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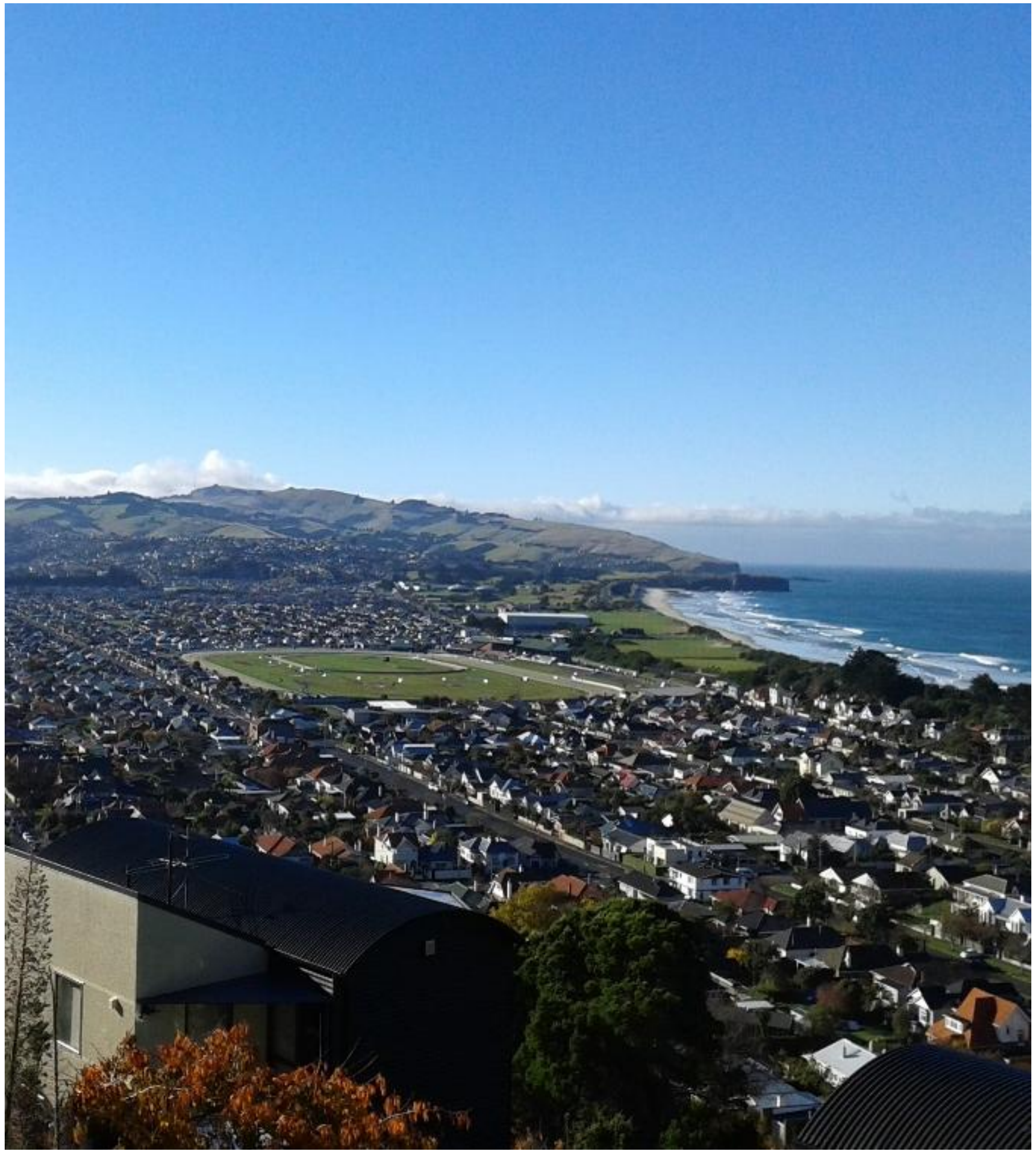
Dunedin City Council

South Dunedin Future

Groundwater Drainage Options Assessment

8 May 2026

6-CD109.77



South Dunedin Future

Groundwater Drainage Options Assessment

Dunedin City Council

WSP
Christchurch
12 Moorhouse Avenue
Christchurch 8011
New Zealand
+64 3 363 5400
wsp.com/nz

REV	DATE	DETAILS
Rev0	03/12/2025	Draft for client review
Rev1	20/02/2026	Final
Rev2	27/03/2026	Final (minor corrections)
Rev3	08/05/2026	Final (further client review)

	NAME	DATE
Prepared by:	Eric van Nieuwkerk	08/05/2026
Reviewed by:	Andrew Raj	08/05/2026
Approved by:	Kevin Wood	08/05/2026

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1 INTRODUCTION

1.1 GENERAL

As part of the South Dunedin Futures (SDF) programme, WSP has undertaken a groundwater modelling investigation to assess how the future water management options proposed in the SDF programme help alleviate groundwater drainage issues in South Dunedin. The approach and results of this investigation are documented in this report, including a series of maps and cross sections included in Appendix A and B which visualise how effective the various options are to control groundwater levels.

1.2 PROJECT BACKGROUND

South Dunedin is a low-lying coastal part of Dunedin that is vulnerable to multiple natural hazards including flooding from stormwater, persistent drainage issues and water ponding due to high groundwater levels, affecting buildings, services and amenities. The issues are likely to be exacerbated by sea level rise in the future, and this has prompted the Dunedin City Council (DCC) and Otago Regional Council (ORC) to initiate the SDF programme. The SDF programme is aimed at improving the area's liveability and resilience against natural hazards with a key focus on flooding and drainage issues.

Several potential adaptation options to improve the water management of the area have been identified in the SDF programme, which includes options to systematically lower the groundwater levels beneath South Dunedin. These options focus on effective combinations of managing stormwater, groundwater and strategic urban planning. Because South Dunedin is low-lying, there are very limited options to drain water to the sea under gravity in the current state. Future sea level rise will make effective gravity drainage unfeasible, and a pumped scheme would be required to sufficiently drain stormwater and groundwater. The considered potential adaptation options therefore include pumped schemes to alleviate the stormwater flooding and groundwater drainage issues.

1.3 SCOPE AND OBJECTIVES

The scope and objectives of the groundwater modelling investigations presented in this report are as follows:

- Use the existing numerical groundwater model from South Dunedin developed by ORC and updated by GNS[1] to assess the effectiveness of the proposed water management adaptation options identified in the SDF programme (described in Section 3).
- Visualise in overview maps and cross sections how groundwater levels would be controlled by the proposed water management adaptation options, and how these compare to groundwater drainage provided by the current network of leaky stormwater and wastewater pipes.
- Assess potential inflows of groundwater to stormwater and groundwater management infrastructure for the proposed water management adaptation options, to inform pumping requirements for the stormwater design.
- Document the findings in a brief report to inform the cost benefit analysis of the proposed adaptation options for the SDF programme.

[1] GNS Science has merged with NIWA to form Earth Sciences New Zealand (ESNZ)

1.4 BRIEF SITE DESCRIPTION

South Dunedin comprises a low-lying dense urban environment of 600 ha which is less than 3 m above mean sea level, and a large part is below the current high tide mark. Because of the low elevation, stormwater drainage under gravity is challenging in the current state, and this will likely be exacerbated by sea level rise.

South Dunedin is located south of the Dunedin city central business district, between the Otago Harbour Basin and the Pacific Ocean. South Dunedin is mainly a residential area with medium density housing (ORC 2012). Groundwater levels in South Dunedin are high and generally less than 1 m below ground level. Near Tonga Park in the centre of the area, groundwater levels are generally less than 0.5 m below ground level. Current high groundwater issues mainly affect the suburbs Forbury, St Kilda West and Tainui and, to lesser extent, the suburb of South Dunedin (Figure 1).

In recent times before European settlement the area comprised salt marshes, lagoons, dunes and intertidal mudflats. South Dunedin was developed into a predominantly residential and commercial / retail area from the 1800's onward, following land reclamation and land filling. Land filling was often poorly compacted, and some residual land settlement is still occurring (ORC 2016).

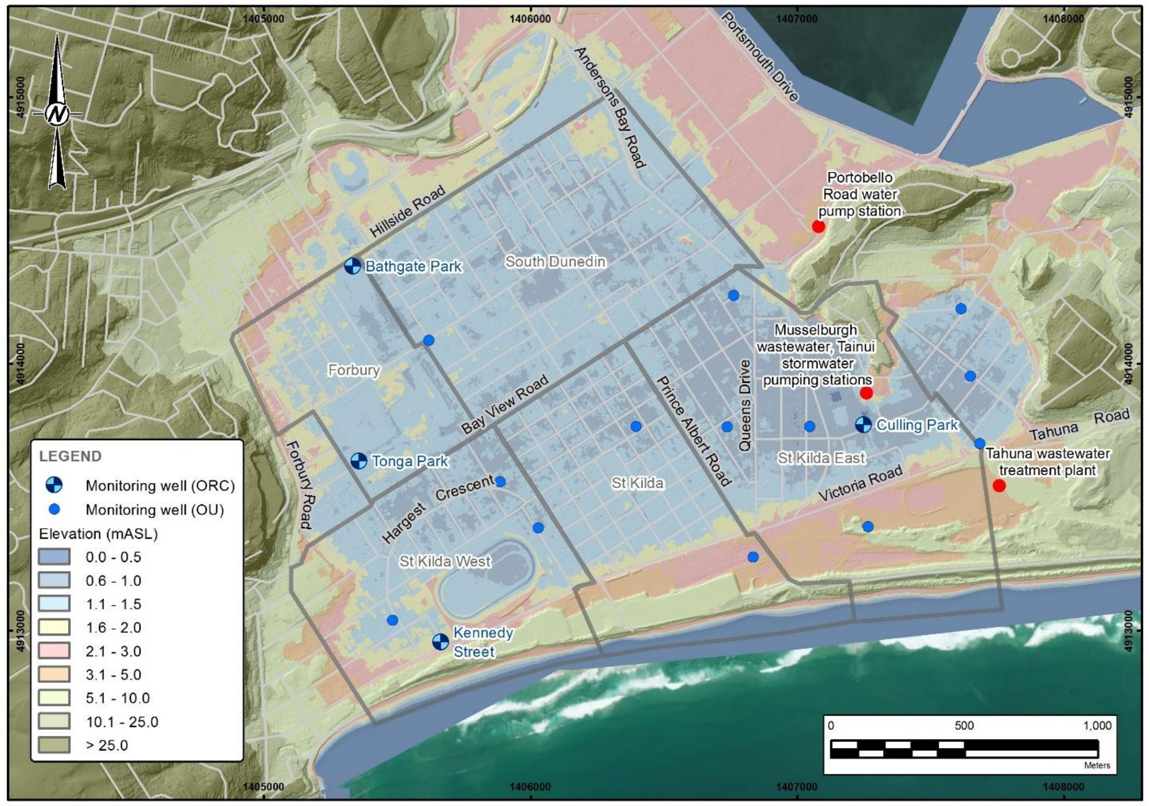

Figure 1: South Dunedin area

The area was once a river valley partly filled with alluvial gravels and sands that has now been buried in soft sediments (sand, silts and clays) forming a land bridge between the surrounding hills as sea levels rose after the last ice age (ORC 2012, ORC 2016 and Fordyce 2013). Glassey *et al* (2021) note that the bedrock geology of South Dunedin and the surrounding area is comprised of Early Miocene Caversham Sandstone and Late Miocene volcanic rocks of the Dunedin Volcanic Group. Caversham Sandstone outcrops in the Caversham Valley area, while the overlying Dunedin volcanic rocks form the hills surrounding the harbour and South Dunedin. Younger Quaternary sediments have filled in the area, comprising sands and silts deposited under marine to estuarine conditions, underlain by sandy and gravelly stream sediments. The total thickness of the Quaternary sediments could be as much as 70 m Glassey *et al* (2021). Large accumulations of dune sand have formed along the southern coast between the Pacific Ocean and South Dunedin. Based on groundwater model calibration, the lateral hydraulic conductivities (i.e., a measure of permeability) of the Quaternary sediments are estimated to range from 2 to 6 m/day with vertical hydraulic conductivity estimates to be 10% of the lateral hydraulic conductivity (Chambers *et al*, 2023).

Groundwater enters old wastewater and stormwater pipes according to DCC (2025) and is accidentally providing some groundwater drainage in South Dunedin. Fordyce (2013) observed high salinity in several groundwater monitoring wells, which may have been caused by the accidental groundwater drainage by the old leaky wastewater and stormwater pipes.

The groundwater system in the dunes south of Victoria Rd may be notably different from that in the rest of South Dunedin. There is limited hydrogeological data and information available for the dunes; however, it could be subject to density-dependent groundwater flow processes. Groundwater in the dunes is replenished with fresh rainfall water, and a fresh groundwater body may have formed that floats on top of much denser salt seawater in the marine sediments beneath the dunes. Freeze & Cherry (1979) describe this as the Ghyben-Herzberg principle, which dictates that the depth of the fresh and salt groundwater interface (z) is roughly 40 times the height of the groundwater table (h), as shown in Figure 2. In practice, the interface may not always be as sharp as assumed in the Ghyben-Herzberg principle, but rather a transition zone has formed. ORC (2012) notes that earth resistivity soundings in South Dunedin roughly conformed to the Ghyben-Herzberg ratios for freshwater and saline water in a coastal aquifer.

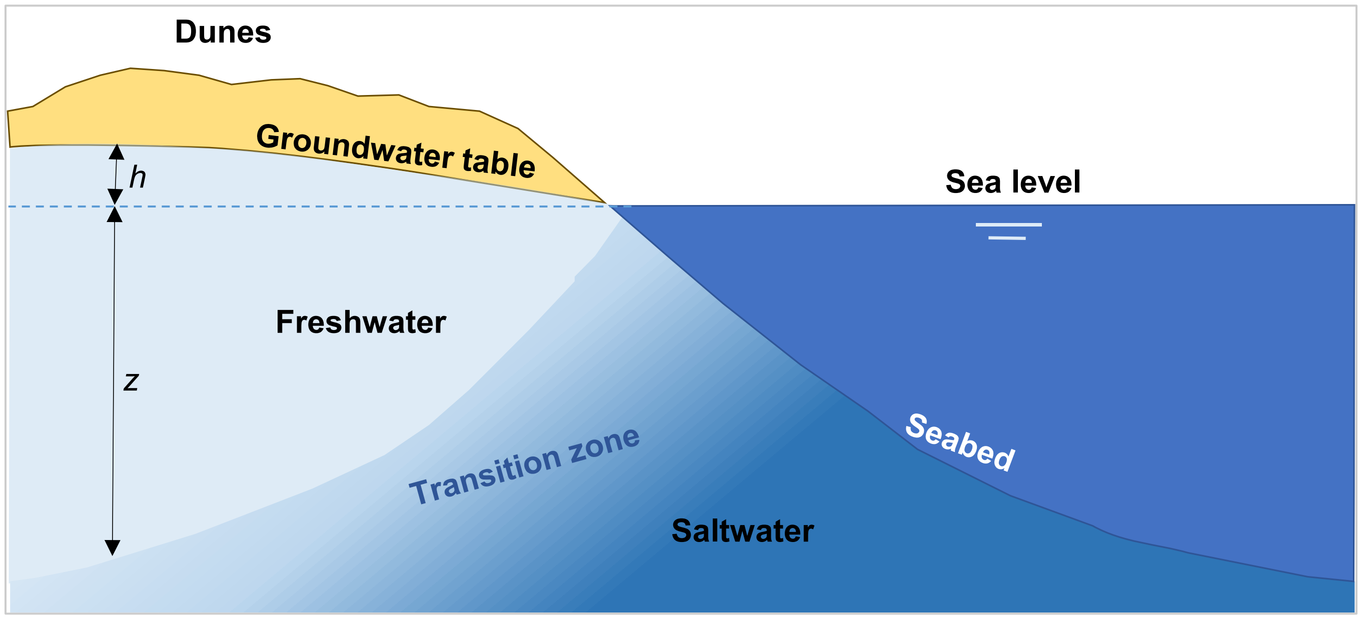

Figure 2: Diagram showing the Ghyben-Herzberg principle

2 APPROACH

2.1 MODELLING TOOLS USED

WSP used the South Dunedin 3-dimensional numerical groundwater model developed by ORC (2012) and updated by GNS (Chambers *et al*, 2023) for the groundwater modelling investigations presented in this report. The key characteristics of this numerical groundwater model are as follows:

— The model is a single layer, steady state model built in MODFLOW. The MODFLOW source code was developed by the USGS (1988). This is a widely used, industry standard, three-dimensional numerical groundwater modelling tool.

