Copernicus Climate Change Service

Sustainable Asset Valuation (SAVi) of Stormwater Infrastructure Solutions in Johannesburg, South Africa

Assessing climate resilience and socio-ecological benefits

SUMMARY OF RESULTS

Issued by: IISD-EU / David Uzsoki

Date: April 2021

Ref: D428h.2.5.1

Official reference number service contract: 2019/C3S_428h_IISD-EU/SC1

IMPLEMENTED BY ECMWF

The International Institute for Sustainable Development (IISD) and KnowlEdge Srl have worked on integrating climate data from the Copernicus Climate Data Store (CDS) to improve the analysis of infrastructure projects performed with SAVi. The project serves to demonstrate the importance and usability of climate data generated through the CDS products in deploying sustainable infrastructure projects to contribute to a climate-resilient, low-carbon economy.

Acknowledgements

The authors of this report would like to thank Liana Strydom (Development Planning Department, City of Johannesburg) and Chris Brooker (PrEng owner of cba Specialist Engineers) for their valuable contributions and feedback. Their engagement and advice were essential for the success of this assessment.

About the Sustainable Asset Valuation (SAVi)

SAVi is a simulation service that helps governments and investors value the many risks and externalities that affect the performance of infrastructure projects.

The distinctive features of SAVi are:

- Valuation: SAVi values, in financial terms, the material environmental, social, and economic risks and externalities of infrastructure projects. These variables are ignored in traditional financial analyses.
- Simulation: SAVi combines the results of systems thinking and system dynamics simulation with project finance modelling. We engage with asset owners to identify the risks material to their infrastructure projects and then design appropriate simulation scenarios.
- Customization: SAVi is customized to individual infrastructure projects.

For more information on SAVi: www.iisd.org/savi

About Copernicus Climate Data Store

The European Commission has charged the European Centre for Medium-Range Weather Forecasts (ECMWF) to implement the Copernicus Climate Change Service (C3S). The main goal of C3S is to deliver high-quality data to support climate change adaptation and mitigation policies (ECMWF, 2017). One of the main features of C3S is the Climate Data Store (CDS), which delivers current, past, and future climate indicators. The CDS contains historical climate observations, Earth observation datasets, global and local climate projections, seasonal forecasts, and global and local climate analyses (ECMWF, 2017).

Data obtained from the CDS Toolbox include location-specific, historical, and future weather indicators, such as precipitation and temperature. Historical data (ECMWF Reanalysis 5th generation [ERA5]) and projections (Coupled Model Intercomparison Project Phase 5 [CMIP5]) are available for consultation and download in the CDS. Selected indicators are also accessible through a dedicated online app created to facilitate the exchange of information between the CDS and several SAVi models. The SAVi tool uses climate information to estimate damage resulting from extreme weather events and climate trends, establish the value addition resulting from improved adaptive capacity, and calculate the supply and demand of ecosystem services (Bassi et al., 2020). For example, through the integration of data on precipitation, evaporation, and crop water requirements into the SAVi model, it is possible to evaluate current and future water supply in a specific landscape and inform planning for irrigation infrastructure (Bassi et al., 2020).

The Integration of Climate Data into the SAVi Model (Bassi et al., 2020) outlines the integration of authoritative Copernicus climate data from the CDS into the SAVi tool. It describes how several climate indicators obtained from the CDS were integrated into SAVi and how its analysis has improved as a result. In light of this integration, the International Institute for Sustainable Development can generate sophisticated SAVi-derived analyses on the costs of climate-related risks and climate-related externalities.

Authors

Laurin Wuennenberg

Andrea M. Bassi

Georg Pallaske

Executive Summary

The Paterson Park Precinct project is part of Johannesburg's Corridors of Freedom Initiative, which seeks to improve social cohesion within the urban environment while maximizing environmental and economic benefits. The project is also part of the Global Environment Facility (GEF) Sustainable Cities Impact Program, which promotes holistic urban planning to maximize environmental and social benefits and to avoid negative trade-offs.

One of the components of the project included an upgrade of the stormwater infrastructure in the precinct area through a combination of grey–green infrastructure. Buildings (social housing, sports facilities, and a recreational centre) are another component of this project and were assessed in a separate SAVi analysis.

The City of Johannesburg is also investigating further stormwater infrastructure upgrading options for other areas. This assessment aims to contribute to that discussion, particularly in light of the city's 2021 Climate Action Plan.

