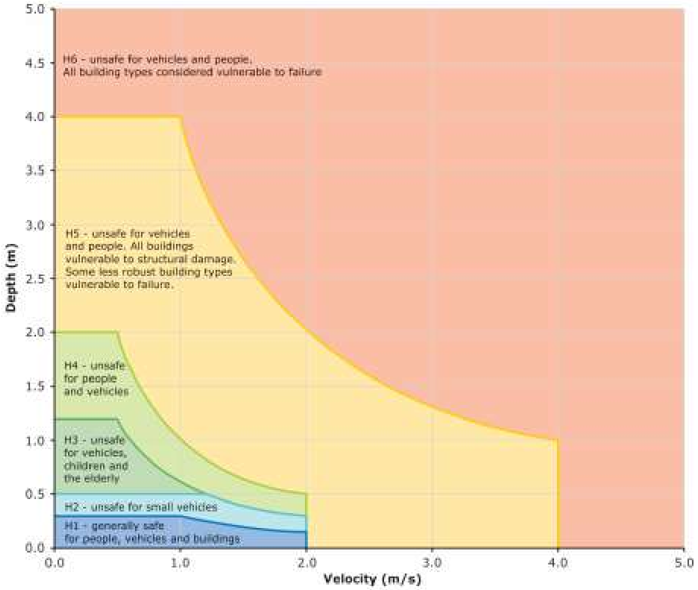
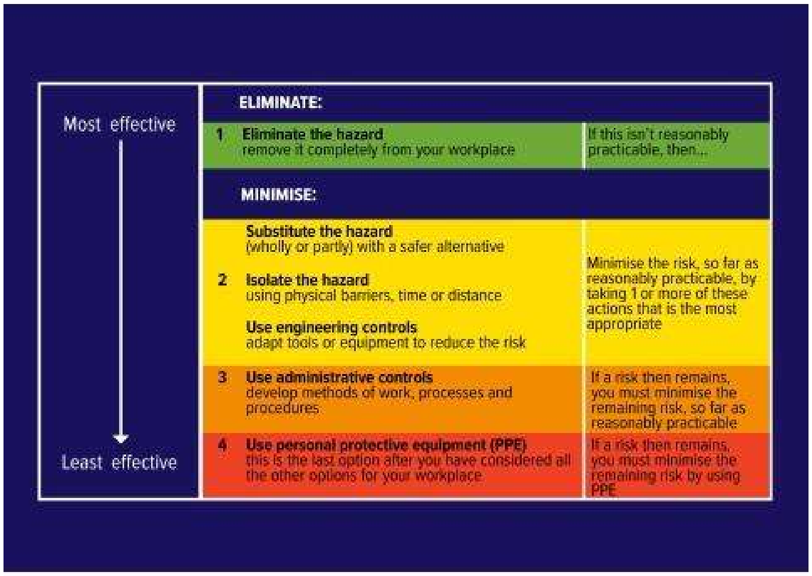


Figure 3: General Flood Hazard Vulnerability Curves (J. Ball, 2019)

3.4 FLOOD RISK MITIGATION

One of the most effective ways to address flood hazards is to eliminate the risk. With stormwater runoff in urban/developed areas, this is generally not achievable, however it can be mitigated and managed. Inspired by work safety risk control philosophy, flood risk mitigation can be ordered in accordance with the 'risk control hierarchy' from most effective to least effective as shown in Figure .



Most effective		**ELIMINATE:**	
	1	**Eliminate the hazard** remove it completely from your workplace	If this isn't reasonably practicable, then...
		MINIMISE:	
	2	**Substitute the hazard** (wholly or partly) with a safer alternative **Isolate the hazard** using physical barriers, time or distance **Use engineering controls** adapt tools or equipment to reduce the risk	Minimise the risk, so far as reasonably practicable, by taking 1 or more of these actions that is the most appropriate
	3	**Use administrative controls** develop methods of work, processes and procedures	If a risk then remains, you must minimise the remaining risk, so far as reasonably practicable
Least effective	4	**Use personal protective equipment (PPE)** this is the last option after you have considered all the other options for your workplace	If a risk then remains, you must minimise the remaining risk by using PPE

Figure 4: Risk Control Hierarchy (Source: Site Safe)