— The original model from ORC (2012) was modified and updated by GNS (Chambers *et al*, 2023) as follows:

  — The hydraulic conductivities of the soil materials encountered beneath South Dunedin where optimised in the model, so the model is better capable of simulating recorded groundwater levels. This is an important step in improving the model's accuracy. In addition, GNS improved the estimation of groundwater recharge into the model and optimised the conductance term that governs the flows into the existing leaky stormwater and wastewater network.

  — The model was converted from a 'deterministic' model into a 'stochastic' model. Stochastic modelling involves running the model with various sets of possible hydraulic properties of soil materials, and then analysing the probability of certain outcomes across the various model runs. Instead of simulating a single outcome, a stochastic model simulates the probability that a certain outcome would occur. For example, it simulates the probability of groundwater seepage at the surface causing drainage issues at a certain location and in a certain scenario (e.g., current state or a future state affected by sea level rise). Stochastic modelling aims to capture the uncertainty in groundwater conditions and hydraulic properties of the soil materials.

GNS used the updated model to investigate the probability of the current groundwater drainage issues in South Dunedin being exacerbated due to future sea level rise (Chambers *et al*, 2023).

2.2 MODEL UPDATES

The updated model from GNS (Chambers *et al*, 2023) was further modified by WSP to make it suitable for simulating the efficacy of various groundwater drainage systems to control groundwater levels. The following modifications were made:

— The model was converted to a deterministic model, which means it provides only a single outcome in terms of a groundwater level surface of groundwater flow field for each scenario. This makes it possible to mutually compare the outcomes of various scenarios as described in Section 3. The hydraulic properties and rainfall recharge estimates for the optimised groundwater model by GNS (Chambers *et al*, 2023) were used for the simulations.

— For improved simulation of groundwater gradients, WSP refined the model grid as follows:

  — Reduced grid spacing to 10 m x 10 m (from the original 40 m x 40 m grid) to better simulate groundwater mounding between drainage features. This improves the representation of drainage depth below surface.

  — Increased the number of layers from 1 layer to 4 layers for better simulation of vertical gradients. Each layer has the same lateral and vertical hydraulic conductivity values as the optimised groundwater model by GNS (Chambers *et al*, 2023).

— We rescaled the conductance of pre-existing drainage features in the model (i.e., representing leaky stormwater and wastewater systems) to achieve a consistent water balance with the optimised GNS model (i.e., a uniform conductance value of 0.8 m^2/day was adopted), and assumed new groundwater drainage features would have a conductance twice as high as the leaky stormwater and wastewater systems as they would be specifically designed for groundwater drainage as opposed to the accidental drainage by leaky pipes.

For the assessment of the efficacy testing of the adaptation options (Section 3.2) we used steady state modelling. Steady state modelling assumes the groundwater system is in equilibrium representing average groundwater conditions. We also developed transient (i.e., time dependent) models for high-level assessments of temporal changes in groundwater levels and flows in response to a significant storm event passing the area, or in case of a failure of the pumped scheme which causes groundwater drainage to cease. This is further described in Section 3.4.

2.3 MODEL LIMITATIONS

The South Dunedin 3D numerical groundwater model, built by ORC (2012) and updated by GNS (Chambers *et al*, 2023), has been further adjusted by WSP with the intent to assess changes in groundwater levels and inflows to water management systems as a result of the implementation of various water management adaptation options. However, the model has not specifically been developed to accurately assess groundwater levels and flows at each location at each time. In addition, the model only implicitly accounts for the interaction with stormwater and surface water drainage systems, and does not account for density-dependent flow. The accuracy of the model is limited to the accuracy and completeness of the available hydrogeological and geological data from field investigations and literature, as described in Chambers *et al* (2023). The results presented in this report should therefore be considered as indicative only.

3 OPTIONS ASSESSMENT

3.1 KEY CONSIDERATIONS

Several potential adaptation options are being considered in the SDF programme. The adaptation options entail pumped scheme water management options, because sea level rise will make stormwater and groundwater drainage under gravity unfeasible at some point in time. The leaky pipes from the current stormwater and wastewater network in South Dunedin provide for some 'accidental' groundwater drainage, because those networks are pumped by the Portobello and Tahuna pumpstations. Nonetheless, South Dunedin is already susceptible to stormwater flooding and groundwater drainage issues in the current state, and therefore the adaptation options considered include a short-term solution designed to address current issues. Sea level rise will exacerbate the issues in the future and a sea level rise of up to 1.1 m is assumed to assess the efficacy of the adaptation options in a more distant future (approximately 100 years from the current state).

The potential adaptation options considered assume that the management of stormwater and groundwater will be combined. It should be considered that stormwater flows during significant events are much larger (i.e. multiple orders of magnitude) than groundwater flows, hence the conveyance of groundwater flows has only a minor impact on the stormwater systems design.

A large basin would be built in Forbury Park in the proposed adaptation options, and this basin will be the downstream collection basin where most of the stormwater and drained groundwater will be conveyed. From there, the water will be pumped to the sea by a pumpstation. The pumpstation would have a high-capacity pump that pumps large flows during and directly after significant storm events. A smaller lower-capacity pump would continuously pump water for groundwater drainage. The low-capacity pump is aimed at maintaining the required water level in the basin that allows all stormwater systems to drain to the basin.

It should also be considered that groundwater drainage is continuous (i.e., there is a continuous baseflow) with increased inflows during and directly after storm events and a gradual reduction in flows over several days or weeks thereafter. This is different from stormwater flows that could be very high during and directly after significant storm events but will quickly recede to almost zero during dry conditions. Whilst modelling suggests groundwater inflows could temporarily triple from the baseflows after notable storm events (Section 3.4 and 4.4.2), these flows will always be very modest compared to stormwater flows.

The lowering of groundwater levels by drainage can cause land settlement as a result of reduced pore water pressure and subsequent consolidation of the soil structure. Certain soil materials are particularly vulnerable to settlement, such as unconsolidated and saturated clay and peat, but some land settlement can also occur in sandy and silty soils encountered beneath South Dunedin. Only a modest lowering of the groundwater level across South Dunedin is therefore considered in this investigation, which is generally less than about 0.8 m but locally up to 1.5 m in the adaptation options considered (Section 3.2). This groundwater drawdown is expected to cause less than 50 mm (0.05 m) of land settlement, although further investigations to confirm this are warranted.

3.2 POTENTIAL ADAPTATION OPTIONS CONSIDERED

The following pumped scheme adaptation options (referred to as 'Futures') are considered in the groundwater modelling investigations that aim to increase resilience against groundwater issues:

— **Current systems**: groundwater levels are partially controlled by the current leaky stormwater and wastewater system, which are installed about 1 m deep. This option serves as a comparison, to inform what will happen in the future if no water management changes are implemented.

— **Future 3 – Protect**: improved stormwater and groundwater management with a piped network and in-catchment storage/retention basins installed to a depth of generally 0.8 m, but up to 3 m in some locations. Bespoke infrastructure would be installed that is purposely designed to drain, convey and discharge both stormwater and groundwater effectively. Only limited room for open water at the surface is envisioned, although several storage and retention basins would be installed in Tonga, Bathgate, Forbury and Culling Park. The Tonga, Bathgate and Culling Park retention basins would be designed to avoid interaction with groundwater (i.e., they will be lined or will be installed above the groundwater table). The Forbury Park basin would be excavated and drained to a level of 1 m below the current sea level. The Forbury Park basin would thus drain groundwater, where the other basins would not interact with groundwater. In this option, it is assumed that the drainage provided by the current leaky stormwater and wastewater system will be maintained. This option also includes partially raising the land by 2.5 m in the west of South Dunedin, which provides a greater separation between the ground surface and the groundwater table, thus reducing the exposure to potential groundwater drainage issues.

— **Future 4 – Restore**: this option includes the same stormwater and groundwater management as Future 3, with the addition of open canals that would be constructed in MacAndrew Rd, Bellona St, and Victoria Rd, which would be excavated to a depth of about 1.5 to 3.0 m. The canals proposed in Future 4 should all be fully hydraulically connected to groundwater, so that they are continuously filled with water and drain groundwater (they should not be lined). The open canals also provide for stormwater storage and conveyance. In addition, they form a key opportunity to improve amenity value of South Dunedin by providing for blue and green open spaces in the area.

— **Future 5 – Reshape**: similar to Future 3, this option includes partially raising the land by 2.5 m. In this option the land raising would be in the west and north of South Dunedin. Stormwater and groundwater would be managed the same way as for Future 4.

Overview maps of these three different Futures are included in Appendix A.

For the groundwater modelling the following scenario simulations were developed based on the various options described above, and their outcomes compared as described in Section 4:

— Current State: current sea level and drainage provided by current leaking stormwater and wastewater systems in roads.

— Future 3: current sea level, raised land in the west, a new stormwater system that also drains groundwater, the Forbury Park basin (at -1 m below sea level), and the existing leaky stormwater and wastewater drainage.

— Future 4: current sea level, a new stormwater system that also drains groundwater, the Forbury Park basin (at -1 m below sea level), three new open canals, and the existing leaky stormwater and wastewater drainage.

— Future 5: Stormwater and groundwater managed as per Future 4, and land raising by 2.5 m in west and north of the area.

— Current system with 1.1 m sea level rise: as per Current State but with +1.1 m sea level rise

— Future 3 with 1.1 m sea level rise: as per Future 3 but with +1.1 m sea level rise

— Future 4 with 1.1 m sea level rise: as per Future 4 but with +1.1 m sea level rise

— Future 5 with 1.1 m sea level rise: as per Future 5 but with +1.1 m sea level rise

The results are shown in Appendix B and discussed in Section 4.

3.3 SUCCES CRITERIA

At this stage the only success criteria considered is the required drainage depth, which refers to the depth below which the groundwater level is ideally maintained. The required drainage depth should be selected so that it avoids water ponding at the surface but also avoids moisture ingress into foundations and crawl spaces beneath buildings, and weakening of soils beneath roads and hardstand areas (which can cause road damage such as potholes). For this investigation a required drainage depth of **0.7 m below ground level** was adopted from SBR (2007). This criteria is based on a 'best practice' approach and is used by councils in The Netherlands for managing groundwater levels in urban areas. The criteria accommodates the capillary rise above the groundwater table, annual groundwater table fluctuations, and the depth to underground services and road foundations, which are often about 0.7 m deep (Figure 3). While there is no single report establishing this criteria as a norm, its effectiveness is documented in various technical standard works that describe the interaction between water, soil, and infrastructure.

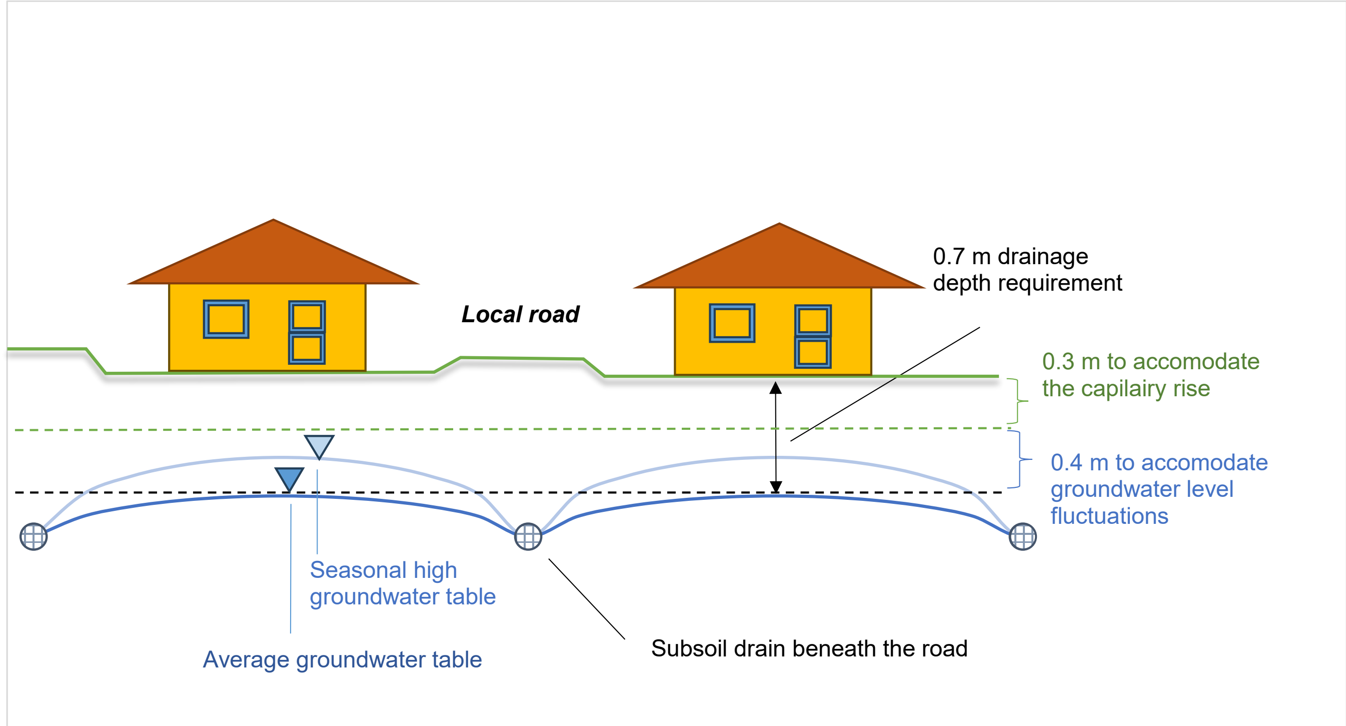

Figure 3: Schematic diagram of required drainage depth

Whilst meeting this success criteria will achieve a liveable area with minimal impacts on buildings, roads and structures, groundwater levels in South Dunedin will always be high and relatively close to the surface. Further lowering the groundwater table by deeper drainage requires more costly pumping and could further increase land settlement, thus it is not recommended.

The high groundwater level also means that the soil's capacity to adsorb rainwater remains very small and that stormwater systems that rely on infiltration to ground, such as soakage pits and infiltration basins, may not be suitable for most of the South Dunedin area.

3.4 EVENT-BASED GROUNDWATER DRAINAGE RESPONSE

The success of the scenarios described above in Section 3.2 are tested for average groundwater conditions. However, during extreme weather events, stormwater and groundwater inflows to the combined stormwater and groundwater systems can rapidly rise and potentially overwhelm the system. Furthermore, pump failure can cause the stormwater and groundwater systems to stop working. Both circumstances can lead to widespread flooding issues.

Indicative transient (i.e., time-dependent) event-based modelling was undertaken to 'stress test' the groundwater management system. This helps to better understand possible groundwater inflows to a pumped combined stormwater and shallow groundwater management system during a major storm event, and how quickly groundwater issues arise after pump failure.

Using the Future 4 scenario with 1.1 m sea level rise, we developed several modelling scenarios with the following key characteristics:

— For the 24-hour storm event we have adopted the 175 mm in 24 hour storm event recorded in June 2015 that resulted in wide-spread flooding in South Dunedin.

— Three different scenarios representing different groundwater recharge rates during the storm event were investigated, with one scenario assuming the combined stormwater and groundwater system can cope with the deluge, and two scenarios in which the system is overwhelmed. In addition, three cases were assessed in which the aquifer storativity[2] varies in one of the scenarios.

