Developing and testing a cost-effectiveness analysis to prioritise green infrastructure alternatives for climate change adaptation

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Highlights:

- Green infrastructure cost-effectiveness ranking index can help decision-makers
- Cost-effectiveness of green infrastructure needs to consider climate change impacts
- Climate change pose different challenges to decision-makers in cities and towns

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Abstract

Green infrastructure has been increasingly identified as an option to help manage climate change impacts in urban areas, although its implementation is still not widely promoted in urban planning. This is due to the lack of detailed analysis for decision-makers regarding construction and maintenance costs for different types, and how effective various measures are at managing precipitation at a catchment scale. This paper contributes to fill this gap in knowledge by developing a Green Infrastructure Cost-effectiveness Ranking Index (GICRI) able to evaluate the stormwater runoff volume reduction of multiple green infrastructure alternatives under different climate change scenarios, over differing spatial configurations, and, combining this performance data with their construction and maintenance costs. After applying this model over two case study areas, this paper provides three main insights. First, climate change projections have a significant impact on green infrastructure cost-effectiveness. Second, as green infrastructure cost-effectiveness is influenced by the spatial scale, there are different challenges for larger cities and smaller regional towns. Building on this, the paper argues that GICRI can be a simple and fast heuristic to increase the use of green infrastructure by informing decision-makers regarding how and where to prioritise investment or where greater modelling is needed.

Keywords: flooding, low-impact development - LID, stormwater management, land-use planning, nature-based solutions, decision-making

1. Introduction

Extreme weather events have become more frequent and severe during the last few decades (Cheng et al., 2017, IPCC, 2014), bringing major challenges to urban areas (Drosou et al., 2019, IPCC, 2019). Green infrastructure (GI) has emerged as a prominent strategy to alleviate some of those adverse effects (Salata and Yiannakou, 2016). GI is acknowledged for its versatility, especially as it potentially offers wider environmental services and benefits, such as improving water quality, recharging groundwater and mitigating floods (Ashley et al., 2018, Ureta et al., 2021). As it can enhance natural and social aspects, GI is likely to contribute both to directly enhancing urban flood resilience and more broadly by increasing resilience to climate change (Cole et al., 2017, Salata and Yiannakou, 2016).

While GI offers promise in addressing climate change effects, uncertainties in decision-making inhibit GI from being widely implemented. For example, information on the costs of implementing GI options is limited due to lack of design standards and data (Houdeshel et al., 2010). Further, some GI benefits are not easily quantified or monetised (Beauchamp and Adamowski, 2012), and few studies have attempted to assess GI benefits and evaluate the associated costs (Nordman et al., 2018, Beauchamp and Adamowski, 2012). To aid implementation in practice, decision-makers require quality information regarding both technical and economic suitability of these alternatives, especially when retrofitted into urban areas as a means to help manage flood risk and adapt to climate change. This paper aims to fill this gap by developing a green infrastructure cost-effectiveness ranking index (GICRI) to assess the cost-effectiveness of reducing stormwater runoff volume using multiple GI options under different climate change projections, including considering both GI construction and maintenance costs. While the study was performed in the context of a highly urbanised city and a small regional town in Aotearoa-New Zealand, we anticipate the approach and findings would have applicability to planning contexts elsewhere.

2. Evaluating benefits and costs for specific GI types

There has been increased acknowledgement of the benefits GI could bring in if it was more widespread introduced to urban environments. For example, some scholars (Lennon et al., 2014, Wang et al., 2020) highlight how GI is a suitable strategy for dealing with extreme rainfall events affecting urban areas in the context of climate change. Others argue that if planned correctly, GI could minimise green gentrification and reduce disparities in the delivery of environmental amenities (Anguelovski et al., 2018). What current studies tend to have in common, however, is an acknowledgement that these benefits are difficult to quantify and that limited financial resources, especially at the municipal level, comprise an important barrier to GI implementation (Beauchamp and Adamowski, 2012). While some GI benefits are extensively known (e.g. improve water quality, reduce stormwater runoff), common economic assessment tools are, first, unable to effectively quantify these and, second, do not correlate the cost-effectiveness of benefits to specific GI options (Flynn and Traver, 2013).

The most common economic evaluation method used to inform decisions are Cost-Benefit Analysis (CBA) (see Table 1 for a summary of the most common methods). CBA allows the comparison of construction and maintenance costs in order to evaluate whether a certain project is viable or not (Wang et al., 2020). CBA seeks to place monetary values on both costs (outcomes) and benefits (incomes) (Liu et al., 2016). Although benefits are commonly estimated using the 'willingness to pay' method (Robinson, 1993), benefit quantification is not straightforward. This means that decision-makers may need to do significant investment without proper assessment and quantification of GI costs and/or benefits (Ashley et al., 2018), therefore making it difficult to meet budget constraints whilst achieving stormwater runoff reduction targets (Zeng et al., 2020).

Other common methods used to assess economic benefits of GI implementation include Life Cycle Cost Analysis (LCC) and Net Present Value (NPV). The key advantage of LCC is the potential to provide cost and revenue estimation over an asset's life cycle (Beauchamp and Adamowski, 2012), including construction, maintenance and operation costs as well as residual value at the end of the asset's life. On the other hand, NPV evaluates present value of different proposals over time (Carter and Keeler, 2008), that is, it is able to calculate a return investment for a specific strategy. Both methods, however, require actual benefits to be quantified and monetised and this presents technical and methodological challenges (Mell et al., 2013, Wild et al., 2017). For example, the minimisation of flood risk is subjective and difficult to be quantified and monetised. Reduction in volume of stormwater runoff can be easily estimated but it depends on stormwater network implementation, maintenance and operation costs to be properly monetised.

As an alternative to LCC and NPV, cost-effectiveness analyses can be performed without attributing a monetary value to benefits. Consequently, cost-effectiveness analysis of GI costs and benefits has been increasingly recognised as a valuable approach for evaluating positive and negative outcomes of potential policies and decisions, and for providing an economic evaluation to inform the decision-making processes (Montalto et al., 2011). In contrast to CBA, which explores whether an option provides benefits that outweigh the costs (Fukahori and Kubota, 2003), NPV, which assesses the value of an asset (Žižlavský, 2014), or LCC, which investigates construction and maintenance costs over an asset's lifetime (Dwaikat and Ali, 2018), cost-effectiveness analysis assesses if an alternative can reduce potential for damage to the greatest extent possible while not having a significant negative economic impact (Fukahori and Kubota, 2003). Different from other approaches, cost-effectiveness analyses can help to identify potential obstacles and recognise the funding necessary to construct and maintain GI (Fukahori and Kubota, 2003). Although cost-effectiveness analyses do not represent the full benefits of GI implementation, they provide sound financial and performance correlations across GI options and are therefore potentially a valuable tool for decision-makers (Montalto et al., 2011).