The risks themselves can be further differentiated according to the entities the affect, i.e., risk to people, risk to vehicles and risk to buildings with some overlaps in the methods. To mitigate risk to people, hazards may be isolated by employing physical barriers. This can take the form of diversion channels, flood walls and other hard engineering controls. Administrative controls such as early warning systems and evacuation plans can be put in place in vulnerable areas. With respect to mitigating risks to vehicles, hazards may be isolated via the use of designated conveyance corridors with restrictions to street parking. Engineering controls through design that limit depth and velocities in trafficked areas may be used while warning signs will function as part of administrative control. For buildings, isolation of the hazard may be achieved via diversion of flows. Engineering controls such as flood barriers, oversized pipes and storage basins can be incorporated into developments at design stages in addition to the use of flood resistant material.

4 CASE STUDIES

This paper further discusses how using a 2D hydrodynamic model could assist engineering design and decision-making and assess flood hazards and risks focused on the Auckland region (using various tools such as Auckland Council Stormwater Flood Modelling Specification and Australian Rainfall Runoff Guidelines). Case studies in Auckland urban areas are used as examples to illustrate these benefits of 2D hydrodynamic modelling and how the model results can be used to facilitate engineering design practices to adapt to the changing climate and build more resilient communities.

4.1 CASE STUDY 1 – LINCOLN STREAM SUB-CATCHMENT (POMARIA ROAD CULVERT)

Case study 1 is used to demonstrate the benefits of using 2D modelling approach over the 1D approach. Lincoln stream is in west Auckland with a contributing catchment that is predominantly residential. Approximately 100m of the stream starting at Paera Place and exiting at 2 Kingdale Place has been culverted crossing Pomaria Road and some residential developments (Figure 5). The contributing catchment area measures 75ha.

Figure 5: Pomaria Road Culvert

In this study, future land use, hydrological and meteorological data (100-yr ARI with 3.8°C climate change applied) were extracted from AC GeoMaps and a 24-hour flow hydrograph generated in HEC-HMS using the TP108 methodology (SCS CN method). The peak flow and hydrograph were used as upstream boundary inputs in the 1D (HY8) and 2D (HEC RAS) models respectively.

The DEM for the study area was generated from the 2016 LiDAR while the basic culvert information was also taken from AC GeoMaps. On inspection of the culvert alignment, it was observed that the data extracted from AC GeoMaps was not consistent with site observations thus some minor adjustments were made. Upstream and downstream invert levels were also not available, thus were extrapolated from the LiDAR with some modifications made around the inlet and outlet structures to allow for modelling.

1D Model (future land use and climate change allowance)

An HY8 model was created for the culvert based on the adjusted DEM and culvert information as described above. The model results as shown on Figure 6 indicate that the Pomaria Road culvert has insufficient capacity to convey the catchment flows. The model provides how much the road is overtopped by and how much flow is carried by the culvert. Furthermore, outlet depth and velocity as well as tailwater depth and velocity are determined. However, the model does not provide information regarding the velocities over the road, the direction, and the extent of the flows, as well as how the flows might interact with over structures over the embankment. To determine this, another model/calculation will have to be employed to provide this information that will be required to help determine the extent of the risk and how best to address it.