— Two different 'pump failure' scenarios were tested (i.e., total cessation of all groundwater drainage, including the drainage provided by the current leaky wastewater and stormwater pipes). With these scenarios we investigated how quickly groundwater levels could rise to the surface and cause water ponding issues due to pump failure. We tested this for a scenario representing average conditions, and for a scenario in which a significant storm event passes the area.

The results are discussed in Section 4.4.2.

As stated, only a high-level event-based modelling was undertaken. We acknowledge further model calibration under transient conditions is required to improve the accuracy of the predictions.

2 Aquifer storativity represents the volume of water that an aquifer releases from storage under a certain decline in groundwater level (Ritsema, 1994). The aquifer storativity affects the response time of groundwater levels and flows to certain 'stresses', such as increased rainfall recharge or groundwater abstraction through drainage.

4 FINDINGS

4.1 SHORT TERM EFFICACY OF OPTIONS

The first map in Appendix B (slide 1) shows where, in the current state, groundwater levels meet the required drainage depth (i.e., success criteria of 0.7 m below ground level mentioned in Section 3.3). The light-yellow areas do not meet the criteria and are currently susceptible to groundwater drainage issues, even before notable sea level rise has taken effect. The second map in Appendix B (slide 2) shows how the proposed Future 3 stormwater and groundwater systems will notably alleviate the issues, with a much smaller area not meeting the required drainage depth.

The installation of the Forbury Park basin and the new stormwater system that combines stormwater conveyance with groundwater drainage in all three Futures, is expected to achieve a notably improved groundwater outcome in the short term (approximately 10 to 20 years). The partial land raising (by 2.5 m) will improve drainage depth in the west of South Dunedin in Future 3 and 5.

Whilst the Future 4 adaptation option (third map in Appendix B; slide 3), which includes the installation of three canals, will further lower groundwater levels, it may not achieve much more short-term benefits for groundwater outcomes.

4.2 LONG TERM EFFICACY OF OPTIONS

The fourth map in Appendix B (slide 4) shows how almost the entire area of South Dunedin will no longer meet the required drainage depth with a sea level rise of 1.1 m (expected within the next ~100 years) if no adaptation option is implemented (only the existing leaky stormwater and wastewater systems drain some groundwater). Areas that are currently susceptible to drainage issues will have wide-spread persistent water ponding on the surface. Those areas will effectively be uninhabitable swamp areas.

The fifth and sixth map (slide 5 and 6) show the effectiveness of Future 3 and 4 to drain groundwater even when the sea level has risen by 1.1 m. In both options most areas meet the required drainage depth without any persistent water ponding at the surface. However, Future 4 is notably more effective than Future 3 to accommodate the consequences of sea level rise. This is because of the addition of open channels, although we acknowledge that a buried drainage system instead of channels may achieve a similar outcome. Future 5 has the same combined stormwater and groundwater management system as Future 4, but partial land raising (by 2.5 m) will improve drainage depth in the west and north of South Dunedin, as indicated on the seventh and eighth map (slide 7 and 8) in Appendix B.

Compared to the current state (with groundwater levels being controlled solely by a leaky stormwater/wastewater system), the new scenarios may reduce the risks of liquefaction during seismic events because groundwater levels are permanently lowered. Nonetheless, some land subsidence could occur due to the permanent groundwater drainage. Further assessment of the influence on liquefaction and land settlement risks associated with the proposed stormwater and groundwater management in all three Futures is recommended.

Eight cross sections are included in Appendix B following the map series (slide numbers 9 to 16). These provide further insight into how the various drainage features (e.g., stormwater systems, leaky stormwater and wastewater pipes in the roads, basins and canals) will control the groundwater level. It is specifically noted that the drainage features will need to be installed deeper than the required drainage depth of 0.7 m to be sufficiently effective in managing groundwater levels, and this was incorporated in the Future 3, 4 and 5 modelling scenarios (Section 3.2).

4.3 EXPECTED GROUNDWATER FLOWS TO MANAGE

The modelled groundwater balance is shown in Table 1 (note: the modelled groundwater balance has a small discrepancy of ~2% which is common in numerical modelling). The total groundwater recharge from rainfall in the South Dunedin area is estimated to be about 4,900 m^3/day on average, and for this investigation this is assumed to remain the same in the future. In the current state, the groundwater inflows into the existing leaky stormwater and wastewater system are modelled to be about 1,900 m^3/day. The modelling shows this accidental groundwater drainage is causing a small amount of saline intrusion (i.e., saltwater draw-in from the sea) of about 50 m^3/day. The remaining 2,900 m^3/day flows out via groundwater to the sea.

Table 1: Modelled groundwater balance for the current state and future scenarios ('SLR' stands for sea level rise)

Water balance component	Current State	Future 3 - current	Future 4 & 5 - current	Current system + 1.1 m SLR	Future 3 +1.1 m SLR	Future 4 & 5 + 1.1 m SLR
Inflows (m^3/day)						
Rainfall recharge	4,915	4,915	4,915	4,915	4,915	4,915
Inflows from the sea (saline intrusion)	52	321	465	262	1,016	1,516
Total inflows	4,967	5,237	5,381	5,177	5,932	6,431
Outflows (m^3/day)						
Pre-existing road drainage	1,934	907	291	2,693	951	377
New stormwater system	-	1,060	786	-	1,700	1,046
Forbury Park pond	-	733	573	-	1,044	809
Bellona St canal	-	-	316	-	-	359
MacAndrew Rd canal	-	-	390	-	-	440
Nile St canal	-	-	155	-	-	178
Courtney St canal	-	-	100	-	-	162
Victoria Rd canal	-	-	518	-	-	884
Total drainage	1,934	2,699	3,129	2,693	3,696	4,256
Outflows to the sea (via groundwater)	2,917	2,421	2,216	2,401	2,179	2,058
Total outflows	4,851	5,120	5,346	5,095	5,874	6,315

In all adaptation options (Future 3, 4 and 5), if these were implemented in the next decade (short term), the amount of groundwater inflows into the water management systems (i.e., combined stormwater and groundwater drainage) will increase notably to about 2,700 m^3/day in Future 3 and 3,100 m^3/day in Future 4 and 5 according to the modelling. As a consequence, saline intrusion will increase exponentially.

In a climate-changed future with sea level rise of 1.1 m, the amount of groundwater drainage to the stormwater and groundwater drainage systems will increase notably, up to 4,300 m^3/day on average for Future 4 and 5. However, the percentage difference between the three scenarios with sea level rise is the same as for those without sea level rise. Saline intrusion will become considerable with sea level rise of 1.1 m and is expected to contribute 25 to 50% to the groundwater inflows into the stormwater and groundwater management systems.

Inflows from the sea (i.e., saline intrusion) will be about one third larger in Future 4 and 5 than in Future 3, both in the short and long term (Table 1). This is mainly due to the proposed Victoria Rd canal in Future 4 and 5, which will capture most of the inflows from the sea because it is closest to the coast. This also means that much of the saline intrusion would be contained by the Victoria Rd canal, minimising saltwater inflows to the rest of the stormwater and groundwater management system.

4.4 OTHER CONSIDERATIONS

4.4.1 GROUNDWATER QUALITY

As described above in Section 4.3, saline intrusion will increase exponentially across all the scenarios considered (including those without adaptation options implemented) further increasing the existing salinity of the shallow groundwater in South Dunedin. The proposed Forbury Park basin and the Future 4 and 5 canals will become brackish or even saline. The change in salinity and overall water quality will likely influence ecological values in the proposed open water drainage features. The planting of salt tolerant vegetation along open water features is recommended, also noting that brackish water could flood land adjacent to the open water features during a significant storm event. In addition, existing underground services (e.g., cables, pipes, fittings, manholes, etc.) could be affected by the salt water, depending on the materials they are made of. Salt tolerant materials should be used for new underground services installations. What the exact impacts are and whether these are negative is still to be investigated.

4.4.2 OPERATION AND MAINTENANCE

Ongoing and continuous pumping will be required in all scenarios to drain the land from stormwater and groundwater. This means that ongoing operation and maintenance costs will be incurred to keep South Dunedin dry, and these costs are expected to increase over time as more pumping will be required with progressive sea level rise.

It should also be considered that continuous pumping to drain stormwater and groundwater is already taking place in many urban areas and several rural areas across New Zealand, and the world. This will likely increase in the future, and proper operation and maintenance of water management systems will become increasingly more important as well as costly.

South Dunedin is not unique in its vulnerability to stormwater flooding and groundwater drainage issues and both technical and management solutions for designs, operation and maintenance of water management systems could be adopted from international case studies where these have been successfully implemented (Golder and Deltares, 2017).

To better understand the operational vulnerability of the proposed combined stormwater and groundwater management system, we investigated how much groundwater inflows to the system could increase during a significant storm event, and whether this could overwhelm the system. In addition, we assessed how groundwater levels respond to a failure of the pumping system, and within what timeframe this could lead to widespread drainage issues in South Dunedin. The key findings are as follows:

- The proposed combined stormwater and groundwater management system is designed to cope with significant storm events, which is referred to as 'design events'. High-level modelling assessments suggest groundwater peak inflows to the system could increase from 0.05 to 0.17 m^3/sec (or from 5,000 to about 15,000 m^3/day) during those design events, assuming that the system copes and no wide-spread surface flooding occurs. The groundwater peak flow is notably less than the peak stormwater inflow to the proposed Forbury Park basin in a 1 in 100 year storm event, which is 7.5 m^3/sec. It is unlikely that groundwater inflows could overwhelm the stormwater conveyance systems during design events, noting that the proposed combined stormwater and groundwater management system was designed to accommodate the combined groundwater and storm water peak inflows.
- Pump failure will cause groundwater levels to gradually rise reducing the drainage depth. Eventually, the area's drainage depth will resemble the unmitigated drainage depth shown in Map 1 and 4 in Appendix B with widespread drainage issues. The modelling assessment suggest that pump failure would not immediately lead to significant groundwater issues and there will in most circumstances be sufficient time to restore the pumping scheme and avoid issue associated with groundwater levels (i.e., water ponding on the surface). If conditions are relatively dry (only moderate rainfall), it could take more than a year for groundwater levels to reach the surface in susceptible areas. Groundwater levels can reach the surface more rapidly if conditions are wet, although it would still take several months for groundwater issues in the area to be widespread. However, this is heavily dependent on the antecedent conditions. If pump failure occurs during or immediately following significant rainfall and widespread surface flooding, groundwater issues could arise immediately.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

South Dunedin is highly vulnerable to flooding and drainage issues due to its low elevation (less than 3 m above sea level) and high groundwater levels (often <1 m below ground). Existing leaky stormwater and wastewater pipes provide some accidental groundwater drainage, but this is insufficient even now. Sea level rise (up to +1.1 m within ~100 years) will make gravity drainage unfeasible. Without intervention, most of South Dunedin will become persistently waterlogged and effectively uninhabitable.

Several future adaptation options have been considered in this groundwater modelling investigation aimed at alleviating stormwater flooding and groundwater drainage issues:

- Current system: Groundwater drainage is only provided by the current leaky stormwater and wastewater system.
- Future 3 – Protect: New piped stormwater system that drains into a Forbury Park basin (excavated into groundwater and with water level maintain at 1 m below sea level), and partial land raising in the west by 2.5 m.
- Future 4 – Restore: Same stormwater and groundwater management as Future 3, but with the addition of open canals (MacAndrew Rd, Bellona St, Victoria Rd) which provides better groundwater drainage and achieves amenity improvements. However, there would be no land raising in this option.
- Future 5 – Reshape: Same as Future 4, but with partially raising the land by 2.5 m in both the west and north of South Dunedin. This option is a hybrid form between Futures 3 and 4, but with additional land raising in the north.

The effectiveness of the investigated future adaptation scenarios is as follows:

- For the short term (10–20 years), Future 3 significantly reduces groundwater issues compared to the current state. Whilst Future 4 and 5 achieve the same, they offer only marginal additional short-term benefit in comparison to Future 3.
- For the long term which includes +1.1 m sea level rise, the current system will fail to provide any meaningful groundwater drainage. Future 3, 4 and 5 are all able to maintain a required drainage depth (0.7 m below ground), preventing surface ponding. In contrast to the short term outcomes, Future 4 and 5 are notably more effective than Future 3 under +1.1 m sea level rise conditions, mainly due to the addition of the Victoria Rd canal in these Futures.

The current accidental groundwater inflow (i.e., drainage) to the leaky stormwater and wastewater system is modelled to be ~1,900 m^3/day. Under current conditions groundwater inflows to the Future 3 water management systems are modelled to be ~2,700 m^3/day, and for Future 4 and 5 ~3,100 m^3/day. The latter will increase to more than 4,300 m^3/day with 1.1 m sea level rise. Saline intrusion will increase significantly, especially with sea level rise (up to 50% of all groundwater inflows to the water management systems).

Overall Conclusion:

- Pumped drainage systems are essential for South Dunedin's future resilience, which are needed to maintain groundwater levels sufficiently below the ground surface in areas that are currently about 2 m below sea level.
- Future 4 (with canals) and Future 5 (same as Future 4, but with partial land raising) provide the best long-term solution for managing groundwater and enhancing amenity, despite higher complexity and cost.
- All options will require ongoing pumping and maintenance, and saline intrusion will be a major factor in future system design.
- Whilst several recommendations for further investigations are outlined in Section 5.2, we are confident that at this stage a sufficient level of knowledge is available to understand how South Dunedin's groundwater system can be effectively managed.

5.2 RECOMMENDATIONS

Several further investigations are recommended to better understand the benefits and pitfalls of the proposed water management adaptation options. The recommendations are listed below with an indication of the level of priority and possible timeline for implementation:

High priority, short term (1-5 years)

- Initiate a pilot trial in which a small-scale groundwater drainage system is installed and tested. Groundwater levels and drainage inflows should be monitored prior to, during and after testing. Groundwater salinity monitoring (in monitoring wells and in the drainage water) is also recommended. This provides valuable information on aquifer permeability, zone of influence of the drainage system, and further insights into the efficacy of groundwater drainage solutions. A pilot trial groundwater drainage test also provides an opportunity for DCC staff and stakeholders to become familiar the concept of groundwater drainage and with the systems involved. We recommend a well-thought-out pilot trial plan is drafted in which the objectives, approach and programme of such a test are clearly described.
- Open water features (Forbury Park basin and proposed canals) will likely become brackish or even saline over time, in all scenarios investigated. The ecological impacts need further assessment, which will inform the design, landscaping (e.g., planting of salt tolerant vegetation) and long-term maintenance of the proposed open water features. Underground services (e.g., cables, pipes, fittings, manholes, etc.) could be affected by salt water, depending on the materials they are made of. A review of ways to mitigate saltwater corrosion of underground services (e.g., use of type of materials) for new underground services installations is recommended.
- Land settlement risks are expected to be minor (<50 mm) due to modest groundwater lowering of the proposed systems (i.e., generally no more than 0.8 m drawdown). However, more detailed investigations are recommended to confirm the magnitude of land settlement and what mitigation options could be considered if this is required.
- An integrated pumped groundwater and stormwater management system will have notable specific design implications (e.g., saline intrusion, varying pump regimes for dry-weather and for storm event control, etc.). An holistic multi-disciplinary approach is required to develop a robust suitable future-ready design of the stormwater and groundwater management system.
- The potential adaptation options considered all require a pumped scheme to be implemented, and this requires ongoing operational and maintenance efforts and costs, which are likely to increase considerably

over time when the consequences of climate change and sea level rise become considerable. A comprehensive cost-benefit analysis is recommended based on further design work.