Few studies (e.g. Chui et al., 2016, Zeng et al., 2020) have comprehensively evaluated the costs associated with multiple GI combinations regarding their construction and maintenance costs, including cost comparisons. A few others (e.g. Wang et al., 2020) have sought to incorporate climate change projections and how they influence cost-effectiveness associated with GI performance, construction and maintenance at the precinct scale. To the best of our knowledge, however, none have compared construction and maintenance costs associated with specific GI types and combinations at the town or city-scale to provide a more holistic picture of GI cost-effectiveness. The consideration of different spatial scales is relevant as both costs and benefits of GI vary based on different variables used for their assessment, including GI type, weather conditions, GI quantity, or land availability/location (Bianchini and Hewage, 2012). Therefore, the assessment of multiple GI combinations at different spatial scales is a tactically wise strategy, as it can provide a more holistic and system view of the cost-effectiveness of various options for addressing a broader range of rainfall and land-use scenarios.

3. Material and methods

A cost-effectiveness analysis was carried out to evaluate the performance of multiple GI options regarding the volume of stormwater runoff reduction, and their construction and maintenance costs (see Figure 1). Decision-makers need reliable information regarding multiple types of GI, their varying costs and key benefits to enhance GI as a viable flood risk management strategy. Since GI benefits are difficult to monetise (e.g. quantifying the enhancement of aesthetics or flood risk minimisation), a cost-effectiveness analysis provides an effective and replicable approach to help identify which GI options are more affordable whilst having greater hydrological performance (i.e. total stormwater runoff volume reduction). To this end, our cost-effectiveness analysis was first informed by the simulation and assessment of the hydrological performance of three GI alternatives: bio-retention cells;

permeable pavements; and rain gardens in multiple combinations, under different rainfall scenarios, and in two different spatial locations in Aotearoa-New Zealand. These GI options were considered because they are realistic retrofit options (Dover, 2015) – that is, they demand small spaces to be implemented, and because they can be constructed in the public realm there is more autonomy to implement as they may not directly impact on private landowners and their properties (Sun et al., 2014).

The costs of constructing and maintaining multiple GI options were then calculated based on the identification and quantification of individual elements of the construction and maintenance stages (e.g. area of vegetation to be planted, surface to be paved), as well as their costing using average tender rates (Ira and Simcock, 2019). While important, the assessment of related environmental costs and benefits associated with GI such as aesthetics, reduction of stormwater network improvement costs or flood risks minimisation did not fall within the scope of this study. Hence, evaluated costs primarily related to GI construction and maintenance techniques (please see the Supplementary Material for further details).

3.1 Case study areas

Climate change is expected to increase the frequency and intensity of rainfall events affecting Aotearoa-New Zealand (NIWA et al., 2012), placing many urban areas at increased risk of flooding (Ministry for the Environment, 2020). The following criteria were used to select two case study areas for assessing the hydrological performance of GI alternatives to mitigate flood risks:

(i) areas at risk of flooding, including an urban infill development area in a rapidly expanding metropolitan area, and a small regional town;
(ii) a 30-year historical overview of flood events and urbanization patterns in the country;
(iii) accessibility to current and future flood risk data; and,
(iv) potential for GI implementation.

Applying these criteria, one catchment in Auckland (North Island) and another in Gore (South Island) were selected for analysis (see Figure 2) as examples of a highly urbanised city and a small regional town, respectively.

3.2 Simulation and assessment of hydrological performance of GI alternatives

This study applied Personal Computer Stormwater Management Model (PCSWMM Professional 2D) to simulate the hydrological performance of multiple GI options for two rainfall scenarios (see Table 2). The rainfall scenarios were extracted from the High Intensity Rainfall Design System V4 (HIRDS), especially created for Aotearoa New Zealand (NIWA, 2018). They included rainfall events of 1 and 120-hour duration calculated under a high greenhouse gases emissions rate set out by the Representative Concentration Pathway (RCP) 8.5 (IPCC, 2014).

Bio-retention cells (BR), permeable pavements (PP) and rain gardens (RG), different combinations of these GI types, and two different spatial allocations (5% and 10% of total sub-catchment area) were added to the urban fabric of selected sub-catchments in both case study locations, totalling 14 GI options for selected GI alternatives (see Table 3). 5% and 10% of GI within each sub-catchment were selected as these quantities represent a realistic figure for decision makers as they demand minimal public space and reduced costs to be implemented and are therefore politically viable urban retrofit alternatives.

Stormwater runoff volume was calculated using PCSWMM Professional 2D based on the following parameters: permeability, soil characteristics, topography and land use for designated sub-catchments in each case study area (see Figure 3 and 4). A set of criteria was used to select the sub-catchments for GI implementation. Initially, a business-as-usual scenario was run (RCP8.5 rainfall without implementation of any GI alternative) to determine which sub-catchments were subject to flooding. This resulted in 47 out of 184 sub-catchments for Auckland and 20 out of 135 sub-catchments for Gore. To narrow down to a manageable number of sub-catchments for analysis, the following criteria were applied:

(i) Sub-catchments where more than 50% of their total area comprised a residential zone;

(ii) Sub-catchments where residents had a lower median income (up to $30,000) compared to the average annual income in Aotearoa-New Zealand[1]; and,

(iii) Sub-catchments which did not satisfy the accessibility requirements established by Access to Natural Greenspace Standard (Natural England, 2010) – that is, green areas not located more than 300 metres from any given residence and being at least 2 hectares in size.

3.3 Cost estimation

Cost estimation was based on Ira and Simcock's (2019) study of GI construction and maintenance costs for Aotearoa-New Zealand. Ira and Simcock's cost estimation is based on standard design and average tender prices so as to obtain generalized and transferable outcomes related to GI implementation. Their initial calculations from 2018 were updated to 2020 New Zealand Dollars equivalent using the inflation calculator available at Reserve Bank of New Zealand website (https://www.rbnz.govt.nz/monetary-policy/inflation-calculator).

Construction costs were individually quantified for different GI options, that is, construction costs per square metre of each option were calculated. The construction costs for each GI option were calculated based on the assumption that all costs are linearly related to the quantity of GI implemented (e.g. if the GI spatial allocation doubles, the costs will increase two-fold and so on).

As PP construction costs can vary depending on the type of pavement used, the constructions costs were calculated based on the equation for implementation of low cost

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[1] The incorporation of a social-equity dimension can assist communities in improving inequities in the provision of environmental services or preventing green gentrification SEKULOVA, F., ANGUELOVSKI, I., KISS, B., KOTSILA, P., BARÓ, F., PALGAN, Y. V. & CONNOLLY, J. 2021. The governance of nature-based solutions in the city at the intersection of justice and equity. *Cities,* 112**,** 103136.. This is significant because cities must avoid situating GI in locations where it can worsen patterns of social exclusion and gentrification, particularly because GI can be used to revitalize derelict neighbourhoods VAN DER JAGT, A. P. N., BERNADETT, K., SHUNSUKE, H. & WAKANA, T. 2021. Nature-based solutions or debacles? The politics of reflexive governance for sustainable and just cities. *Frontiers in Sustainable Cities,* 2..

permeable paving (Ira and Simcock, 2019) which includes 5% for design, consenting and project management fees:

$$PP\ construction\ costs = (85 + 1m2\ of\ pavers) + \left((85 + 1m2\ of\ pavers) * 0.05\right) \quad (1)$$