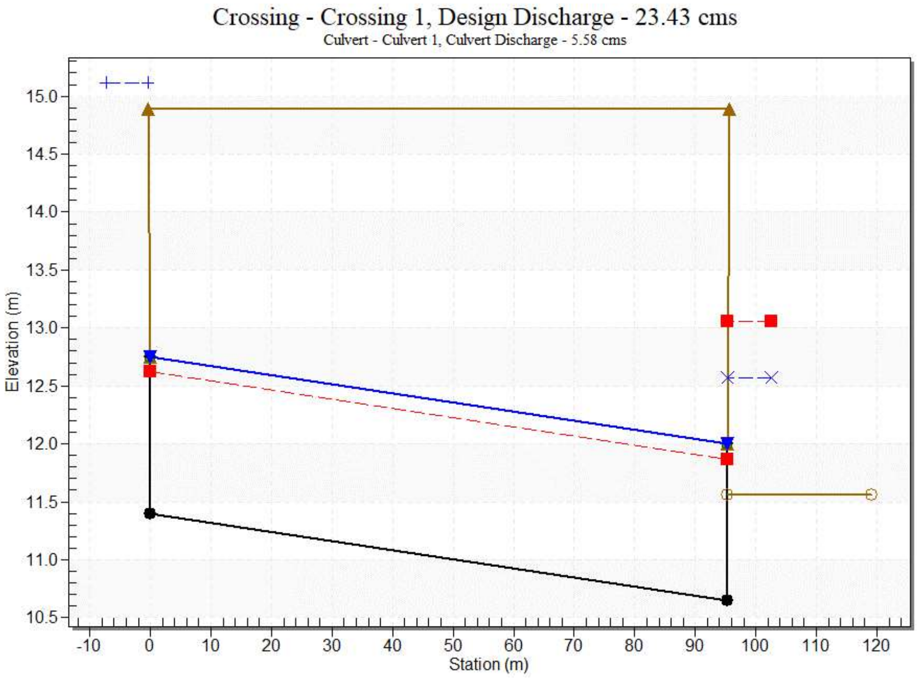


Figure 6: Pomaria Road Culvert HY8 Model Output

2D Model (future land use and climate change allowance)

A 2D model was created for the same culvert based on the same information as described above. As with the 1D model, the 2D model also showed the capacity limitations of the culvert with the added benefit of showing how the overtopped flows interact with the surface (Figure 7). Furthermore, several other parameters such as the overtopped flow, direction, depths, flood levels and velocities at various locations may be extracted from the model (Figure 8 showing sample cross section). This information allows to identify properties or structures that are flooded for the modelled event.