Low priority, long-term (>5 years)

- The saline intrusion that already occurs beneath South Dunedin and likely to increase in the future could be strongly driven by density-dependent flow. This process is currently not explicitly incorporated in the numerical groundwater modelling undertaken to date. Further modelling investigations to improve the understanding of saline intrusion and groundwater processes beneath the dune areas is recommended. These would inform the timeline within which a future stormwater and groundwater management system will become saline, and what measures are most effective to partially mitigate the saline intrusion. This may inform long-term decision making in relation to the stormwater and groundwater management of the area.
- Further investigations into the temporal changes in groundwater levels and flows in response to a significant storm event passing the area, or in case of a failure of the pumped scheme which causes groundwater drainage to cease, could be considered. Transient model calibration is required to confirm representative aquifer storativities to increase the accuracy of the model predictions. However, this may not impact design choices as a combined stormwater and groundwater management system will be designed to accommodate much higher stormwater flows.
- The permanent lowering of the groundwater table by the considered adaptation options could potentially reduce liquefaction effects, and further high-level investigation in the beneficial effects on liquefaction is recommended. However, this investigation may not be required to inform further design work for the pumped stormwater and groundwater management system.
- Additional modelling assuming various sea level rise conditions (i.e., associated with different sea level rise predictions and at different time steps) is recommended to better understand when the tipping points occur at which the subsequent stages of adaptation options are best implemented. Earth Sciences New Zealand (ESNZ) indicated they could provide improved high-resolution vertical land movement estimates to help inform this investigation. This may inform long-term decision making in relation to the stormwater and groundwater management of the area.

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APPENDIX A – GROUNDWATER DRAINAGE OPTIONS MAPS

Current State - Drainage Features
Cross section lines
Drainage features (current state)
Topography (m above DDB)
255
0
A
A'
B
B'
C
C'
D
D'
Maryhill
Kensington
The Glen
Cargills Corner
South Dunedin
Forbury Corner
Portsmouth Dr
Sunshine
Rawhiti St
Musselburgh Rise
Musselburgh
Tainui
Chisholm Park
Saint Kilda
St Kilda Kindergarten
Ocean Beach Domain
John Wilson Ocean Dr
Allandale Rd
Easther Cres
Bayfield Rd
Arawa St
Oxford St
Melbourne St
Bay View Rd
Hillside Rd
Macandrew Rd
Fawcett St
Young St
Richardson St
Plunket St
Douglas St
Jackson St
Bay View Rd
N
250 125 0 250 500 750 1,000
Meters

wsp


Future 3 - Drainage Features
Cross section lines
Future 3 - raised land
Forbury Park pond
Drainage features (current state)
Short term pipes
Topography (m above DDB)
255
0
250 125 0 250 500 750 1,000
Meters
N
A
A'
B
B'
C
C'
D
D'
Forbury Park pond
(1 m below sea level)
Maryhill
Kensington
The Glen
Caversham Bypass Mtwy
Cargills Corner
South Dunedin
Forbury Corner
Saint Kilda
Saint Clair
Ocean Beach
Domain
St Kilda
Kindergarten
Musselburgh
Tainui
Chisholm Park
John Wilson Ocean Dr
Portsmouth Dr
Portobello Rd
Rawhiti St
Musselburgh Rise
Hillside Rd
Macandrew Rd
Melbourne St
Oxford St
Bay View Rd
Fawcett St
Young St
Calder St
Bellona St
Richardson St
Hargest Cres
Ings Ave
Allandale Rd
Easther Cres
Forbury Rd
Nelson St
Fitzroy St
Eastbourne St
Baker St
Law St
Burns St
Bradshaw St
Kirkcaldy St
Reid Rd
Glasgow St
Mcbride St
Andersons Bay Rd
Fingall St
Prince Albert Rd
New St
Queens Dr
Ascot St
Royal Cres
Rona St
Marlow St
Botha St
Tainui Rd
Arawa St
Bayfield Rd
Teviot St
Timaru St
Otaki St
Orari St
Dalgety St
Plunket St
Douglas St
Jackson St
Ajax St


Future 4&5 - Drainage Features
Cross section lines
Future 5 - raised land
Forbury Park pond
Drainage features (current state)
New canals
Short term pipes
Topography (m above DDB)
255
0
MacAndrew canal (0.6 m below sea level)
Bellona canal (0.8 m below sea level)
Victoria canal (0 to 1 m below sea level)
West canal (1 m below sea level)
Coughtrey canal (0 to 1 m below sea level)
Forbury Park pond (1 m below sea level)
A
A'
B
B'
C
C'
D
D'
Maryhill
Kensington
The Glen
Cargills Corner
Forbury Corner
Saint Kilda
Musselburgh
Tainui
Chisholm Park
Ocean Beach Domain
Saint Clair
St Kilda Kindergarten
Musselburgh Rise
Portsmouth Dr
John Wilson Ocean Dr
Allandale Rd
Forbury Rd
Queens Dr
Hillside Rd
N
250 125 0 250 500 750 1,000
Meters

APPENDIX B – GROUNDWATER DRAINAGE RESULTS MAPS AND CROSS SECTIONS


Current State
Cross section lines
Drainage features (current state)
Current State
<0 (susceptible to water ponding)
0 - 0.7 (exceed criteria)
0.7 - 1.5 (meets criteria)
>1.5 (low susceptibility)
A
A'
B
B'
C
C'
D
D'
N
250 125 0 250 500 750 1,000
Meters
Maryhill
Kensington
The Glen
Caversham Bypass Mtwy
Cargills Corner
South Dunedin
Forbury Corner
Saint Kilda
Musselburgh
Sunshine
Tainui
Chisholm Park
St Kilda Kindergarten
Ocean Beach Domain
Saint Clair
John Wilson Ocean Dr
Portsmouth Dr
Portobello Rd
Musselburgh Rise
Rawhiti St
Orari St
Otaki St
Timaru St
Teviot St
Andersons Bay Rd
Mcbride St
Hillside Rd
Glasgow St
Reid Rd
Burns St
Law St
Baker St
Eastbourne St
Fitzroy St
Nelson St
Bradshaw St
Macandrew Rd
Melbourne St
Fingall St
Oxford St
Fawcett St
Kirkcaldy St
Bay View Rd
Young St
Calder St
Bellona St
New St
Prince Albert Rd
Queens Dr
Ascot St
Royal Cres
Rona St
Marlow St
Botha St
Tainui Rd
Arawa St
Bayfield Rd
Forbury Rd
Hargest Cres
Richardson St
Dalgety St
Douglas St
Jackson St
Ajax St
Plunket St
Ings Ave
Easther Cres
Allandale Rd
Eagle Technology

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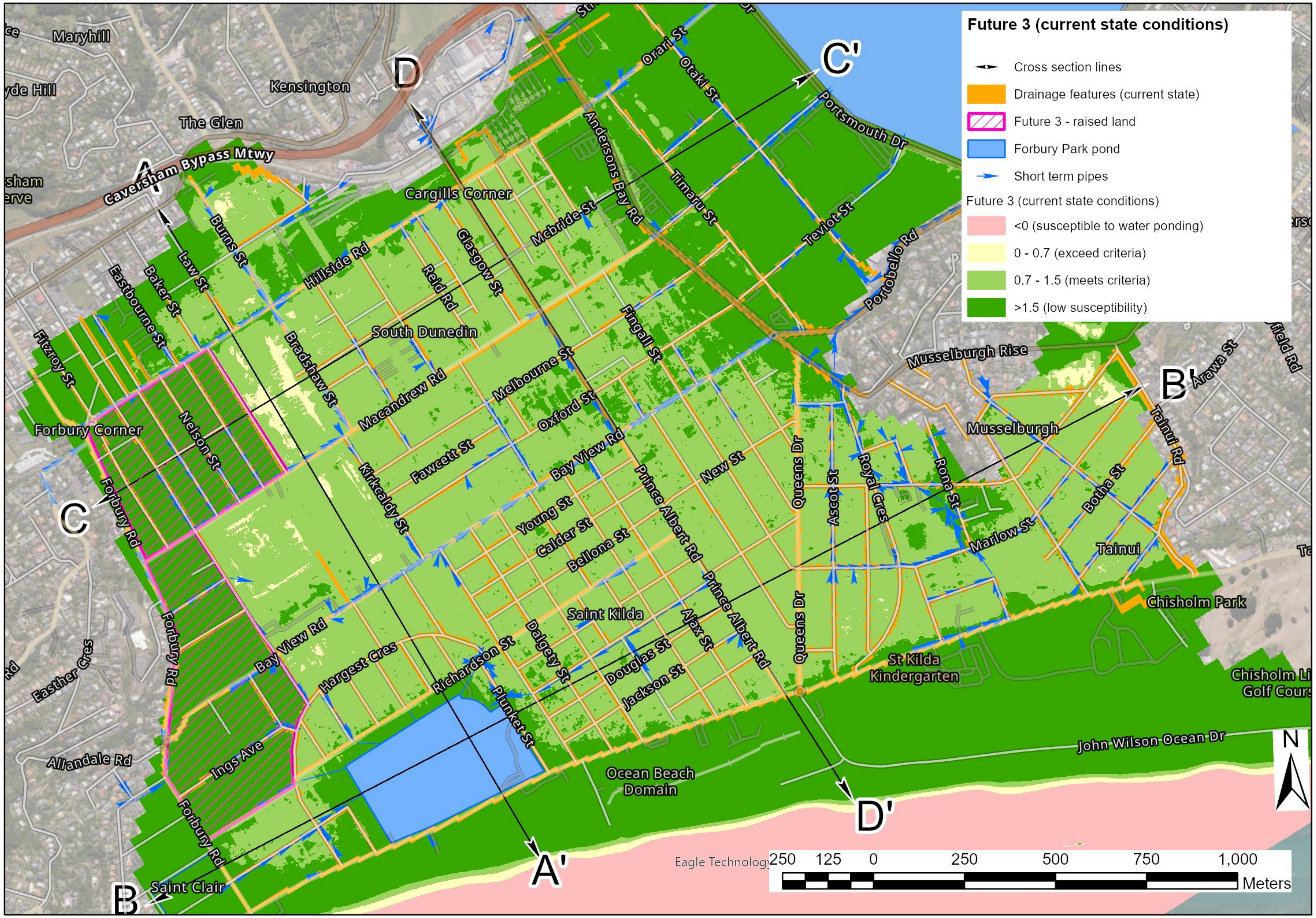
Future 3 (current state conditions)
Cross section lines
Drainage features (current state)
Future 3 - raised land
Forbury Park pond
Short term pipes
Future 3 (current state conditions)
<0 (susceptible to water ponding)
0 - 0.7 (exceed criteria)
0.7 - 1.5 (meets criteria)
>1.5 (low susceptibility)
A
A'
B
B'
C
C'
D
D'
Maryhill
Kensington
The Glen
Caversham Bypass Mtwy
Cargills Corner
South Dunedin
Forbury Corner
Musselburgh Rise
Musselburgh
Tainui
Chisholm Park
Saint Kilda
St Kilda Kindergarten
Ocean Beach Domain
Saint Clair
John Wilson Ocean Dr
Burns St
Law St
Baker St
Eastbourne St
Fitzroy St
Nelson St
Bradshaw St
Hillside Rd
Reid Rd
Glasgow St
Mcbride St
Andersons Bay Rd
Otaki St
Orari St
Timaru St
Portsmouth Dr
Teviot St
Portobello Rd
Macandrew Rd
Melbourne St
Oxford St
Fingall St
Fawcett St
Bay View Rd
Kirkcaldy St
Young St
Calder St
Bellona St
Prince Albert Rd
New St
Queens Dr
Ascot St
Royal Cres
Rona St
Marlow St
Botha St
Tainui Rd
Arawa St
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Richardson St
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Plunket St
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Jackson St
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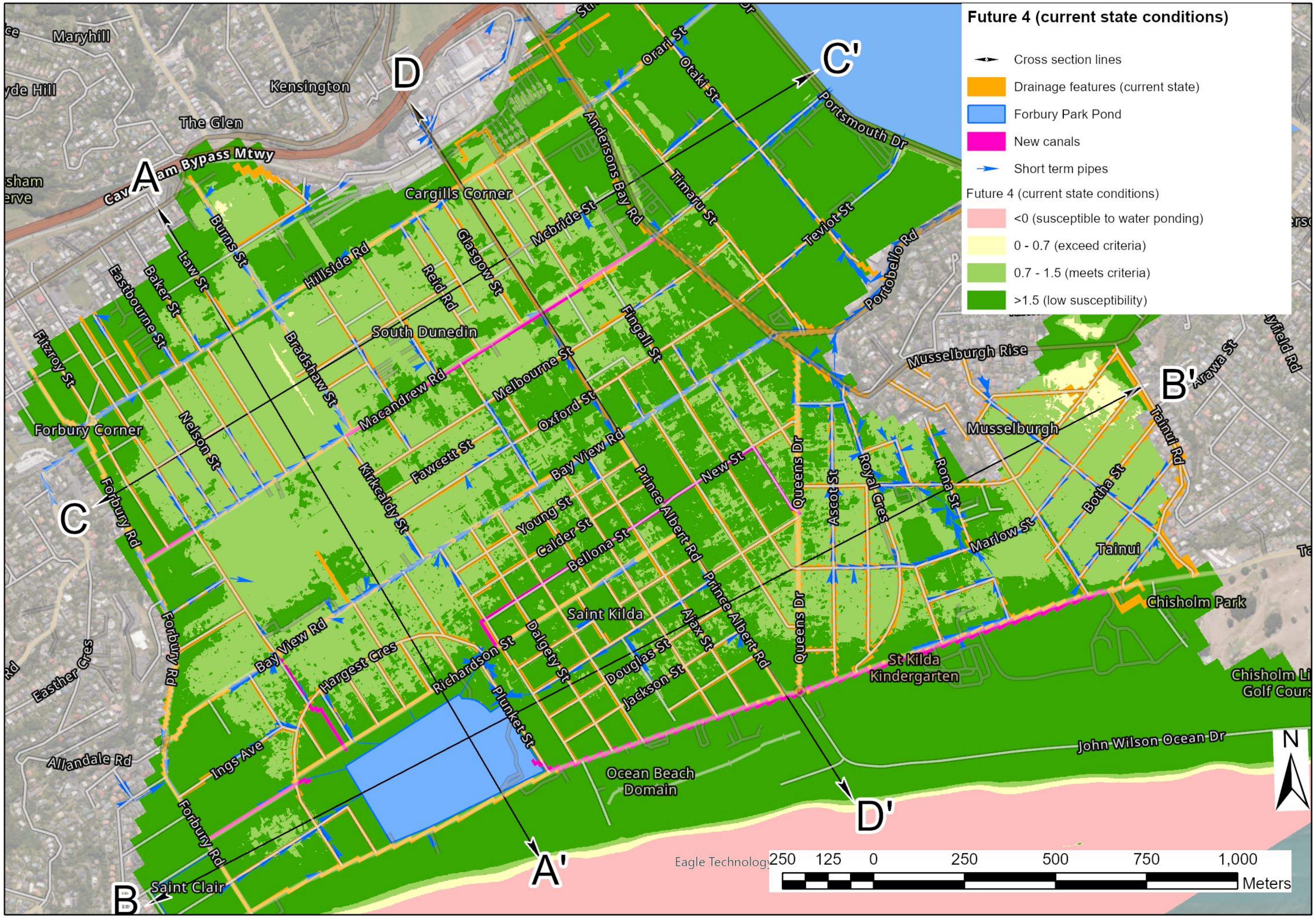