Construction costs for BR and RG include costs of designing, consenting and constructing these alternatives. Based on the range in constructions costs from Ira and Simcock (2019), the following formula was used:

$$BR\ or\ RG\ construction\ costs = \frac{(higher\ construction\ costs + lower\ construction\ costs)}{2} \quad (2)$$

Ira and Simcock's (2019) assessed three different models of GI maintenance (based on the frequency of maintenance), namely: amenity, functional and bare minimum. The bare minimum provides the lowest level of maintenance frequency while amenity has the highest frequency. This includes, for example, one functional drainage maintenance per year for the bare minimum, against two of the functional model and four of the high amenity. The functional model is considered the optimum level of maintenance - that is, the frequency of maintenance has acceptable levels and the associated costs are affordable (Ira and Simcock, 2019). Therefore, for the present study, PP and RG maintenance costs were based on functional maintenance and included both routine (e.g. trimming of hedges, cleaning of overflows and outflows) and corrective maintenance (e.g. removal of dead plants). PP and RG maintenance costs were directly estimated based on:

$$Maintenance\ costs = (RM * FFRM * GI\ area) + (CM * FFCM * GI\ area) \quad (3)$$

Where RM represents the routine maintenance average cost for the GI option, FFRM is the functional frequency for the routine maintenance, CM is the corrective maintenance average cost for the GI option, and FFCM is the functional frequency for the corrective maintenance.

For BR cells, zero additional maintenance (ZAM) costs were considered. BR cells can operate as a conventional streetscape from a maintenance perspective, therefore offering a cost-effective solution as its maintenance can be incorporated into the existing maintenance routine (Manningham Council, 2018). This means BR cells would be installed into typical, residential areas without needing any other maintenance regime other than conventional roadside maintenance, including street sweeping, gross pollutant collection, coarse material removal, grass mowing and landscape vegetation maintenance (Ira and Simcock, 2019).

3.4 GI cost-effectiveness ranking index (GICRI) analysis

The cost-effectiveness of GI options was assessed based on costs for constructing and maintaining the alternatives and their performance in reducing stormwater runoff volume. This cost-effectiveness analysis allowed the identification of the optimal option of GI alternatives. The meaning of cost-effectiveness in this study is limited to the relationship between construction and maintenance costs and stormwater runoff volume reduction (i.e. no land acquisition costs, nor other GI benefits were considered). Cost-effectiveness analysis considered different rainfall scenarios, multiple Gi alternatives and different spatial allocation and was based on a calculation of the ratio:

$$Cost - effectiveness\,ratio = \frac{Stormwater\,runoff\,volume}{Construction\,or\,maintencance\,costs} \tag{4}$$

Based on the cost-effectiveness ratio results, GI combinations were ranked in terms of their costs-effectiveness through a GICRI.

4. Results

4.1. Stormwater runoff volume reduction

Table 4 shows the stormwater runoff volume reduction for different GI options (and their combinations) and rainfall intensities and durations in comparison to the business-as-usual scenario. The results were obtained after running 60 simulations in PCSWMM.

4.2 Construction and maintenance costs

Table 5 shows the initial construction costs for different GI options and combinations in 2020 New Zealand Dollars.

Maintenance costs, like construction costs, vary according to the area of GI being implemented and were calculated based on GI unitary costs (e.g. costs for maintaining 1 m^2 of GI) and then converted to each GI option (Table 6).

4.3. GI cost-effectiveness ranking index (GICRI)

The cost-effectiveness analysis compared the hydrological performance of multiple GI options under different rainfall scenarios (see Table 4) against the costs of constructing and maintaining these options. The GI cost-effectiveness ranking index (GICRI) regarding GI construction and maintenance is discussed separately below.

4.4.1. Construction costs x stormwater runoff volume reduction

The relationship between construction costs and the stormwater runoff volume reduction for Auckland is shown in Figure 5. Among the chosen GI options, BR had the third-highest reduction in stormwater runoff volume and the lowest construction costs, therefore representing the most cost-effective option (see Supplementary Material for more detailed information). RG and RG+PP, on the other hand, showed the highest construction costs and the lowest stormwater runoff volume reduction efficiency under the RCP8.5/1h scenario. RG+BR and RG+BR+PP were the options with the lowest cost-effectiveness under the RCP8.5/120h scenario.

In Gore, similar results were observed (see Figure 4). BR was also identified as the alternative with the lowest construction costs and the highest stormwater runoff volume reduction capability. RG was the option with the highest cost of construction and lowest potential to reduce stormwater runoff volume. BR+PP was also demonstrated to be cost-effective. For example, BR+PP had the highest efficiency in minimizing stormwater runoff volume and the second lowest construction cost when 10% of GI was introduced under 120 hours of rainfall.

The impacts on stormwater runoff volume reduction did not represent a two-fold reduction when introducing 5% of any GI alternative compared to 10% of implementation. In other words, the investment would cost twice as much, but the gains in minimising stormwater runoff volume would not be obtained at the same rate.

4.4.2. Maintenance costs x stormwater runoff volume reduction

In Auckland, both rainfall scenarios demonstrated that the best options regarding maintenance costs per year and stormwater runoff volume reduction capacity are BR, BR+PP, and PP (from the most cost-effective to the lowest) (see Figure 6). RG had the lowest cost-effective results, as it had the highest maintenance cost per year and the lowest capacity to reduce stormwater runoff volume.

BR, BR+PP and PP also provided the best cost advantage concerning maintenance costs in Gore for both rainfall scenarios (see Figure 6). These options presented the highest stormwater runoff volume reduction ability with the lowest cost. Again, RG demonstrated to have a high maintenance cost and a limited capacity to reduce stormwater runoff volume.

In both case study areas, the cost-effectiveness associated with maintenance costs was not impacted by the duration of the rainfall. That is, the alternatives with highest cost-effectiveness capacity for 1-hour of rainfall are the same as the ones for the 120-hour event. This would be a finding of interest to decision-makers looking for consistent performance.

5. Discussion

GI alternatives have been recognised as a means to address urban climate change impacts, including more intense and frequent rainfall events (Eckart et al., 2017, Melo et al., 2020). While the pressure from climate change impacts has stimulated new approaches to flood risk management (e.g. consideration of alternatives to traditional stormwater network), financial resources tend to be a major barrier to municipal planning and infrastructure investment, including for improving, upgrading and maintaining stormwater infrastructure (Beauchamp and Adamowski, 2012). Based on our approach and results, there are three key insights that can guide future assessments of GI implementation: the need to include climate change impacts in GI cost-effectiveness analysis; the acknowledgement that highly urbanised cities and small regional towns present different challenges to GI implementation; and, the use of a GI cost-effectiveness ranking index (GICRI) to guide decisions.