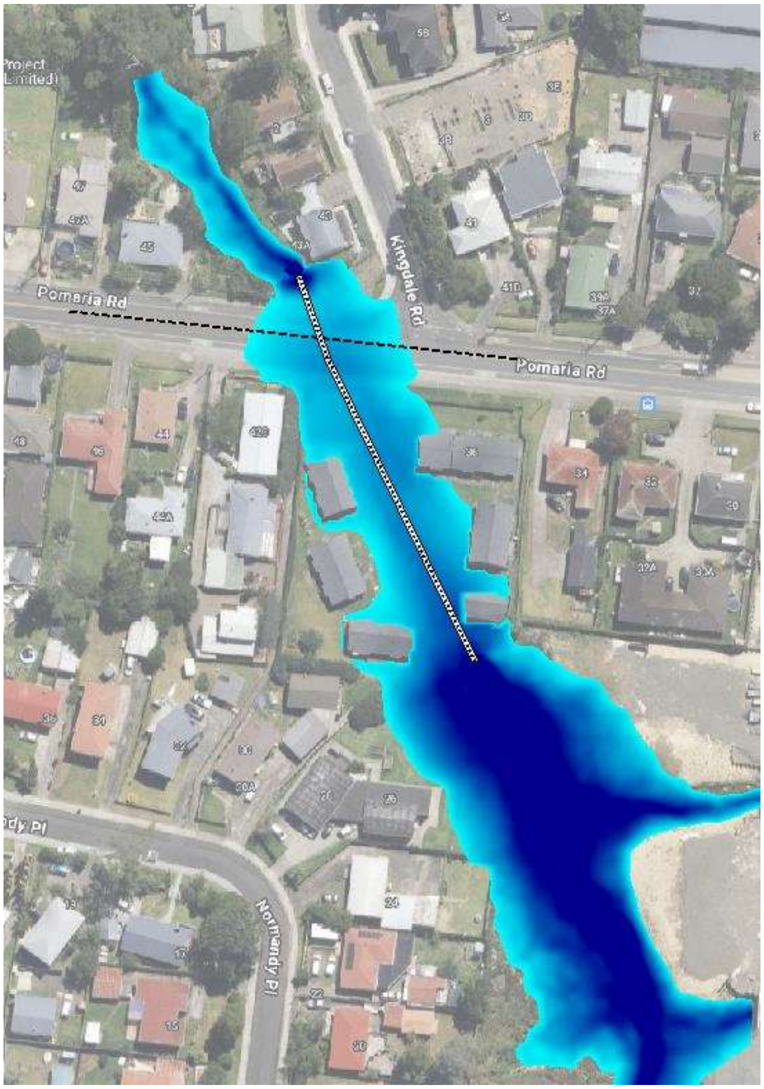


Figure 7: Existing Culvert MPD + CC

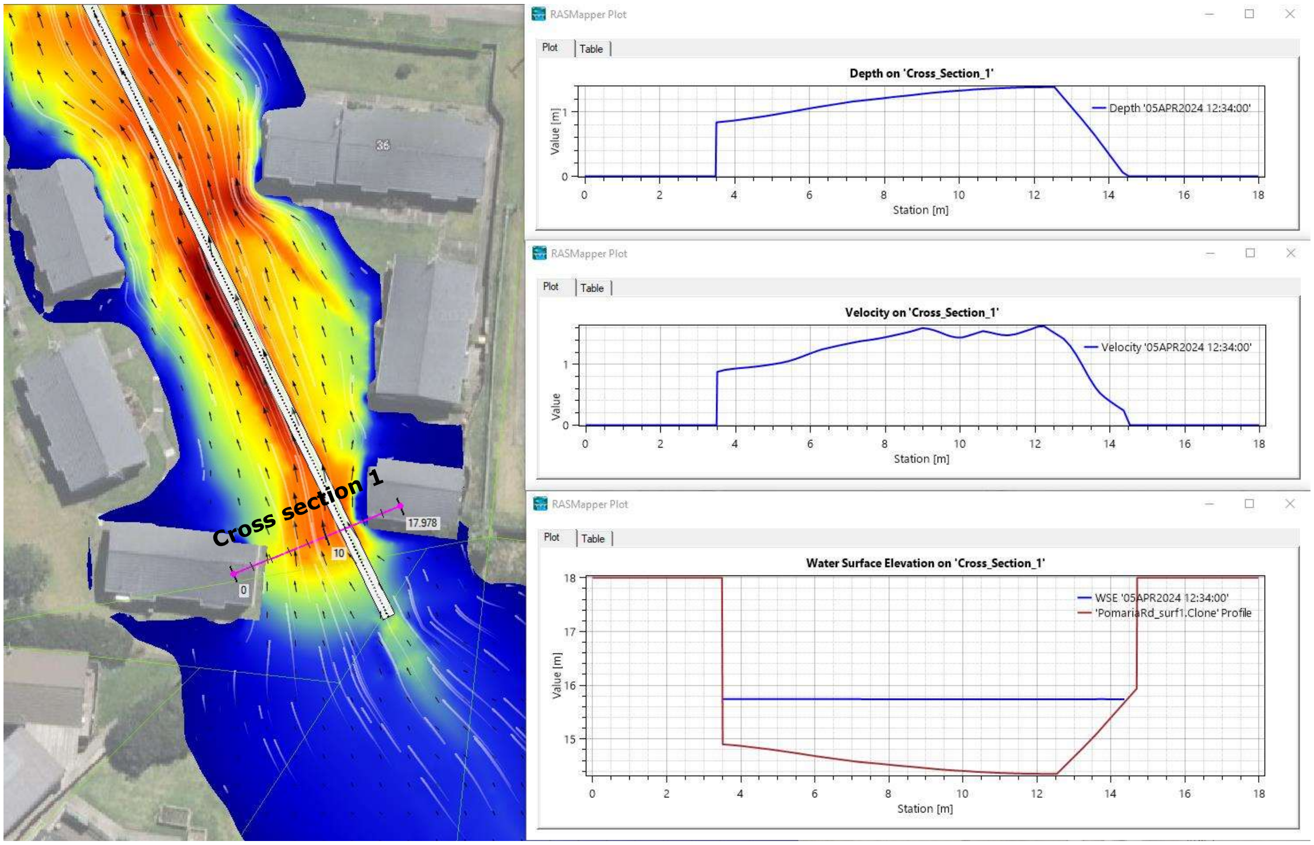


Figure 8: Sample cross section showing various parameters

As part of the mitigation hierarchy, planners and engineers can look to eliminate the hazard, isolate it, manage it, or engineer solutions around it as described in Section 3.4. Affected properties could be removed entirely with the stream daylighted and the road bridged. It is however noted that some of these strategies are not always feasible due to numerous reasons. In this case study we consider the method of implementing an engineering solution. The clearest path is the upsizing of the culvert, assuming that other challenges such as constructability, cover, and clashes with existing services in the corridor can be efficiently surmounted. We tested a 4m-wide by 2m-high box culvert at the same alignment and grade as the existing culvert and found that we can remove the flood risk from the road and significantly reduce the flood risk at the affected residential properties (Figure 9) including the risk to life of occupiers.