This SAVi assessment was customized and applied to assessing three stormwater infrastructure options, derived from interventions in the Paterson Park Precinct:

- **Grey stormwater infrastructure:** civil-engineered, concrete culvert
- **Nature-based stormwater infrastructure:** stream renaturalization
- **Hybrid stormwater infrastructure:** a combination of a concrete culvert section and a renaturalized stream section, as implemented in the Paterson Park Precinct in 2018.

The SAVi assessment of the three stormwater infrastructure options provided the following:

- **Integrated Cost–Benefit Analysis (CBA):** The project costs and the social, environmental, and economic (co-)benefits of the three options were assessed and valued in monetary terms over 20- and 40-year time horizons.
- **Climate Change Scenario Analysis:** The CBA performance of the three infrastructure options was assessed under four different climate scenarios over 20- and 40-year time horizons.

Three messages arise from the results of the SAVi assessment:

- Over the life cycle of the infrastructure, the hybrid solution and the full renaturalization of the stream are the most cost-efficient investments. The grey stormwater infrastructure requires the highest upfront investment, while annual operation and maintenance costs are higher for the renaturalized stream.
- The hybrid solution and renaturalized stream provide additional benefits, some of which the grey stormwater infrastructure, by design, cannot provide. Among these benefits are improved flood mitigation resulting in avoided costs of flood damages, additional employment from landscaping, and environmental benefits such as carbon sequestration

and additional water supply. The avoided cost of flood damages is by far the largest additional benefit of the nature-based stormwater infrastructures. The full renaturalization of the stream avoids approximately ZAR 103 million in flood damage costs over a 20-year period and more than ZAR 184 million over a 40-year period. The hybrid solution yields almost ZAR 87 million and ZAR 168 million, respectively, over the same time horizons. Another significant additional benefit is that the hybrid and renaturalized options, by design, increase soil permeability and contribute to additional water supply.

- Under different climate change scenarios, the case for nature-based infrastructure (NBI) options becomes even clearer: the more volatile precipitation patterns become, the larger the benefits in comparison with a grey-built solution. Indeed, a grey stormwater solution's capacity is limited by design and therefore less equipped to deal with extreme weather events. This also illustrates the importance of using climate parameters when assessing the costs and benefits of different infrastructure options.

Table ES1. How decision-makers can use this analysis

Stakeholder	Role in the project	How will the stakeholder use the results of the assessment with Copernicus Climate Change Service (C3S) data?
City of Johannesburg	Design and oversight of the precinct project.	• To make the case for nature-based stormwater infrastructure based on the improved evidence for the climate resilience of NBI and vulnerabilities of stormwater infrastructure alternatives and related costs. • To negotiate with other city departments about city-wide NBI stormwater upgrades because of the performance and the co-benefits. • To inform the city's climate action plan, which will be advanced in 2021.
United Nations Environment Programme (UNEP)	Coordinator and supervisor of several project components of a GEF-funded project, including the eco-district pilot in the Paterson Park Precinct.	• To demonstrate that green infrastructure solutions for stormwater management can reduce costs for the city and increase climate resilience. • To showcase the value of NBI for reducing costs for the city and enhancing overall environmental regeneration and resilience. • To use the SAVi outputs as evidence to inform and design other urban projects. • To raise awareness about how climate data can be integrated into urban planning and the design of stormwater infrastructure.

Global Environment Facility (GEF)	Main donor for the design, assessments, and implementation of several eco-districts in Johannesburg, including the Paterson Park Precinct.	• As quantitative evidence for the GEF that funding of NBI is aligned with their objectives to promote environmental sustainability and climate change adaptation. The latter is implemented through the GEF's Least Developed Countries Fund (LDCF) and the Special Climate Change Fund (SCCF). • To appreciate the valuations on NBI and their co-benefits. • To build a market for and build expertise on NBI for resilient cities by implementing eco-districts. • To define funding priorities for resilient cities.

Table of Contents

List of Figures

List of Tables

Abbreviations

BAU	business as usual
C3S	Copernicus Climate Change Service
CBA	cost–benefit analysis
CDS	Climate Data Store
CLD	causal loop diagram
GDP	gross domestic product
GEF	Global Environment Facility
GHG	greenhouse gases
NBI	nature-based infrastructure
RCP	Representative Concentration Pathway
SAVi	Sustainable Asset Valuation tool
UNEP	United Nations Environment Programme

Glossary

Causal loop diagram (CLD): A schematic representation of key indicators and variables of the system under evaluation that shows the causal connections between them and contributes to the identification of feedback loops and policy entry points.