Future 4 (current state conditions)
Cross section lines
Drainage features (current state)
Forbury Park Pond
New canals
Short term pipes
Future 4 (current state conditions)
<0 (susceptible to water ponding)
0 - 0.7 (exceed criteria)
0.7 - 1.5 (meets criteria)
>1.5 (low susceptibility)
A
A'
B
B'
C
C'
D
D'
Maryhill
Kensington
The Glen
Cargills Corner
South Dunedin
Forbury Corner
Musselburgh
Tainui
Saint Kilda
St Kilda Kindergarten
Chisholm Park
Ocean Beach Domain
Saint Clair
Musselburgh Rise
John Wilson Ocean Dr
Portsmouth Dr
Portobello Rd
Allandale Rd
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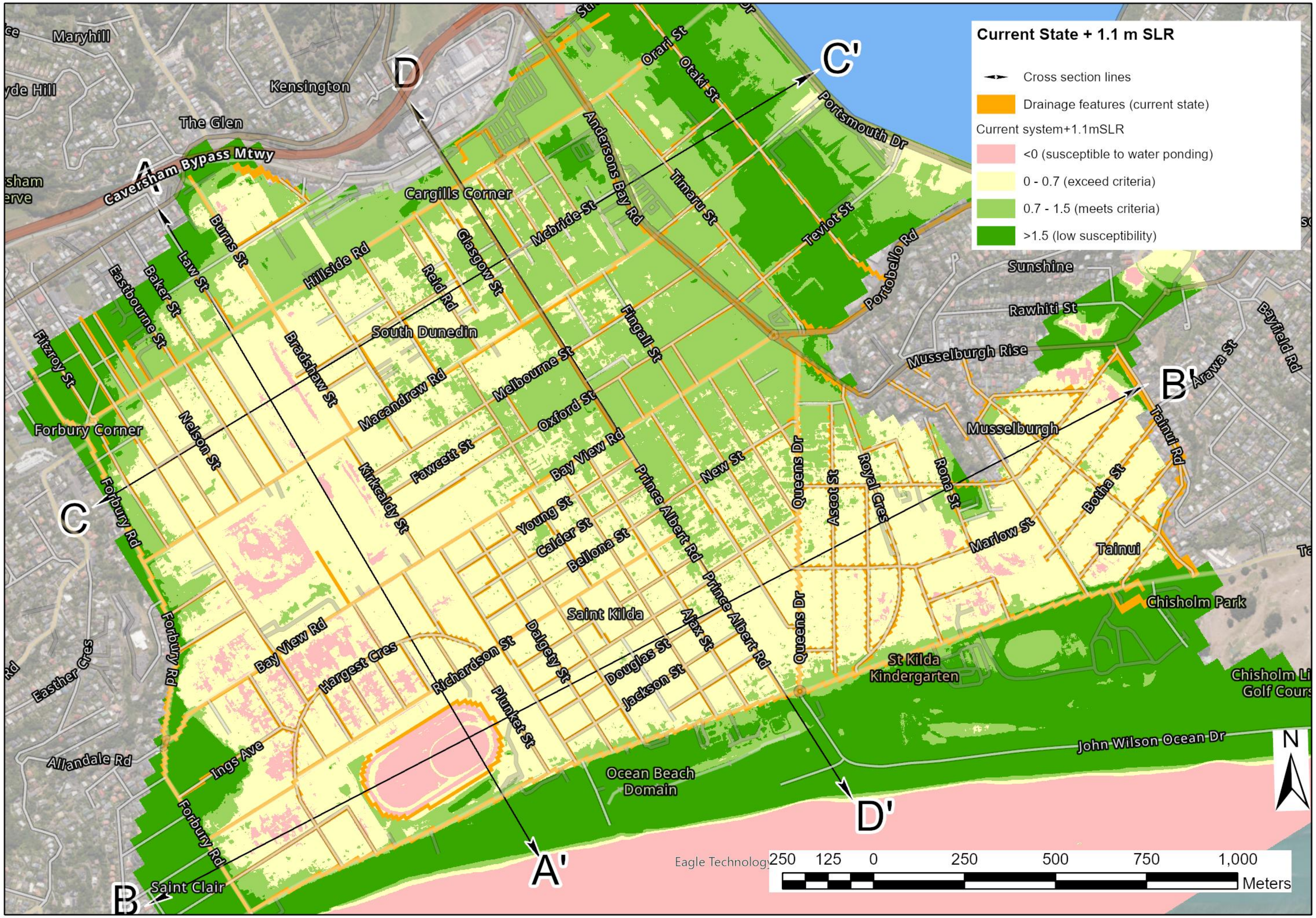
Current State + 1.1 m SLR
Cross section lines
Drainage features (current state)
Current system+1.1mSLR
<0 (susceptible to water ponding)
0 - 0.7 (exceed criteria)
0.7 - 1.5 (meets criteria)
>1.5 (low susceptibility)
A
A'
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Maryhill
Kensington
The Glen
Caversham Bypass Mtwy
Cargills Corner
South Dunedin
Forbury Corner
Saint Kilda
Musselburgh
Sunshine
Tainui
Chisholm Park
St Kilda Kindergarten
Ocean Beach Domain
Saint Clair
John Wilson Ocean Dr
Portsmouth Dr
Portobello Rd
Musselburgh Rise
Rawhiti St
Queens Dr
Prince Albert Rd
Hillside Rd
Bay View Rd
Forbury Rd
Allandale Rd
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Meters
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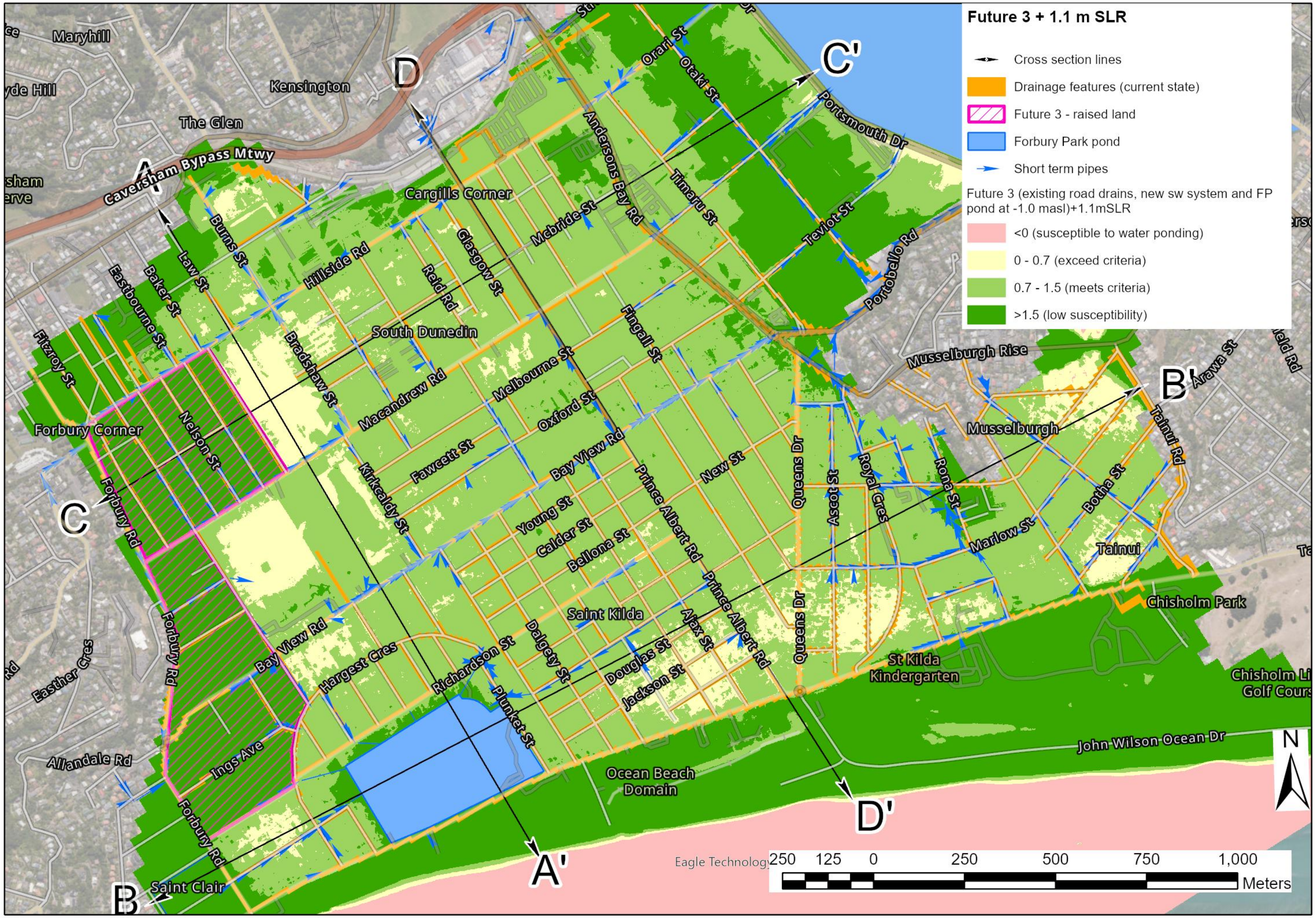
Future 3 + 1.1 m SLR
Cross section lines
Drainage features (current state)
Future 3 - raised land
Forbury Park pond
Short term pipes
Future 3 (existing road drains, new sw system and FP pond at -1.0 masl)+1.1mSLR
<0 (susceptible to water ponding)
0 - 0.7 (exceed criteria)
0.7 - 1.5 (meets criteria)
>1.5 (low susceptibility)
Maryhill
Kensington
The Glen
Caversham Bypass Mtwy
Cargills Corner
South Dunedin
Forbury Corner
Musselburgh Rise
Musselburgh
Tainui
Chisholm Park
Saint Kilda
St Kilda Kindergarten
Ocean Beach Domain
Saint Clair
John Wilson Ocean Dr
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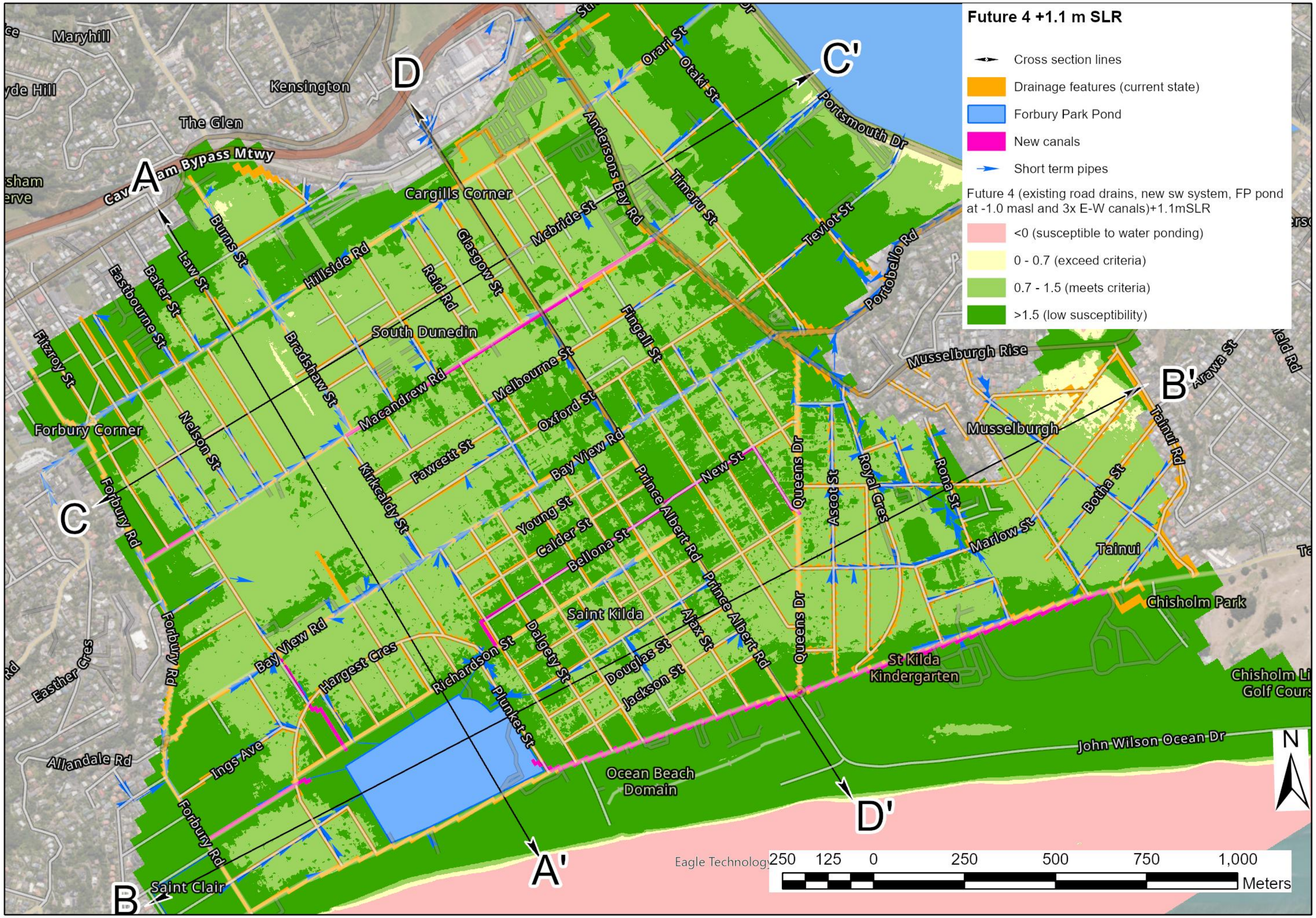
Eagle Technology