In real-life project scenarios, the results from the 2D model can be used to assist in decision making at all stages. In planning stages of a project, avoidance of situating buildings in floodplains can be explored especially where projection indicate extensive inundation in the future. In cases where the catchment is developed and likely to continue to intensify, several options would need to be considered as the issues are better understood while ensuring that the catchment has greater resilience as the changes compound. This could take the form of enlargement of culvert sizes as described above, the increase of barrels or in some cases the removal of existing buildings and other affected structures. These measures/methods can be tested far more effectively and efficiently in this 2D modelling regime than with traditional methods and 1D models.

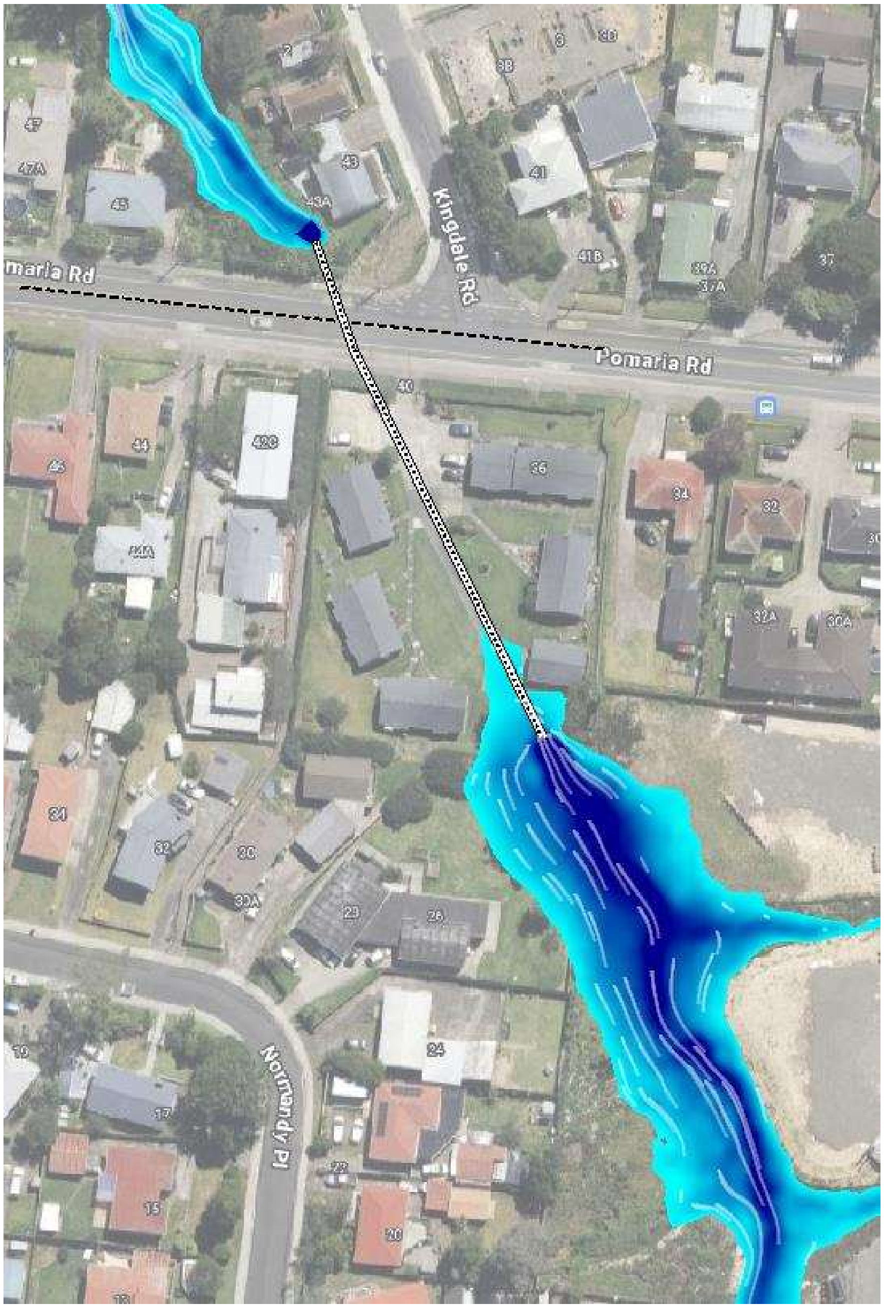


Figure 9: MPD CC culvert upgrade

4.2 CASE STUDY 2 – LINK DRIVE CULVERT

The Link Drive subcatchment is in the northern part of Auckland comprising residential and industrial/commercial land usage. There is a series of culverts in the area with the ones used in this case study crossing Target Road and Link Drive (Figure . In addition to the culverts, the conveyance infrastructure comprises a combination of pipelines and concrete channels. The Target Road culvert (Figure 11) is a 3m wide x 1.5m high structure that connects the residential areas to the commercial areas downstream. The Link Drive culvert is an 825mm pipe that discharges to 5m culvert further downstream.

In this case study, we explore risk assessment based on a 2D modelling approach.

Figure 10: Target Road Culvert and Link Drive Culvert (Source: Auckland Council GeoMaps)

Figure 11: Target Road Culvert

A 2D Model was also built for this case study using similar data sources and approach to that in Case Study 1, however for the future rainfall, a 3.8°C climate change adjustment was used. Following the model run, results were processed and hazard classifications in generated in accordance with the guidelines presented in Section 3.3.

Hazard Assessment

A hazard map was created in the study area (Figure 12) to establish how the hazards compare with the requirements under the AT TDM (refer to Table 3). The results indicate that at the Target Road culvert and the Link Drive culvert crossings, the product of the flood depth and the velocity exceeds 0.6m²/s. The flood risk surpasses the safety threshold for both pedestrians and vehicles. Additionally, the findings also highlighted areas that surpass pedestrian safety thresholds, at 0.4m²/s, during the 100-year ARI with a 3.8°C climate change adjustment. This information can be used to form a site-specific emergency escape plan for the local employees and others.