Discounting: A financial process to determine the present value of a future cash value.

Externality: An externality is a negative or positive impact, often referred to as a cost or benefit that affects a third party who did not play a role in determining the impact. The third party, who can be private (individual, organization) or society as a whole, did not choose to incur the cost or to receive the benefit. Hence, an externality is not reflected in the market price of a good or service (Kenton, 2019).

Feedback loop: "Feedback is a process whereby an initial cause ripples through a chain of causation ultimately to re-affect itself" (Roberts et al., 1983).

Indicator: Parameters of interest to one or several stakeholders that provide information about the development of key variables in the system over time and trends that unfold under specific conditions (United Nations Environment Programme [UNEP], 2014).

Methodology: The theoretical approach(es) used for the development of different types of analysis tools and simulation models. This body of knowledge describes both the underlying assumptions used as well as qualitative and quantitative instruments for data collection and parameter estimation (UNEP, 2014).

Model transparency: The degree to which model structure and equations are accessible and make it possible to directly relate model behaviour (i.e., numerical results) to specific structural components of the model (UNEP, 2014).

Model validation: The process of assessing the degree to which model behaviour (i.e., numerical results) is consistent with behaviour observed in reality (i.e., national statistics, established databases) and the evaluation of whether the developed model structure (i.e., equations) is acceptable for capturing the mechanisms underlying the system under study (UNEP, 2014).

Net present value (NPV): The difference between the present value of cash inflows net of financing costs and the present value of cash outflows. It is used to analyze the profitability of a projected investment or project.

Risk: A risk in the context of infrastructure finance refers to the chance that a factor outside the direct control of an asset owner or operator materializes as a cost for an asset. The materiality of a risk is considered in relation to the asset under assessment. Risks can be social, environmental (physical), economic, or regulatory in origin. An externality caused by the same asset under assessment may or may not turn into a risk.

Scenarios: Expectations about possible future events used to analyze potential responses to these new and upcoming developments. Consequently, scenario analysis is a speculative exercise in which several future development alternatives are identified, explained, and analyzed for discussion on what may cause them and the consequences these future paths may have on our system (e.g., a country or a business).

Simulation model: Models can be regarded as systemic maps in that they are simplifications of reality that help to reduce complexity and describe, at their core, how the system works. Simulation models are quantitative by nature and can be built using one or several methodologies (UNEP, 2014).

Social costs of carbon: The economic cost caused by an additional tonne of carbon dioxide emissions or its equivalent through the carbon cycle (Nordhaus, 2017).

Stock and flow variables: “A stock variable represents accumulation and is measured at one specific time. A flow variable is the rate of change of the stock and is measured over an interval of time” (UNEP, 2014, p. 51).

System dynamics: A methodology developed by Forrester in the late 1950s (Forrester, 1961) to create descriptive models that represent the causal interconnections between key indicators and indicate their contributions to the dynamics exhibited by the system as well as to the issues being investigated. The core pillars of the system dynamics method are feedback loops, delays, and non-linearity emerging from the explicit capturing of stocks and flows (UNEP, 2014).

1. Introduction

The International Institute for Sustainable Development (IISD) and KnowlEdge (KE) are collaborating with the Copernicus Climate Change Service (C3S), one of the six thematic information services provided by the EU'S Copernicus Earth Observation Programme, to integrate world-class data on climate into the Sustainable Asset Valuation (SAVi) methodology and enhance its capacity for climate resiliency assessments of infrastructure projects.

The SAVi methodology quantifies and values the environmental, social, and economic externalities of infrastructure projects as well as financial performance implications caused by diverse risk factors faced by the same projects, such as those associated with climate change. The methodology can also be applied to conduct comparative assessments between alternative infrastructure solutions. More information on the SAVi methodology can be found on this website: https://iisd.org/savi

One of the defined pilot applications of the enhanced SAVi methodology served to assess different stormwater infrastructure options for the Paterson Park Precinct, an urban development zone in Johannesburg, South Africa. The assessment scope and objectives were developed together with the Development Planning Department of the City of Johannesburg, South Africa.