5.1. Cost-effectiveness of GI options needs to consider climate change impacts

Historically, cities have been planned without considering how the alteration of the local hydrology could impact on stormwater runoff and associated fluvial and pluvial flooding (Brown et al., 2009). There was less pressure on urban areas to adapt to and manage extreme rainfall events, as there were more permeable surfaces. Added to that, climate change impacts also present further challenges to urban areas. Hence, when implementing GI for stormwater management, climate change projections should be incorporated in the assessment to inform planning decisions about likely future outcomes (Carter et al., 2018). By using different climate change scenarios (RCP8.5 with 1 hour and 120 hours of rainfall duration), our findings demonstrated how these influence the cost-effectiveness of GI options. In particular, climate change projections have a significant impact on GI cost-effectiveness related to its hydrological performance and construction costs. For example, in a highly urbanised city, when converting 5% of a given sub-catchment to GI, the RG+BR+PP cost-effectiveness performance was ranked sixth for a 1-hour and fifth for a 120-hour rainfall event, respectively. In the small regional town context, using the 10% as GI conversion rate, BR+PP ranked fifth for a 1-hour and fourth for a 120-hour rainfall event, respectively.

On the other hand, GI cost-effectiveness comprising hydrological performance and maintenance costs was not affected by rainfall duration. GI alternatives ranked the same for both rainfall events (see Figure 6). Similar ranking results were also found regardless of the spatial context - that is, a highly urbanised city or a small regional town. Only two GI options were differently ranked when comparing the two spatial settings: RG+BR - 5% and RG+PP – 5%. This is because of the particularities of GI performance at different spatial scales (e.g. performance of GI can vary depending on quantity of pervious area and urban configuration).

Our results enabled a better understanding of how different GI types and combinations perform during short and long rainfall events, and corresponding optimal solutions for both scenarios. By accounting for climate change projections, our results can guide planning decisions to not only respond to specific events based on past and historical data and information, but also plan for the future and how climate change will alter risk profiles.

5.2. Decision-making challenges are different in highly urbanised cities and small regional towns

GI cost-effectiveness and implementation challenges in highly urbanised cities differ from those in small regional towns. First, our findings demonstrated that GI combinations, such as the implementation of 5% of PP, have satisfactory performance in highly urbanised cities (ranked fifth for 1hour of rainfall and seventh for 120 hours of rainfall considering construction costs), but a lower performance in small regional towns (eighth position for 1 hour of extreme rainfall and ninth for 120 hours in regard to construction costs).

Second, due to the urban configuration, including the high quantity of impervious surface and presence of channelized water courses, highly urbanised cities are usually more exposed to flash floods. While they may have greater technical and financial capacity to develop and implement flood risk management strategies, these cities tend to have less availability of space to deploy GI options and land costs may be exceedingly expensive as demand for housing to accommodate growth is pressing. In these situations, GI alternatives could be added to multiple small areas such as at the precinct scale (Thiagarajan et al., 2018, Liu and Russo, 2021) to better manage flood risks. Our results further confirm that alternatives that demand less availability of space, such as PP, can be a cost-effective approach to be incorporated in bigger cities even with scarcity of space by replacing sealed surfaces with permeable alternatives.

On the other hand, small regional towns are frequently constrained by limited technical and financial capacity (e.g. budget limitations, reduced technical capacity available) (Bulkeley, 2013), but are more likely to have physical space to implement GI alternatives (e.g. their urban fabric is generally made up of larger lots and single detached dwellings which opens up greater opportunities for GI installation from a spatial perspective). Our findings indicate that the combination of RG with other GI options (such as BR or PP) can have a satisfactory cost-effectiveness in small regional towns. The implementation of 5% of BR+RG was ranked as the fourth most cost-effective alternative for 1 hour of rainfall and the fifth for 120 hours when considering construction costs. This is an important finding as the implementation of RG can also enhance their townscapes, add aesthetic values (Yuan et al., 2017), as well as function as green spaces providing more amenities for surrounding communities.

5.3 Ranking GI cost-effectiveness can allow faster decisions

Using a simplified cost-effectiveness ranking index approach (GICRI), our study takes a first step in providing a comprehensive overview of the most suitable (and affordable) GI options to specific spatial settings. It provides a simple and fast approach to enable decision-makers to evaluate a range of possible GI alternatives by applying cost-effectiveness analysis while taking climate change projections, different duration of rainfall events, multiple GI combinations, and spatial distribution into account. In doing so, scarce funds can be prioritised to investigate the most suitable and affordable options rather than a larger number of alternatives. A simple, step by step process guiding this is shown in Figure 7.

The first step calculates cost-effectiveness of GI by assessing their hydrological performance for the various rainfall scenarios while separately accounting for their construction and maintenance costs. This information is then used to create a GICRI list (see Figures 5 and 6) based on the cross-analysis of how alternatives perform for construction and maintenance costs as well as different extreme rainfall scenarios (step 2). Once the more suitable alternatives are identified (step 3), funds can be prioritised to further investigate the feasibility of implementing the most cost-effective GI options for specific spatial settings (step 4). For example, our GI cost-effectiveness analysis indicated that alternatives with relatively low construction and maintenance costs, such as BR and PP could be easily implemented in small quantities (e.g. 5% of land conversion) across urban areas to reduce stormwater runoff volume, without financially overburdening governments or property owners (steps 1). BR could be installed along sidewalks and PP could replace sealing in driveways and accessways. Hence, both alternatives were ranked among the most cost-effective for both case study areas, different rainfall scenarios and also considering construction and maintenance costs (step 2). By comparison, our results showed that one of the most cost-effective alternatives in terms of construction costs considering a 5% of implementation setting was RG+BR (ranked fourth for 1 hour and fifth for 120 hours of rainfall). The same option, however, ranked tenth for maintenance costs which brings down its overall cost-effectiveness. This information helps to prioritise which GI options are the most suitable for specific settings, and divert (scarce) funds to further investigate a smaller range of GI alternatives (step 4). This is important because there could be many variables influencing GI performance. Variables such as combination of GI, type of soil, permeability rate, for example, can influence which alternative is more suitable.

6. Conclusion

Urbanisation and climate change impacts will continue to challenge planning for climate resilience. Innovative and proactive approaches are still required to address these challenges. To this end, this paper developed a GI cost-effectiveness ranking index (GICRI) to investigate the implementation of multiple options of GI solutions in two different urban areas in Aotearoa-New Zealand. The analysis considered the hydrological performance of multiple GI types and combinations against a high emissions scenario (RCP8.5 – range year 2038-2050), including 1 and 120 hours of rainfall duration, and the introduction of 5 and 10%

of GI alternatives across chosen sub-catchments in Auckland (a highly urbanised city) and Gore (a small regional town). GI cost-effectiveness was assessed based on their construction and maintenance costs compared to their capacity of reducing stormwater runoff volume. Our findings confirmed that BR and BR+PP are the most cost-effective alternatives for minimising stormwater runoff volume. Furthermore, the use of small quantities of these relatively cheap GI alternatives implemented across the catchment has shown to be more cost-effective both in terms of construction and maintenance costs.