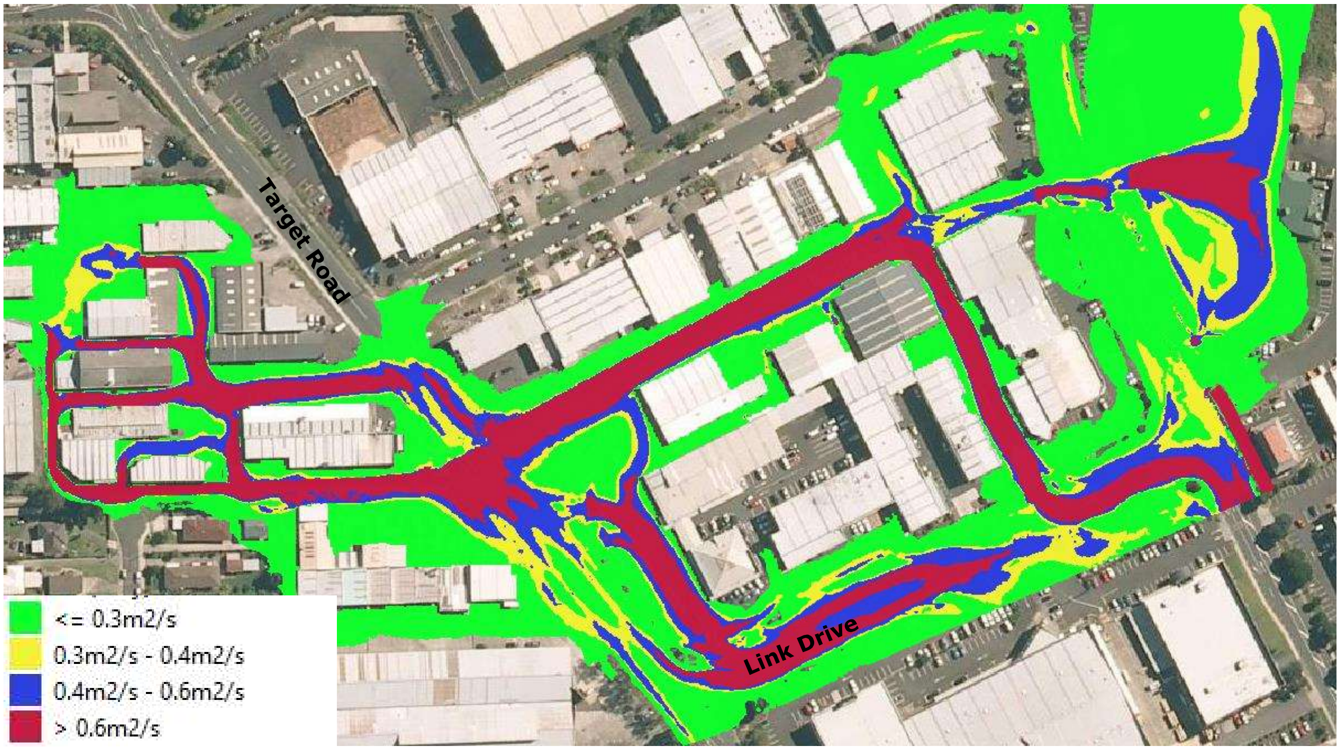


Figure 12: DxV Assessment

Another assessment was conducted for the study area against the ARR guidelines. The results are shown in Figure 13.