Future 4 +1.1 m SLR
Cross section lines
Drainage features (current state)
Forbury Park Pond
New canals
Short term pipes
Future 4 (existing road drains, new sw system, FP pond at -1.0 masl and 3x E-W canals)+1.1mSLR
<0 (susceptible to water ponding)
0 - 0.7 (exceed criteria)
0.7 - 1.5 (meets criteria)
>1.5 (low susceptibility)
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Maryhill
Kensington
The Glen
Cargills Corner
South Dunedin
Forbury Corner
Musselburgh Rise
Musselburgh
Tainui
Chisholm Park
Saint Kilda
St Kilda Kindergarten
Ocean Beach Domain
Saint Clair
John Wilson Ocean Dr
Portsmouth Dr
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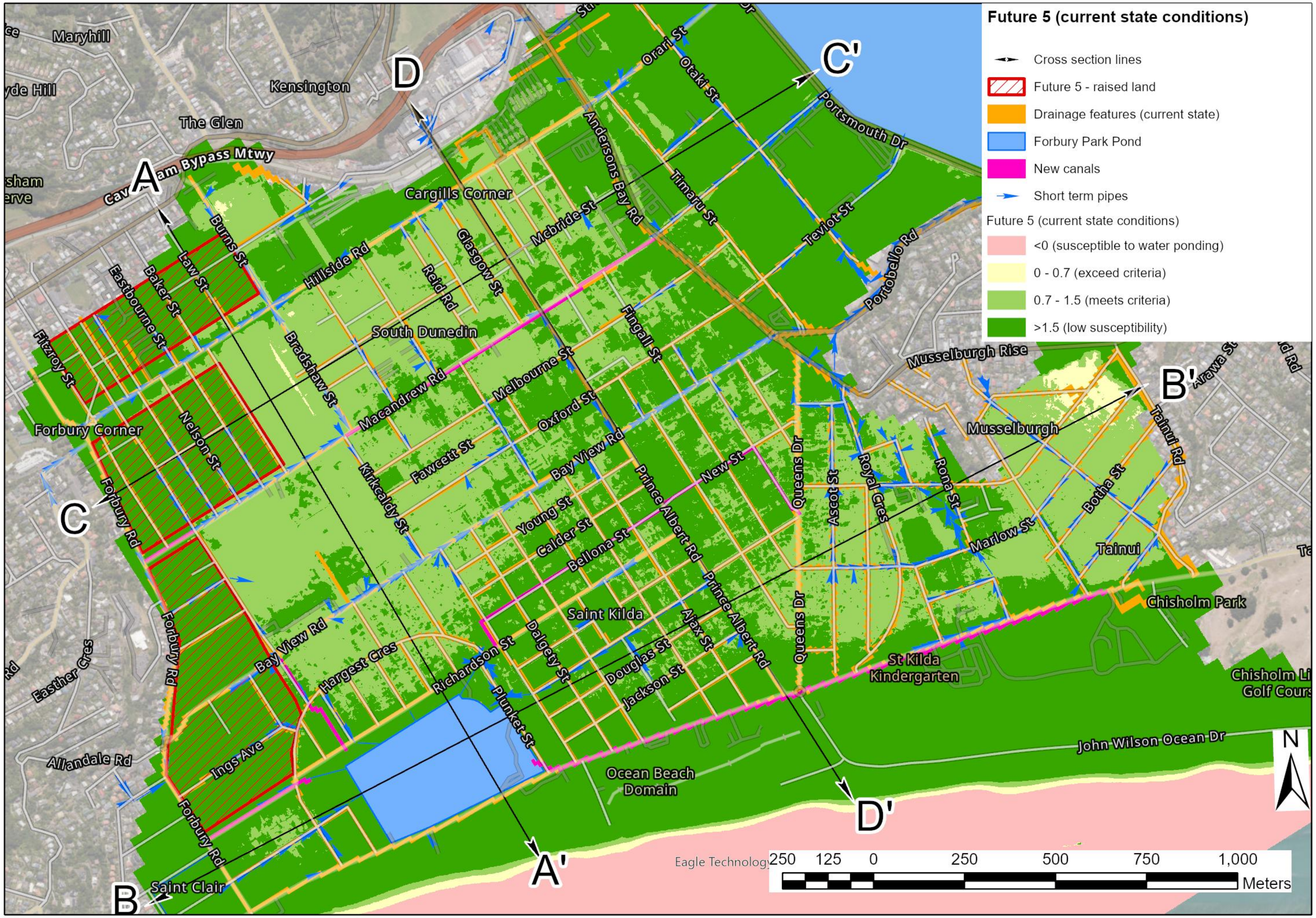
Future 5 (current state conditions)
Cross section lines
Future 5 - raised land
Drainage features (current state)
Forbury Park Pond
New canals
Short term pipes
Future 5 (current state conditions)
<0 (susceptible to water ponding)
0 - 0.7 (exceed criteria)
0.7 - 1.5 (meets criteria)
>1.5 (low susceptibility)
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Maryhill
Kensington
The Glen
Cargills Corner
South Dunedin
Forbury Corner
Musselburgh
Tainui
Saint Kilda
St Kilda Kindergarten
Chisholm Park
Ocean Beach Domain
Saint Clair
Musselburgh Rise
John Wilson Ocean Dr
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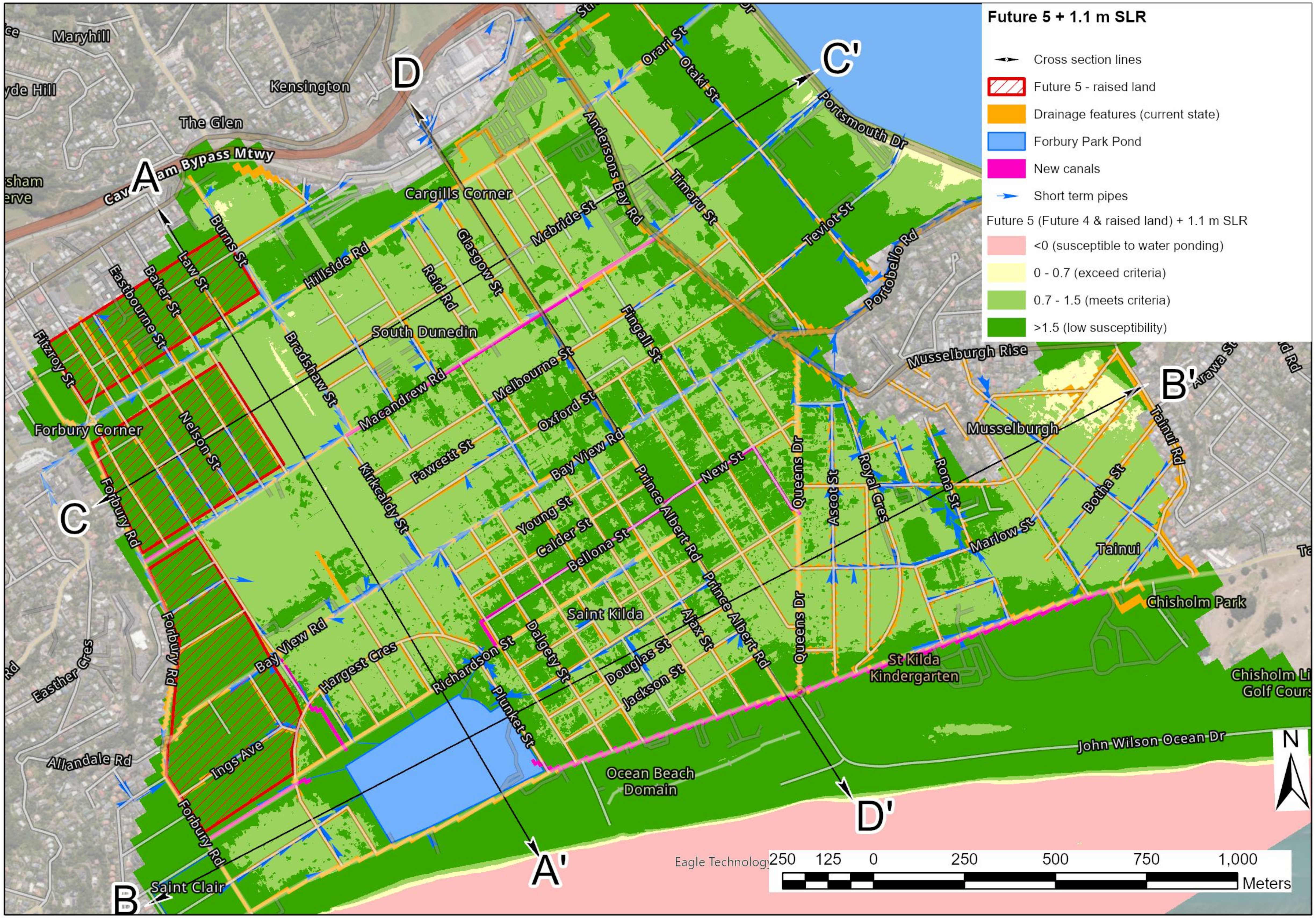
Future 5 + 1.1 m SLR
Cross section lines
Future 5 - raised land
Drainage features (current state)
Forbury Park Pond
New canals
Short term pipes
Future 5 (Future 4 & raised land) + 1.1 m SLR
<0 (susceptible to water ponding)
0 - 0.7 (exceed criteria)
0.7 - 1.5 (meets criteria)
>1.5 (low susceptibility)
A
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Maryhill
Kensington
The Glen
Cargills Corner
South Dunedin
Forbury Corner
Musselburgh
Musselburgh Rise
Tainui
Saint Kilda
Chisholm Park
St Kilda Kindergarten
Ocean Beach Domain
Saint Clair
Burns St
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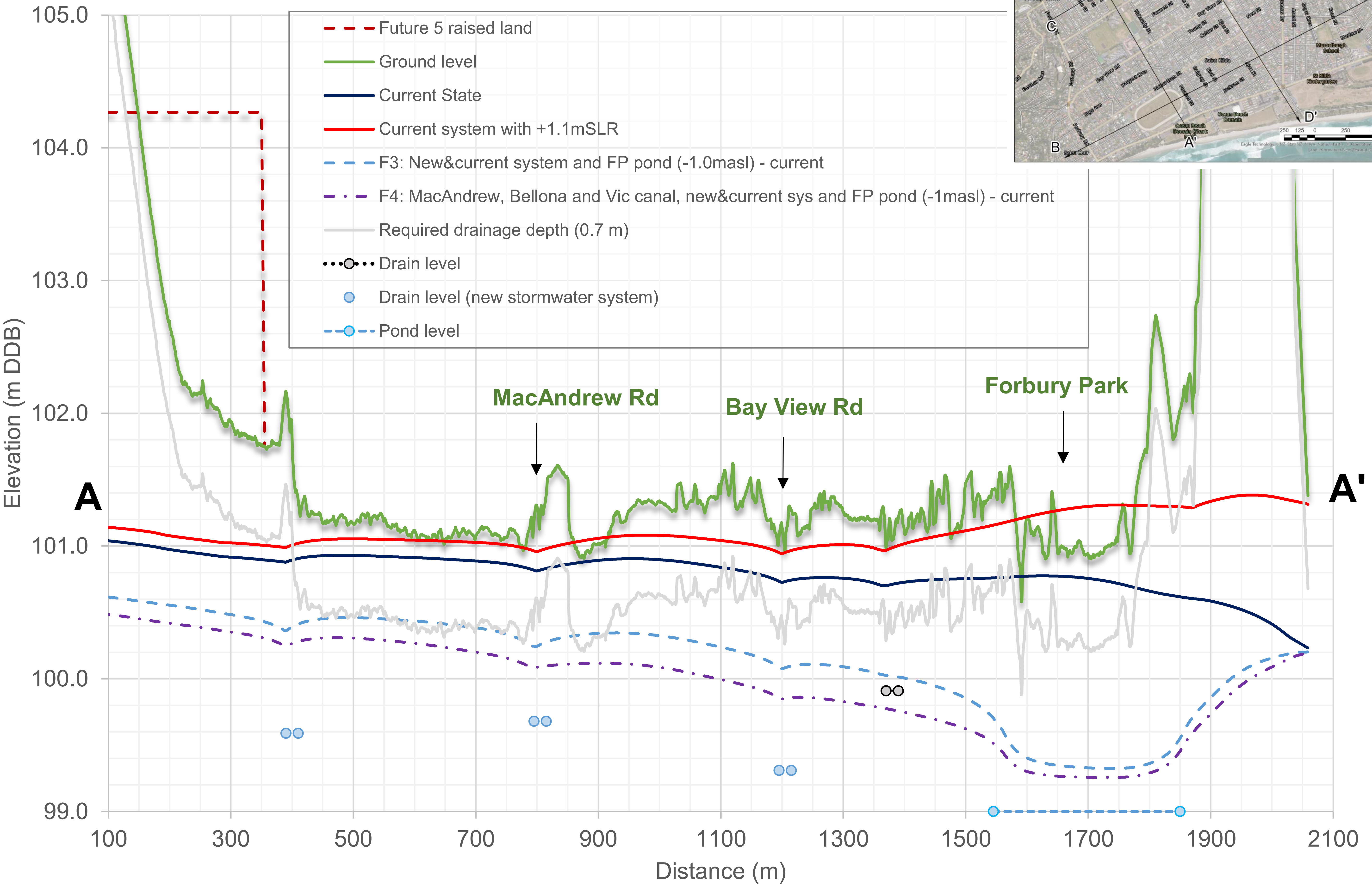
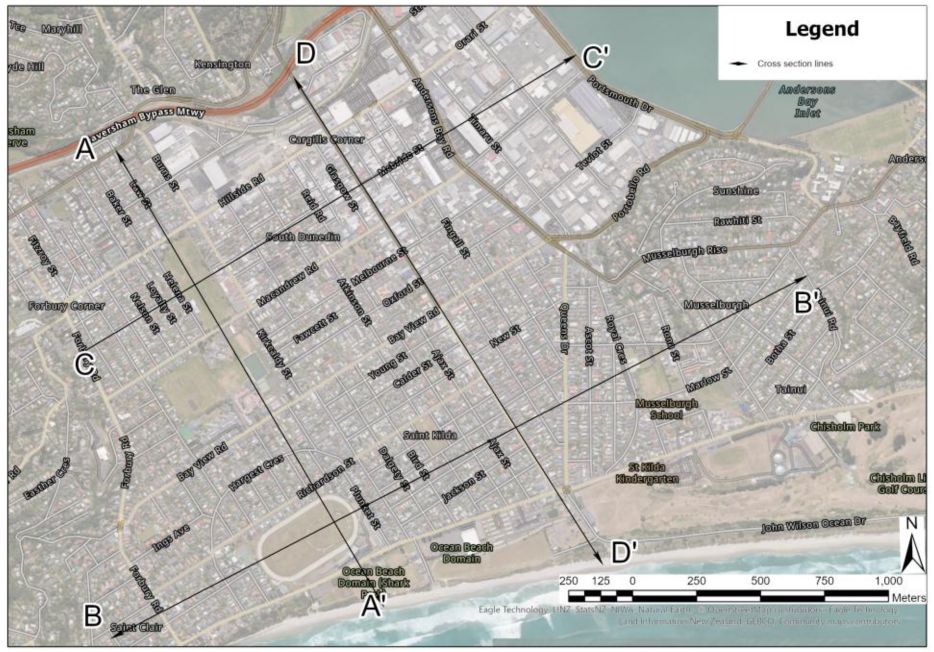
Baker St
Eastbourne St
Fitzroy St
Nelson St
Forbury Rd
Hillside Rd
Bradshaw St
Reid Rd
Glasgow St
Mcbride St
Andersons Bay Rd
Timaru St
Orari St
Otaki St
Portsmouth Dr
Teviot St
Portobello Rd
Macandrew Rd
Melbourne St
Oxford St
Fingall St
Kirkcaldy St
Fawcett St
Bay View Rd
Young St
Calder St
Bellona St
New St
Prince Albert Rd
Queens Dr
Ascot St
Royal Cres
Rona St
Marlow St
Botha St
Tainui Rd
Hargest Cres
Richardson St
Plunket St
Dalgety St
Douglas St
Jackson St
Ajax St
Ings Ave
Allandale Rd
Easther Cres
John Wilson Ocean Dr
Eagle Technology
250 125 0 250 500 750 1,000
Meters
N

Section A-A" (current)





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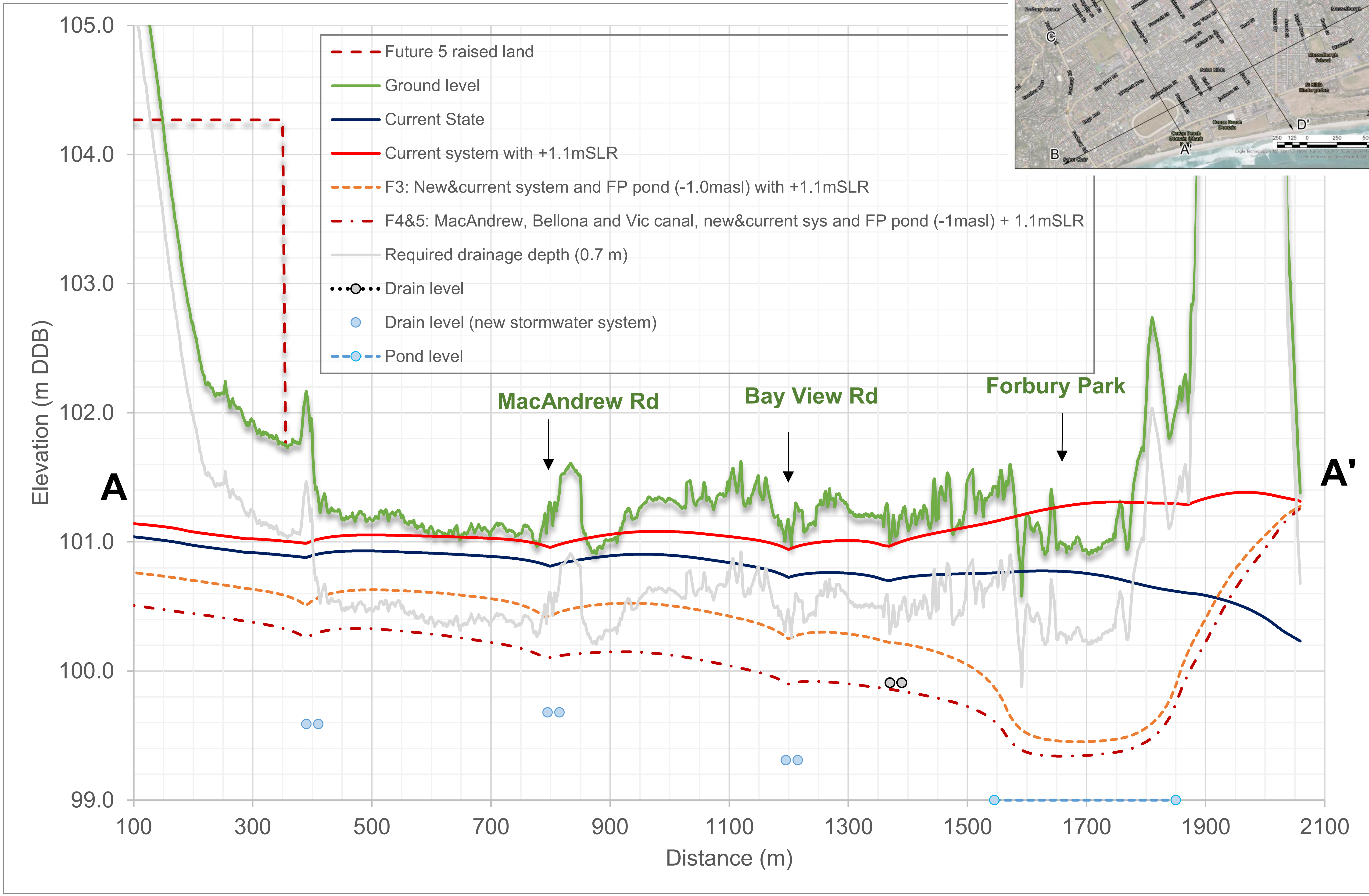