Nevertheless, the implementation of GI alternatives is still affected by lack of a comprehensive understanding regarding cost-effectiveness, generalist analysis and political decision-making. In order to address these issues, we recommend studies should be tailored to consider different spatial contexts, and corresponding climate change projections. Acknowledging temporal and spatial scales can provide more comprehensive evaluation of GI performance and better identify their benefits. If the co-benefits of GI are perceived as being more valuable than the construction and maintenance costs, the economic argument for the implementation of GI can be strengthened. Cost-effectiveness analyses could reduce the uncertainty regarding GI efficiency and the related costs and properly inform investment decisions, regulations and financial schemes and educational activities.

By conducting a cost-effectiveness analysis of multiple GI options under different rainfall patterns, this paper helps further strengthen the connection between flood risk management and land-use planning and advance this research agenda. This study, however, has some limitations as it applies generic construction and maintenance costs, and only focuses on stormwater volume runoff reduction as a benefit (e.g. improvements in water quality and benefits in reducing floods were not considered). Additionally, while GI alternatives may be effective in reducing flood risks in urban retrofit scenarios, their implementation can be costly. So, ideally, GI must be combined with other stormwater management solutions to maximise their potential in retrofit projects. Additionally, opportunities also need to be created for advancing the knowledge on the cost-effectiveness of GI options considering other benefits (e.g. water quality improvements, amenity, recreation, public health) and alternative engineering designs (e.g. quality of open space and type of landscape or integration with transport systems) to specific locations.

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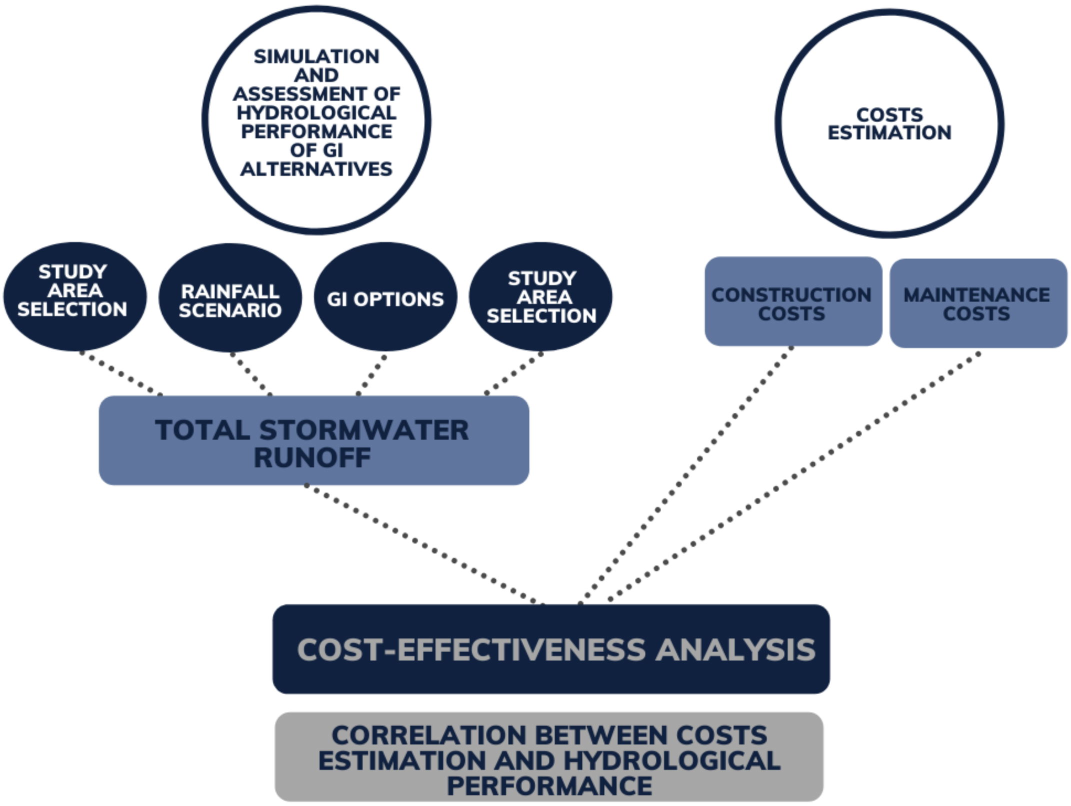