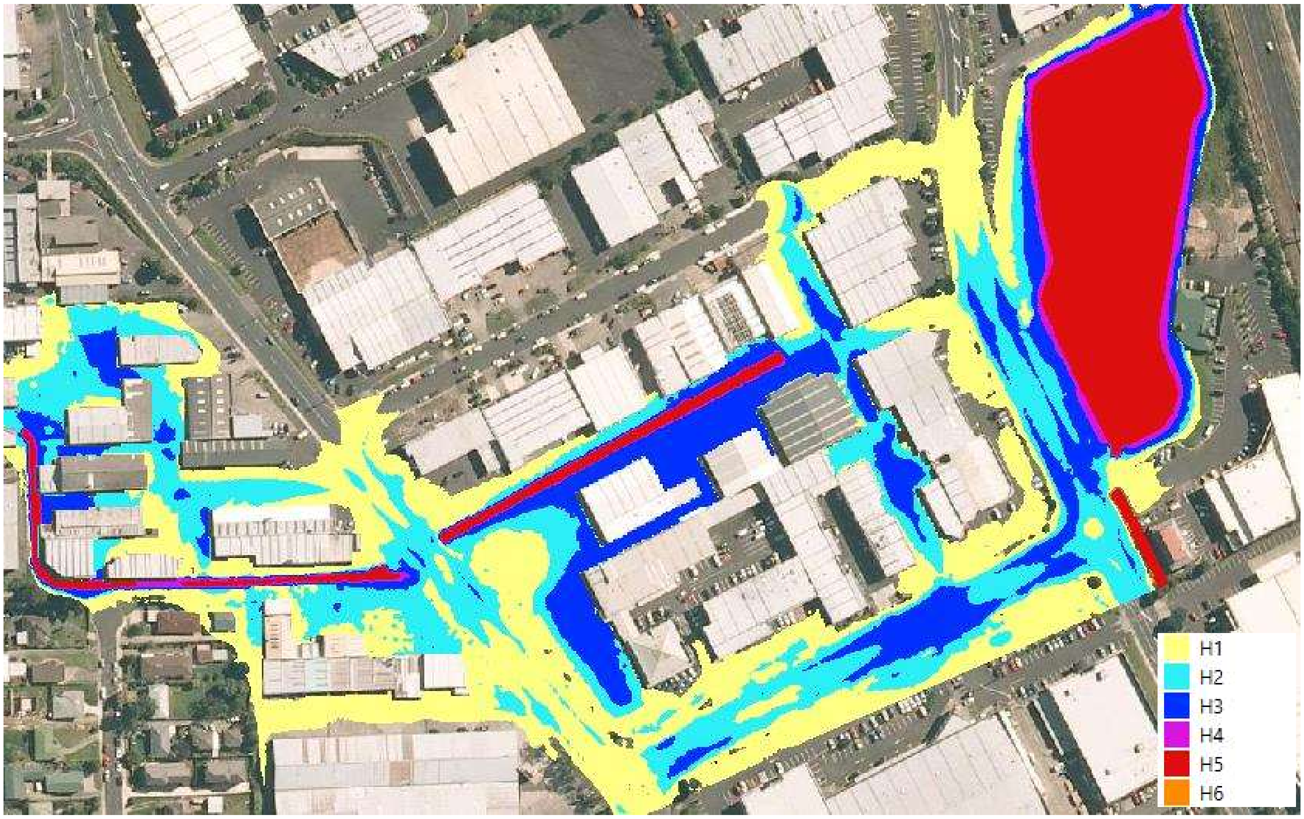


Figure 1: MPD CC Hazards

The ARR assessment indicates that during a 100-year ARI rainfall (with climate change), the flood hazard within and adjacent to the open channel is classified as H5, highlighting a significant risk to people. The assessment also reveals that during the same event, the hazard for parking areas falls within H3 classification, indicating that these areas are unsafe for vehicles, children, and the elderly. Accessing and exiting the carpark during such conditions would pose a safety risk. The study area is deemed generally unsafe for vehicles, children, and the elderly (ARR, Hazard Class H3) while buildings within the study area that do not have adequate freeboard are likely to be inundated, no structural damage is anticipated.

Ideally, hazard vulnerability classifications should be limited to H1, indicating areas that are generally safe for vehicles, people, and buildings, and no greater than H2, which denotes areas unsafe for small vehicles.

For this study, we tested replacing the 825mm Link drive culvert with a 3m-wide by 1.5m-high box culvert and the results (Figure 14) indicate that the risk can be significantly reduced.

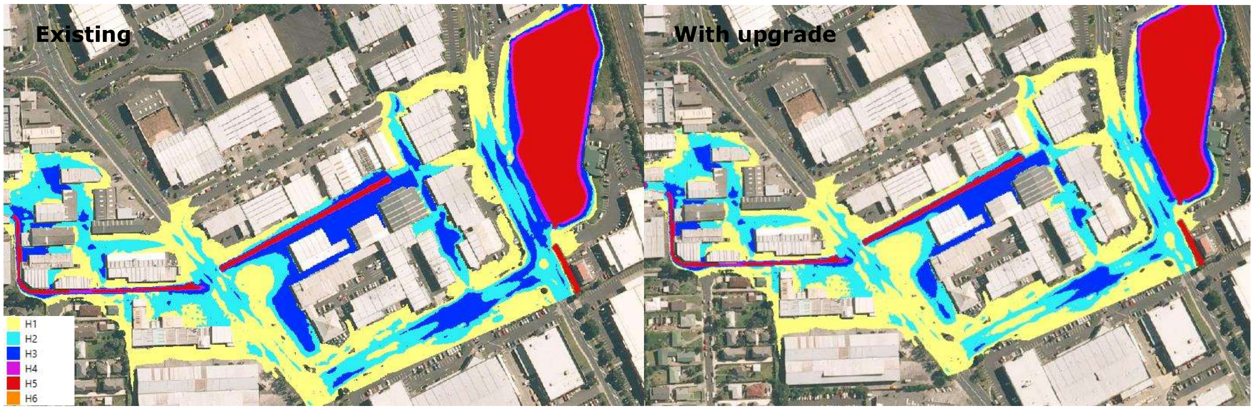


Figure 2: Culvert upgrades

With culvert upgrade, the flood risk within the open channel remains high. However, the flood risk on Link Drive and Target Road reduces from H3 to H2. To further mitigate the risk to people, we can isolate the hazard using physical barriers along the open channel and implement a grated inlet. Additionally, we can introduce administrative controls such as preparing escape plans. To mitigate the risk to vehicles, installing 'no parking' signs in areas where the risk is rated H3 may be proposed however this may be subject to other usage requirements. The desktop assessment shows that the better we understand flood risk, the more efficiently we can mitigate it.

5 CONCLUSION

The culvert, a critical component of the stormwater conveyance system, holds immense significance. An improperly designed culvert can create a 'choking' point within the conveyance network, hindering water flow and exacerbating flooding risks during storm events.

With advancements in computational power and improvements in data quality, 2D modelling techniques have emerged as a powerful tool for understanding and predicting culvert behaviour. Through 2D modelling, we can gain a deeper understanding of how culverts respond under various conditions. In an urban setting, it is clear that 2D modelling is a far better tool than traditional and 1D models for designing and assessing culverts hence should be always be considered for a greater understanding of flooding behaviour.

This enhanced understanding of culvert behaviour is invaluable for assessing the resilience of stormwater systems. It enables us to identify vulnerabilities, anticipate potential failures, and devise appropriate mitigation strategies. Ultimately, this proactive approach not only safeguards communities against the adverse impacts of flooding but also fosters the development of resilient infrastructure capable of withstanding the challenges posed by climate change and urbanisation.

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