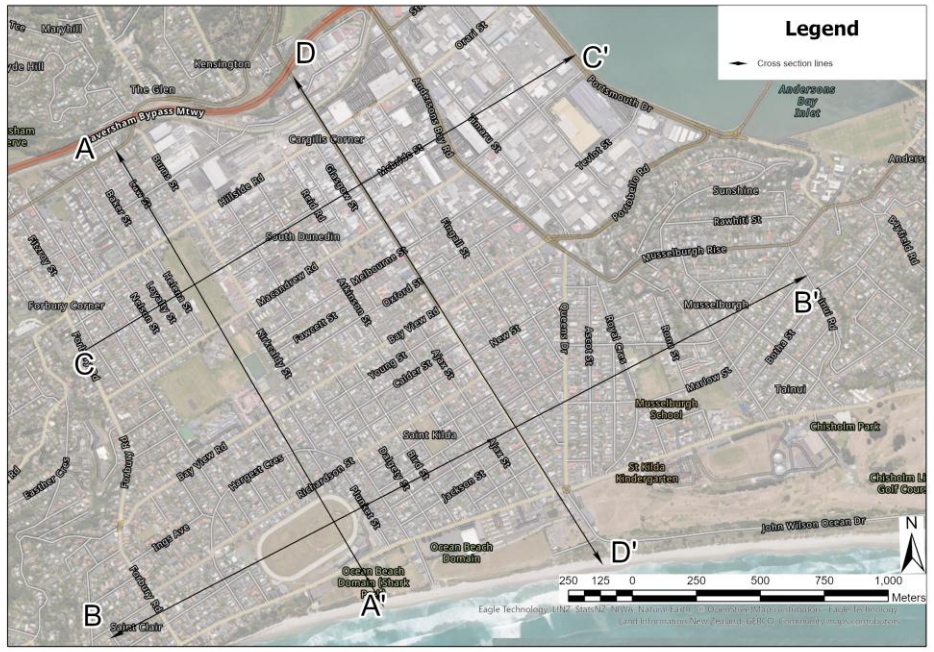

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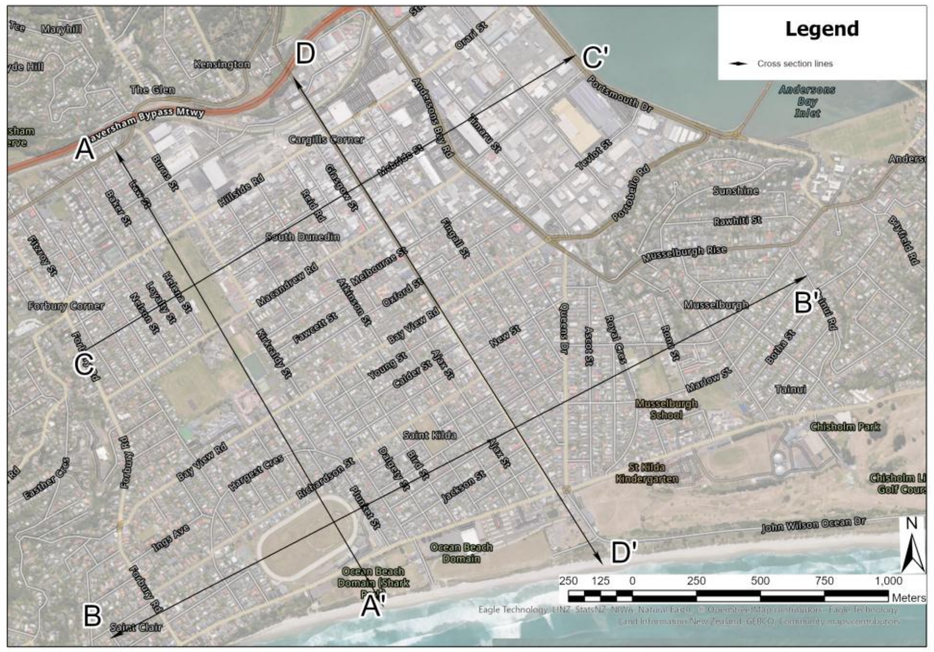

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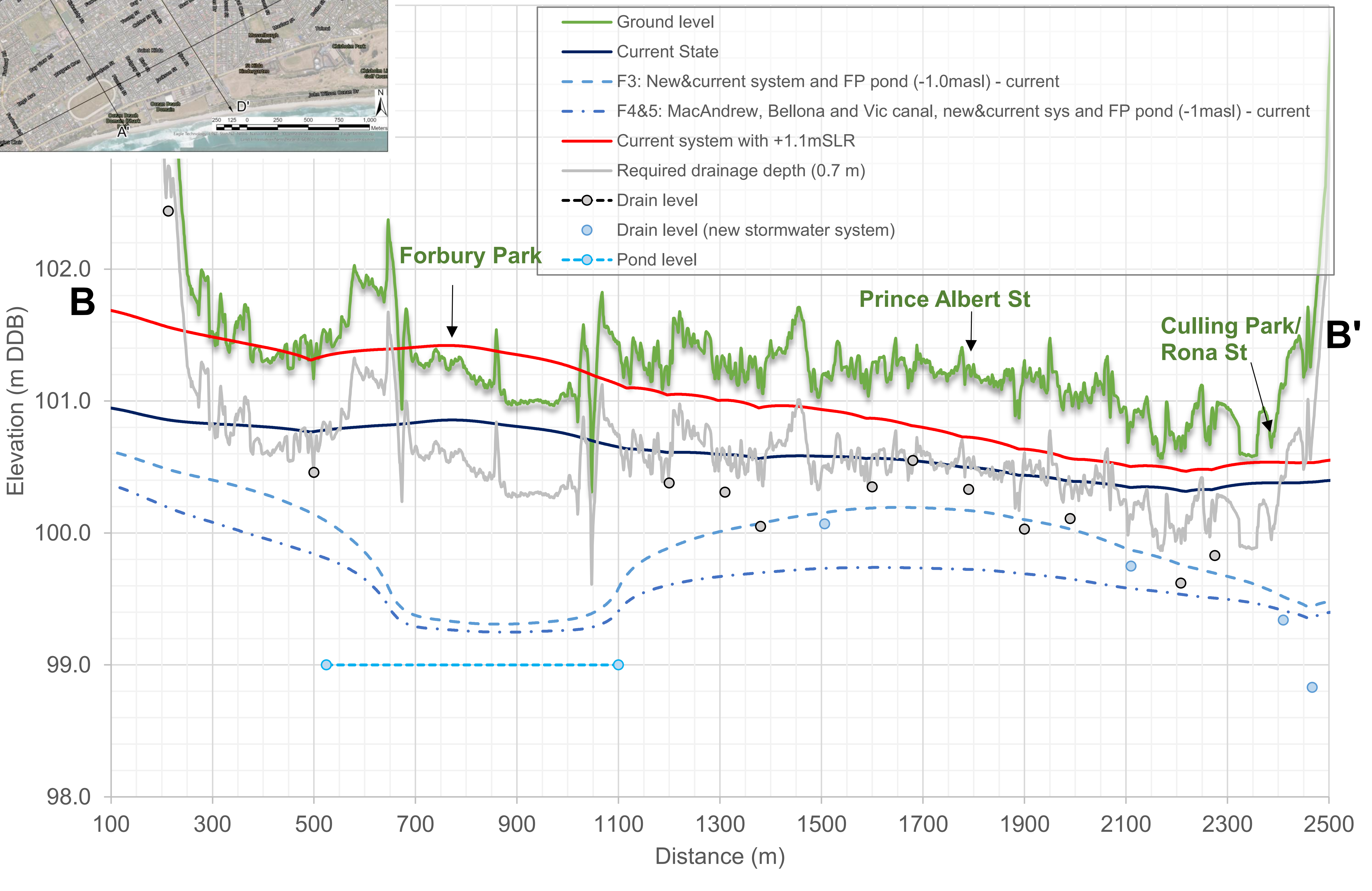

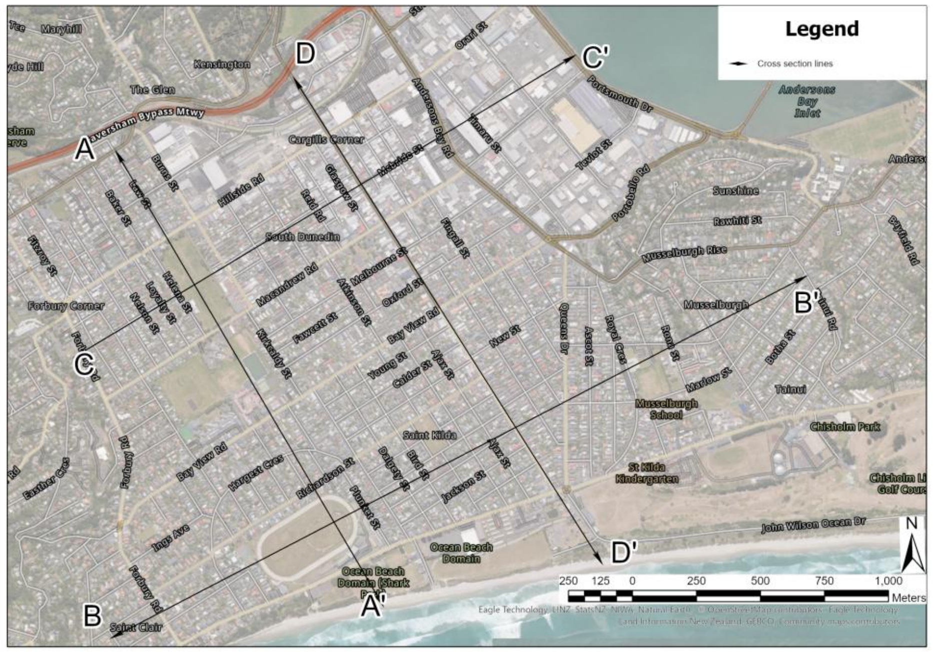

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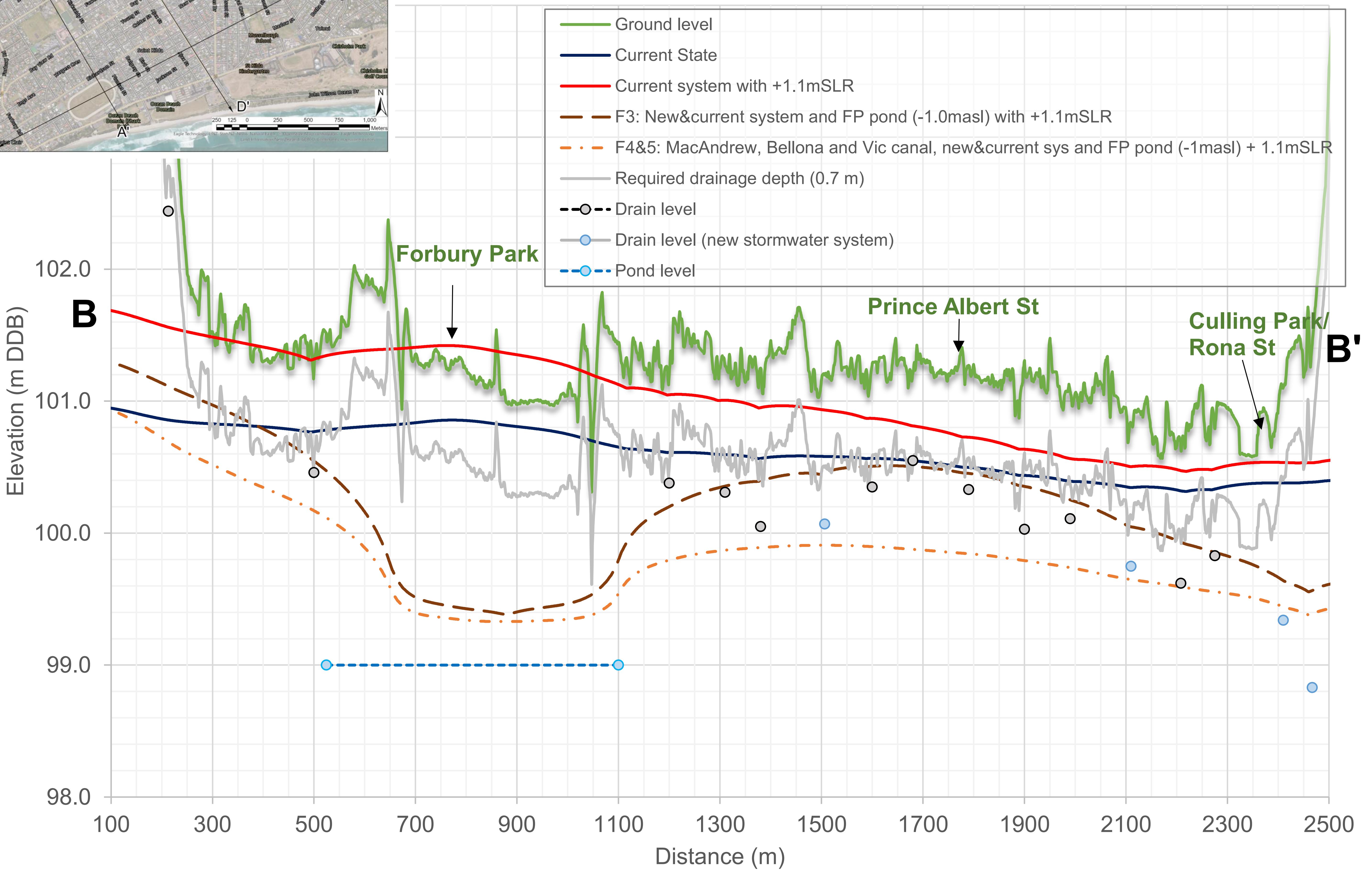

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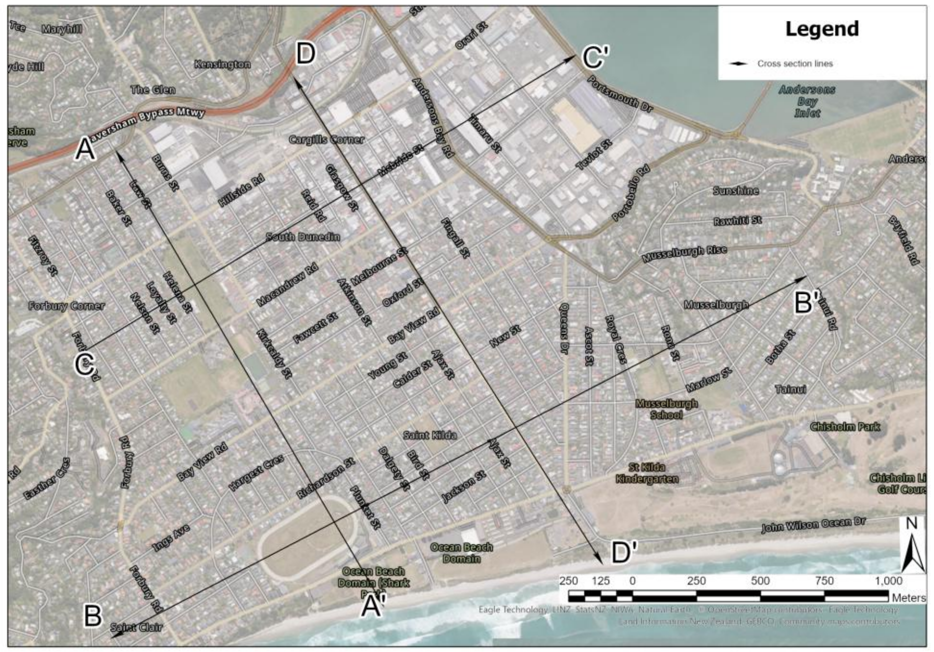