Figure 1: Framework for developing GICRI

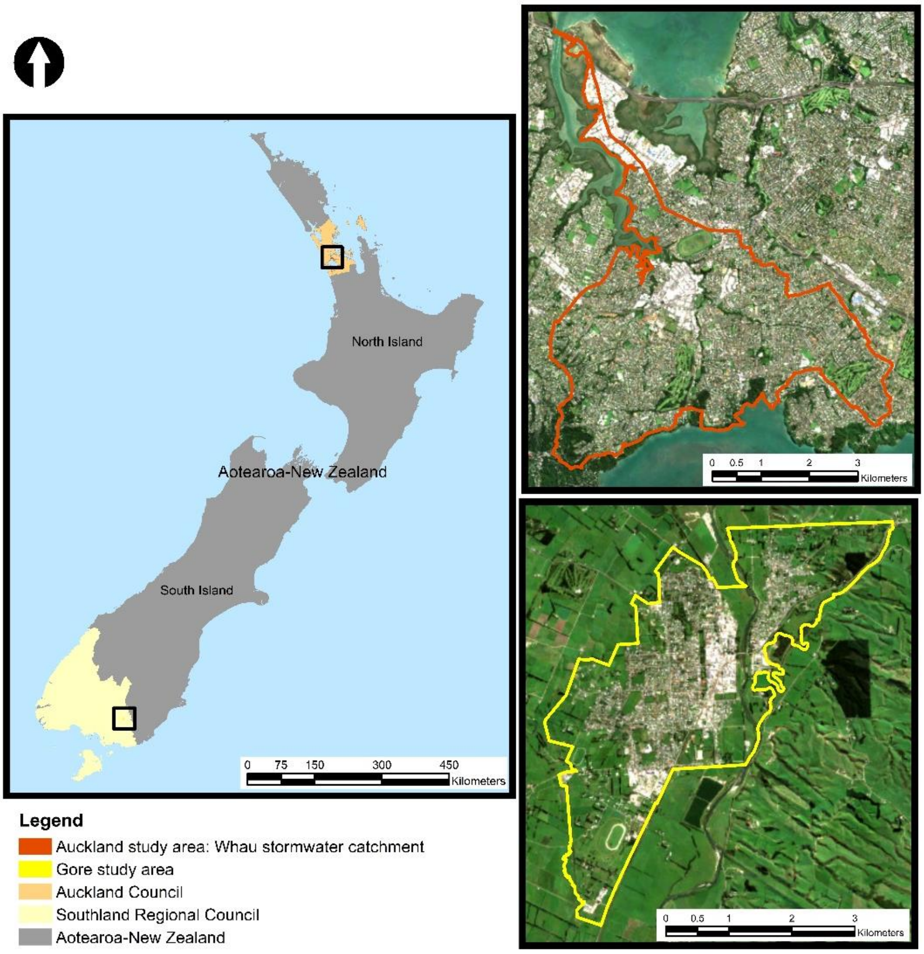


Figure 2: Case study areas

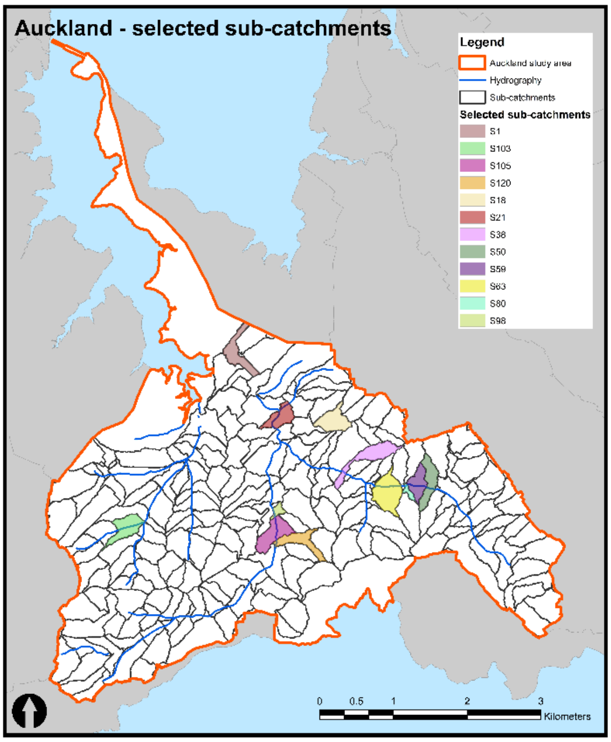
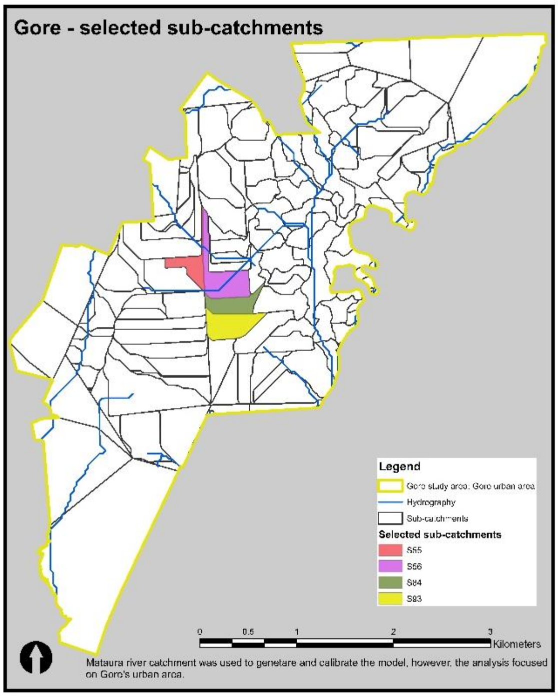


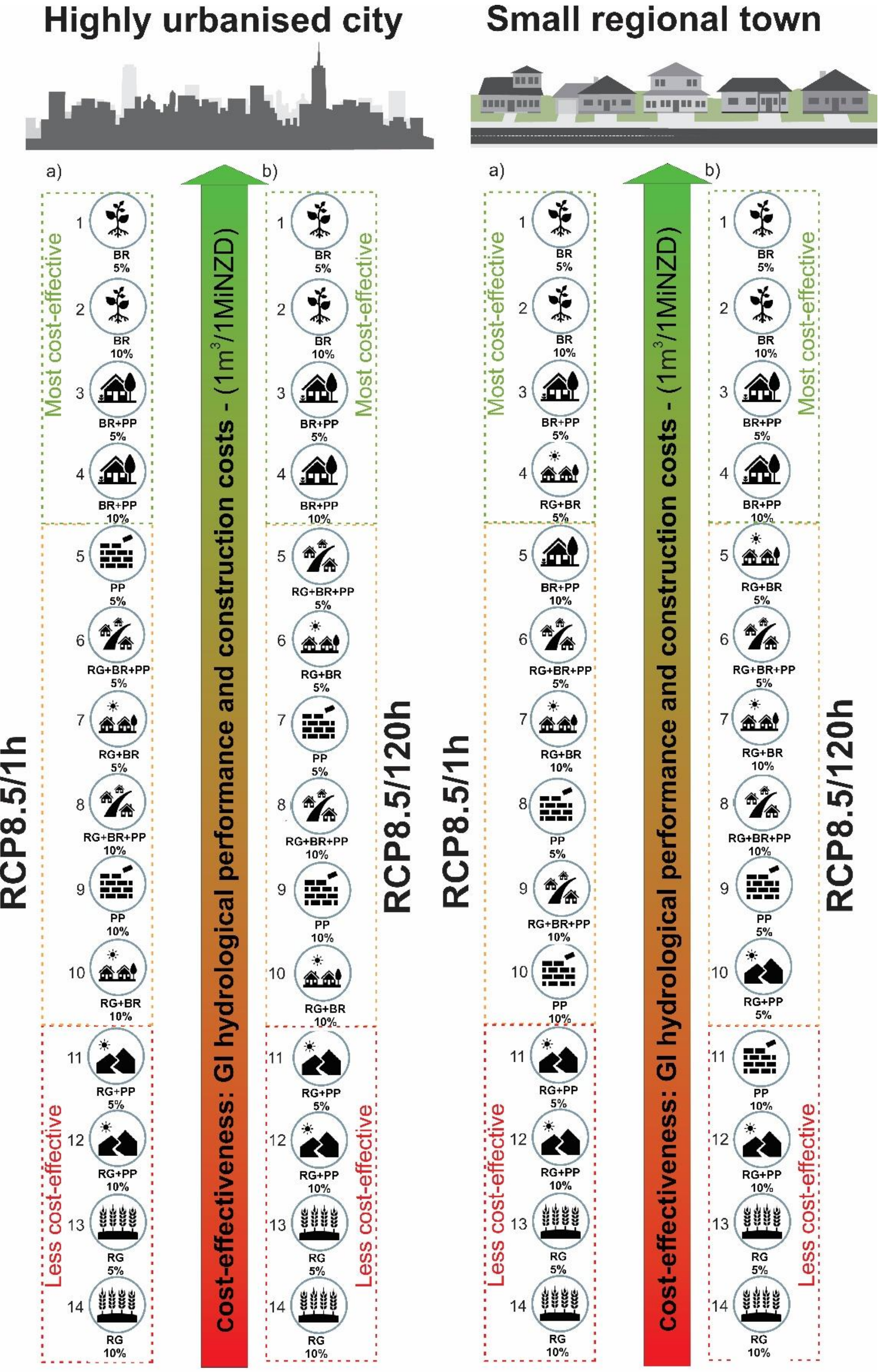
Figure 3: Selected sub-catchments – Auckland



Gore - selected sub-catchments

Mataura river catchment was used to genetare and calibrate the model, however, the analysis focused on Gore's urban area.