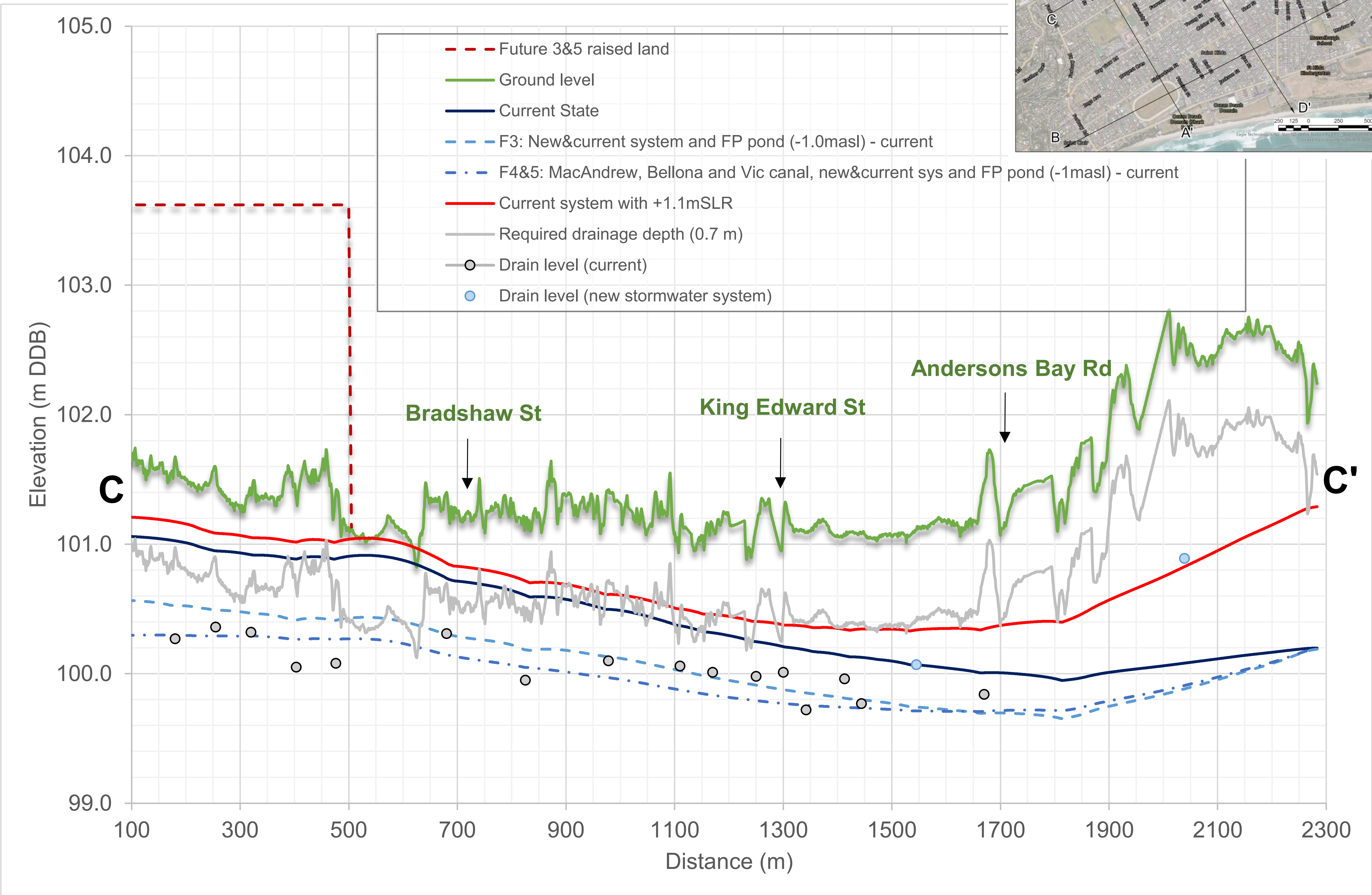

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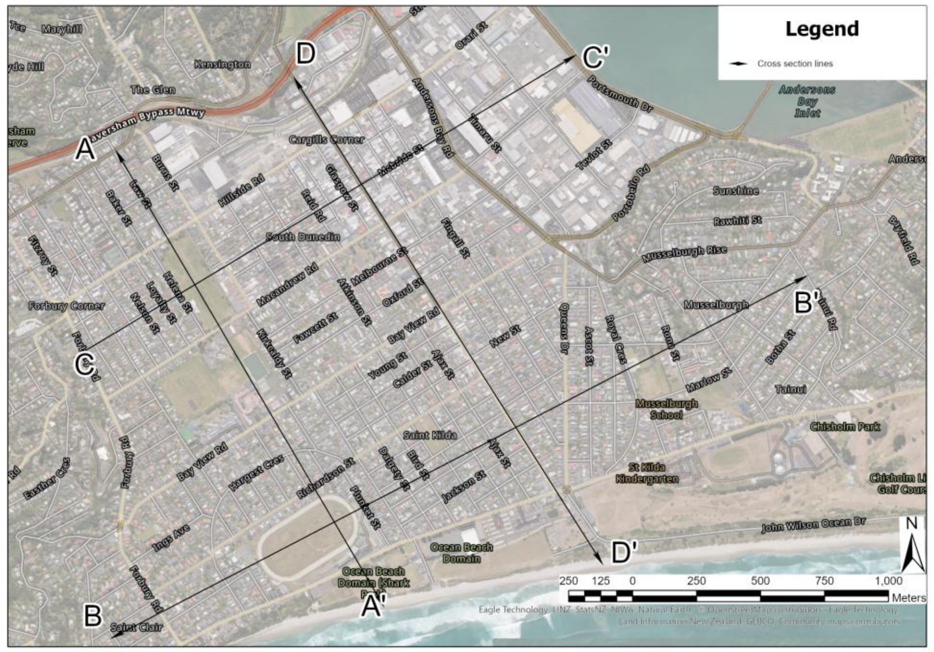

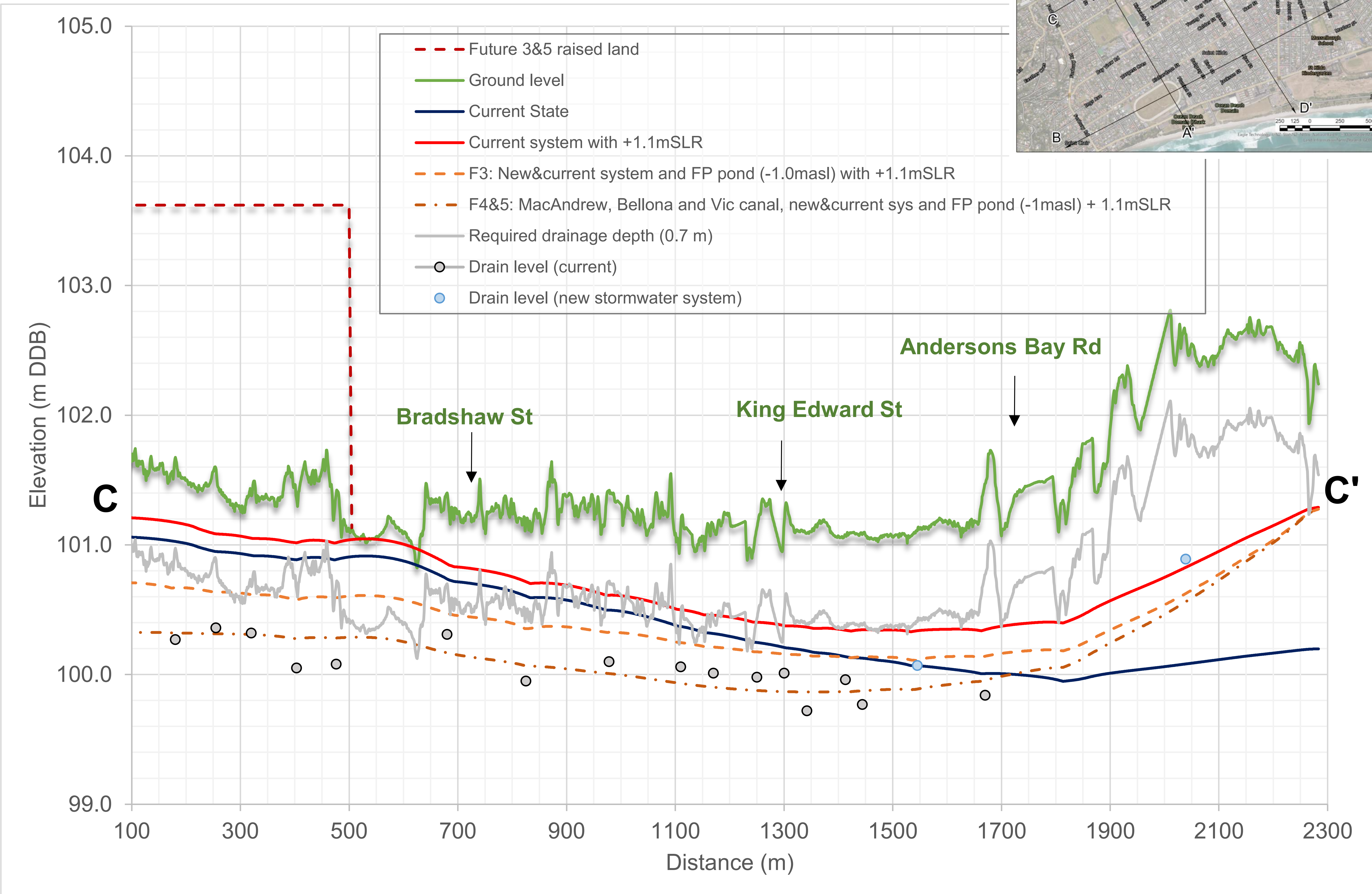

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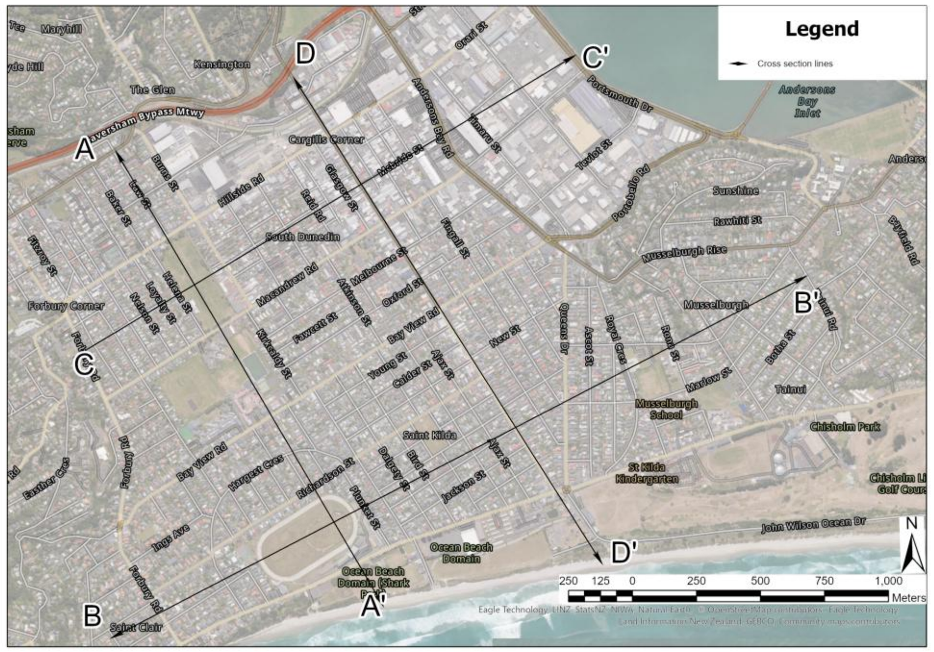

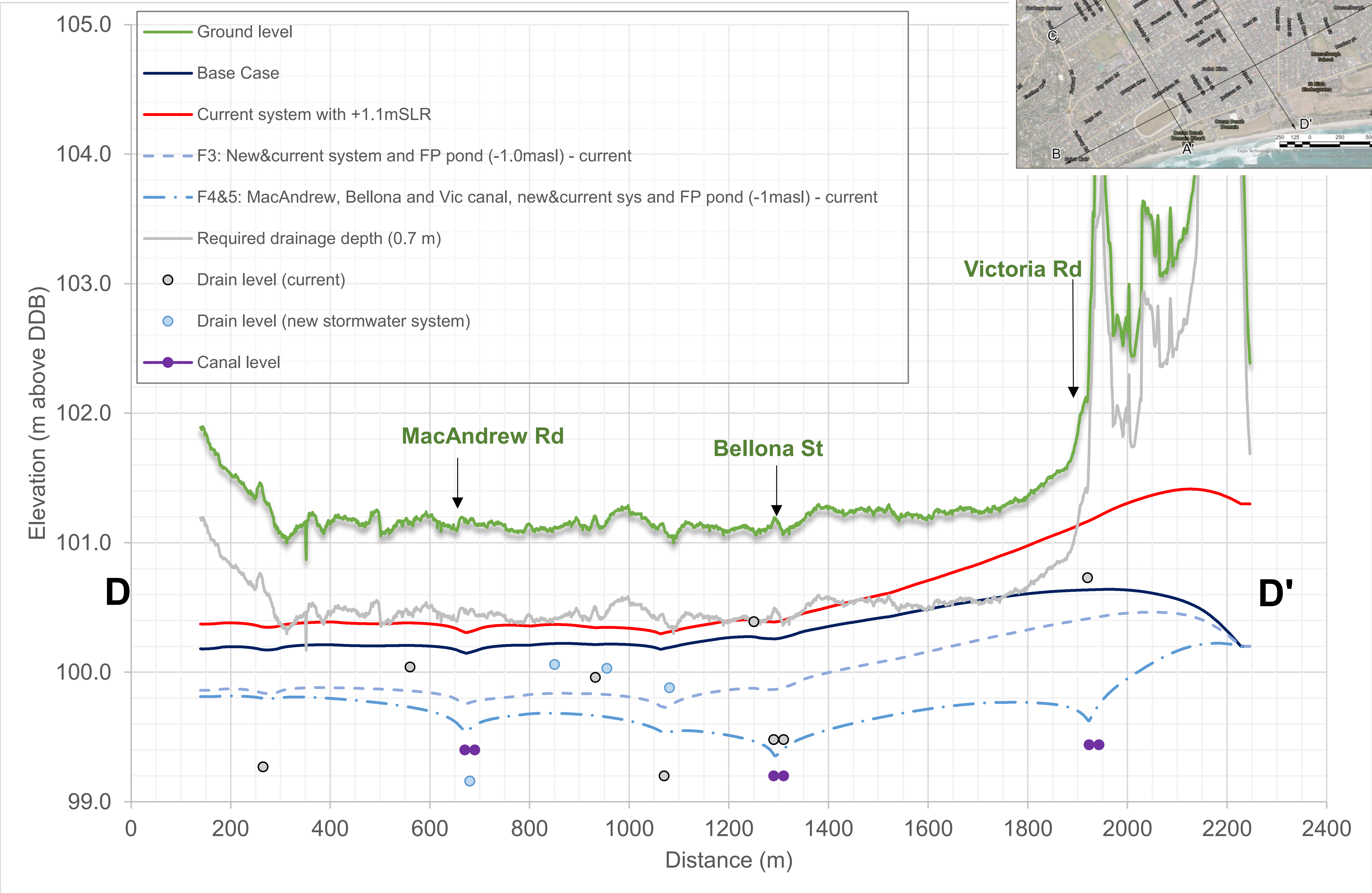

Section D-D" (SLR)