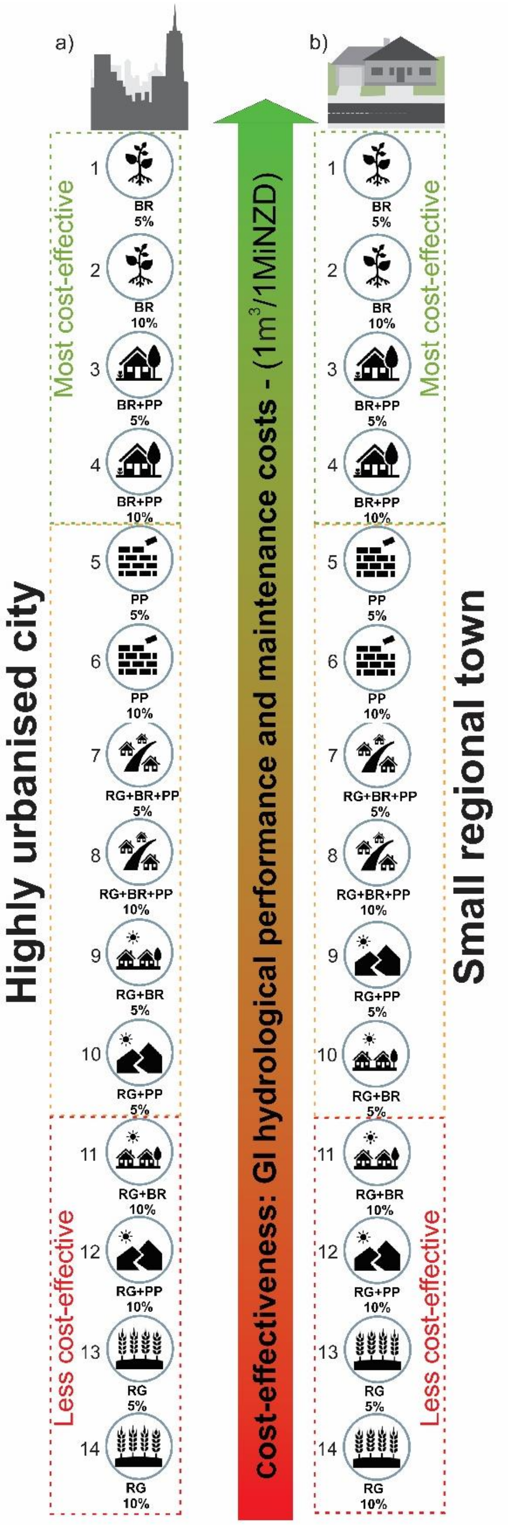
Figure 4: Selected sub-catchments – Gore



a) Cost-effectiveness in terms of hydrological performance and construction costs for one event of 1-hour of rainfall in highly urbanised cities ranges from 10.64 to 43.66m^3 of stormwater runoff volume for 1MiNZD and in small regional towns ranges from 10.8 to 39.12m^3 of stormwater runoff volume for 1MiNZD.

b) Cost-effectiveness in terms of hydrological performance and construction costs for one event of 120-hours of rainfall in highly urbanised cities ranges from 666.13 to 2,838.06m^3 of stormwater runoff volume for 1MiNZD and in small regional towns ranges from 490.72 to 1,976.88m^3 of stormwater runoff volume for 1MiNZD.

Figure 5: GICRI - correlation between construction costs and stormwater runoff volume reduction - highly urbanised city and small regional town



) Cost-effectiveness in terms of hydrological performance and maintenance costs for one event of 1-hour of ainfall in highly urbanised cities ranges from 41.87 to 1,265.61 m^3 of stormwater runoff volume for 1MiNZD ınd from 2,622.61 to 79,217.59 m^3 of stormwater runoff volume for 1MiNZD for 120-hours of rainfall.

) Cost-effectiveness in terms of hydrological performance and maintenance costs for one event of 1-hour of ainfall in small towns ranges from 42.51 to 1,162.30 m^3 of stormwater runoff volume for 1MiNZD and from ,931.99 to 55,179.8 m^3 of stormwater runoff volume for 1MiNZD for 120-hours of rainfall.

Note: Note that the cost-effectiveness rate differs for 1-hour and 120-hour rainfall events, although GI alternatives perform equally when compared against one other.

Figure 6 – GICRI - summary of correlation between maintenance costs per year and stormwater runoff volume reduction

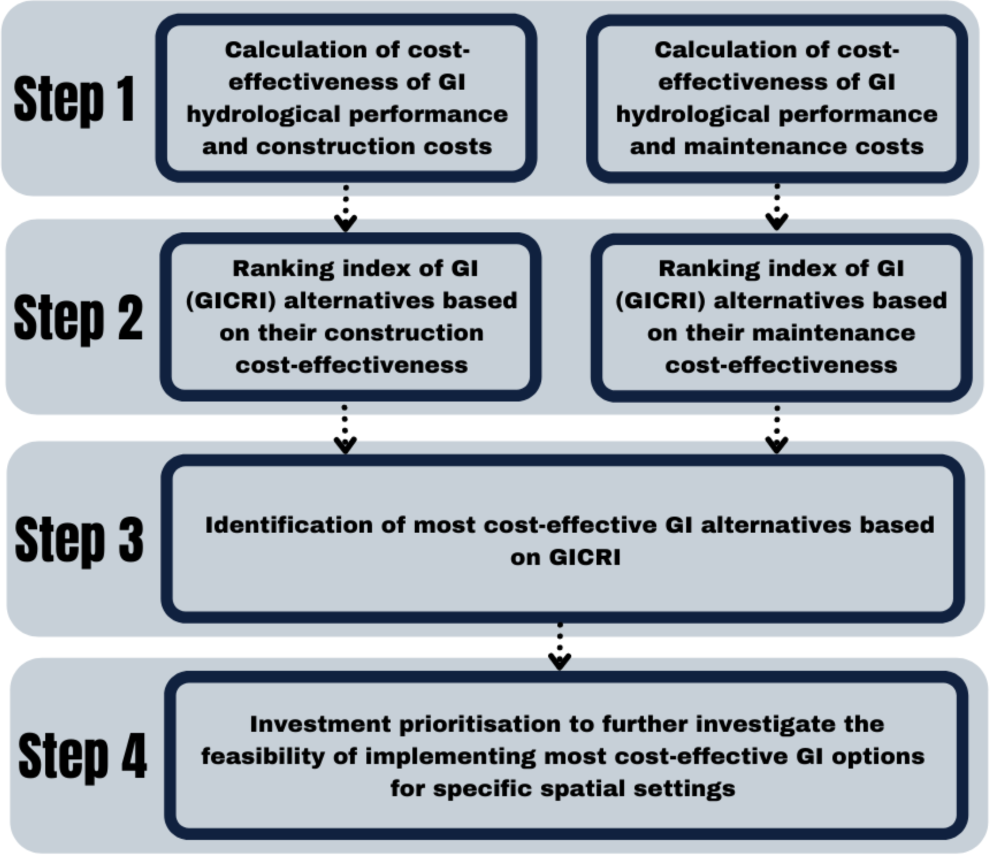


Figure 7 – Application of GI cost-effectiveness ranking index (GICRI) to inform decision-making

Table 1- Comparison between common economic analysis methods used to evaluate GI implementation

Method	Application	Limitations
Cost benefit analysis (CBA)	CBA compares the predicted or estimated costs and benefits of GI implementation to evaluate if the benefits surpass the costs (Liu et al., 2016).	Potential subjectivity when monetising intangible benefits (Keating and Keating, 2014), such as flood minimisation, groundwater recharge (Liu et al., 2016).
Life Cycle Cost Analysis (LCC)	LCC is the total cost associated with construction, maintenance and residual value at the end of an GI alternative life (Beauchamp and Adamowski, 2012).	Benefits (e.g. saving operational costs of drainage) and other economic effects (e.g. different cost for maintenance) need to be quantified and monetised.
Net Present Value (NPV)	NPV assesses the difference between the present value of cash inflows (benefits) and the present value of cash outflows (costs) over of GI implementation a period of time (Carter and Keeler, 2008).	Benefits need to be quantified, monetised and converted into cash inflows (Carter and Keeler, 2008).
Cost-effectiveness analysis	Cost-effectiveness allows a comparison of costs with outcomes (benefits) measured in natural units (Montalto et al., 2007).	Full benefits of GI implementation are not evaluated (Montalto et al., 2007).

Table 2: Selected rainfall scenarios used for simulating the hydrological performance of GI alternatives

Scenario name	Duration of Rainfall	High-intensity rainfall event
RCP8.5/1h	1 hour	RCP 8.5 (range year 2038-2050)
RCP8.5/120h	120 hours	RCP 8.5 (range year 2038-2050)

Table 3: Different options of GI alternatives and spatial allocation assigned to each rainfall scenario

GI option		Spatial Allocation	GI alternative	Quantity of GI alternative
1	BR	5 %	Bio-retention cells	5%
2	PP		Permeable pavement	5%
3	RG		Rain garden	5%
4	BR + PP		Bio-retention cells	2.5%
			Permeable pavement	2.5%
5	RG + PP		Rain garden	2.5%
			Permeable pavement	2.5%
6	RG + BR		Rain garden	2.5%
			Bio-retention cells	2.5%
7	RG + BR + PP		Rain garden	1.5%
			Bio-retention cells	1.5%
			Permeable pavement*	2%
8	BR	10 %	Bio-retention cells	10%
9	PP		Permeable pavement	10%
10	RG		Rain garden	10%
11	BR + PP		Bio-retention cells	5%
			Permeable pavement	5%
12	RG + PP		Rain garden	5%
			Permeable pavement	5%
13	RG + BR		Rain garden	5%
			Bio-retention cells	5%
14	RG + BR + PP		Rain garden	3%
			Bio-retention cells	3%
			Permeable pavement	4%

Table 4 - Reduction of stormwater runoff volume based on different GI options and rainfall intensities and duration

Spatial allocation	Rainfall scenario	GI options	Stormwater runoff reduction *			
			Auckland		Gore	
			m^3	%	m^3	%
5%	RCP8.5/1h	BR	260	2.4	93	2.3
		PP	280	2.6	102	2.5
		RG	190	1.7	77	1.9
		BR + PP	270	2.5	99	2.4
		RG + PP	240	2.2	89	2.2
		RG + BR	230	2.1	106	2.6
		RG + BR + PP	240	2.2	92	2.2
	RCP8.5/120h	BR	16,900	2.8	4,700	2.5
		PP	16,900	2.8	4,700	2.5
		RG	11,900	1.9	3,500	1.8
		BR + PP	16,900	2.8	4,700	2.5
		RG + PP	14,400	2.4	5,100	2.7
		RG + BR	14,400	2.4	4,600	2.4
		RG + BR + PP	15,200	2.5	4,400	2.3
10%	RCP8.5/1h	BR	460	4.2	161	3.9
		PP	500	4.6	178	4.3
		RG	420	3.8	154	3.8
		BR + PP	480	4.4	178	4.3
		RG + PP	440	4.0	162	3.9
		RG + BR	420	3.8	162	3.9
		RG + BR + PP	450	4.1	171	4.2
	RCP8.5/120h	BR	30,500	5.0	8,200	4.3
		PP	30,500	5.0	8,200	4.3
		RG	25,800	4.2	7,000	3.6
		BR + PP	30,500	5.0	8,600	4.5
		RG + PP	27,100	4.4	7,600	4.0
		RG + BR	27,100	4.4	7,800	4.1
		RG + BR + PP	28,500	4.7	8,200	4.3

* The stormwater runoff volume in the business-as-usual scenario for Auckland is 10,980m^3 (RCP8.5/1h) and 612,100m^3 (RCP8.5/120h); and for Gore is 4,102m^3 (RCP8.5/1h) and 191,800m^3 (RCP8.5/120h).

Table 5 - Construction costs for different options of GI types and quantities

Spatial allocation	GI options	Construction Costs/m^2 (NZD)	Estimated Implementation Costs (NZD)	
			Auckland (area 113ha)*	Gore (area 45.1ha)*
5%	BR	$104.30	$5,892,616	$2,352,669
	PP	$266.99	$15,083,889	$6,022,350
	RG	$312.90	$17,677,989	$7,058,007
	BR + PP	$185.64	$10,488,252	$4,187,509
	RG + PP	$289.94	$17,848,011	$6,540,077
	RG + BR	$208.60	$12,840,769	$4,705,338
	RG + BR + PP	$225.78	$13,106,786	$5,232,132
10%	BR	$104.30	$11,785,232	$4,705,338
	PP	$266.99	$30,167,779	$12,044,700
	RG	$312.90	$35,355,979	$14,116,014
	BR + PP	$185.64	$20,976,505	$8,375,019
	RG + PP	$289.94	$35,696,022	$13,071,659
	RG + BR	$208.60	$25,681,538	$9,404,418
	RG + BR + PP	$225.78	$26,207,315	$10,464,265

* Area of the selected sub-catchments

Table 6 - Maintenance costs for different GI options including single types and combination and spatial allocation

Spatial allocation	GI options	Maintenance Costs/year/m^2 (NZD)	Estimated Maintenance Costs/year (NZD)	
			Auckland (area 113ha)	Gore (area 45.1ha)
5%	BR	-	-	-
	PP	$7.47	$422,219.98	168,574.34
	RG	$79.47	$4,490,111.13	1,792,694.59
	BR + PP	$3.74	$211,109.99	84,287.17
	RG + PP	$43.47	$2,676,130.98	980,619.25
	RG + BR	$39.74	$2,446,113.06	896,333.38
	RG + BR + PP	$28.69	$1,516,588.85	605,236.12
10%	BR	-	-	-
	PP	$7.47	$844,439.97	337,148.67
	RG	$79.47	$8,980,222.26	3,585,389.17
	BR + PP	$3.74	$422,219.98	168,574.34
	RG + PP	$43.47	$5,352,261.96	1,959,964.70
	RG + BR	$39.74	$4,892,226.11	1,791,502.46
	RG + BR + PP	$28.69	$3,031,588.21	1,210,472.25