An enlargement of an outdated culvert through Paterson Park south and the daylighting and renaturalization of the culvert and stormwater channel through the northern side were completed in 2018. Although this was a critical intervention to improve the stormwater management capacity of the area for ongoing urban development, it has not resolved the need for further stormwater infrastructure upgrades to be carried out. As the city is currently investigating further stormwater infrastructure upgrading options, the SAVi methodology was customized and applied to assessing three stormwater infrastructure options that were derived from the earlier interventions in the Paterson Park Precinct:

- **Grey stormwater infrastructure:** civil-engineered, concrete culvert.
- **Nature-based stormwater infrastructure:** stream renaturalization
- **Hybrid stormwater infrastructure:** a combination of a concrete culvert section and a renaturalized stream section, as implemented in the Paterson Park Precinct in 2018.

The SAVi assessment of the three stormwater infrastructure options inquired the following:

- **Integrated Cost–Benefit Analysis (CBA):** The project costs and the social, environmental, and economic (co-)benefits of the three options were assessed and valued in monetary terms over 20- and 40-year time horizons.
- **Climate Change Scenario Analysis:** The CBA performance of the three infrastructure options was assessed under four different climate scenarios over 20- and 40-year time horizons.

The results of this SAVi assessment and the drawn conclusions serve to inform the City of Johannesburg about important considerations for implementing effective and climate-resilient stormwater infrastructure as part of sustainable urban planning that delivers environmental and socio-economic benefits to the urban population and the City of Johannesburg.

2. Stormwater Challenges and Management Options in Johannesburg, South Africa

South Africa is experiencing continuous urbanization, and cities such as Johannesburg have to cope with urban inequality and high levels of inefficient use of resources. The city faces a range of environmental sustainability issues (City of Johannesburg, 2020b):

1. Urbanization is placing unprecedented growing pressure on infrastructure and services, inducing large-scale transformation, fragmentation, and the degradation of natural assets, as well as causing a decline in air and water quality in the city.
2. The city is a major greenhouse gas (GHG) emissions generator and highly vulnerable to climate hazards (extreme storms, floods, droughts, heat waves).
3. The municipal solid waste management system is underdeveloped and causes negative environmental and health impacts.
4. Natural areas and open spaces are not adequately valued and promoted.
5. Water quality is poor and exceeds legal and environmental thresholds in all catchments with adverse impacts for humans, the economy, and ecosystems.
6. Water scarcity is a prevalent reality.
7. Biodiversity is not appropriately protected and managed.
8. Air quality is poor.
9. Accountability and responsibility for resolving such environmental sustainability issues are not adequately allocated across public actors of the city, civil society, and the private sector.

Moreover, the city's recently completed Climate Action Plan identifies the following main risks caused by climate challenges (City of Johannesburg, 2020a):

- Changes in interannual precipitation (rainfall) variability
- Changes in precipitation intensity
- Increasing temperatures and additional heat island effects.

Urban flooding is identified as one of the key risks for the city. It is likely that significant populations will be more exposed to the potential climate impacts, particularly increased precipitation intensity and the associated risk of flooding.

Likewise, the entire Gauteng Province has suffered from floods almost every year since 2014, and Johannesburg was hit by heavy rain and resulting flash floods, in particular in 2016 (Al Jazeera, 2016) and 2020 (Floodlist, 2020). In addition, the Johannesburg Road Agency (2014) acknowledged earlier that various areas in Johannesburg have suffered from flooding events in past years that caused damage to road infrastructure, bridges, and stormwater drains due to above-average rainfall.

Paterson Park is located between Orange Grove and Norwood and is a key open area for enhancing social cohesion, community activities, and public infrastructure (City of Johannesburg, 2017). These neighbourhoods have experienced urbanization and densification in the past, which has led to more sealed surface area and therefore to less absorption capacity of soils and more stormwater runoff. The 1:100-year[1] flood line is located in a less elevated area of the Orange Grove precinct and runs through the Paterson Park area—see Figure 1 (City of Johannesburg, 2017). Due to these factors and the lack of alternative spaces for stormwater attenuation, Paterson Park and the surrounding areas can be considered vulnerable to floods. Moreover, more intense storms and increased frequency of precipitation due to climate change could cause regular damage to properties and public infrastructure, implying that flood control management must be addressed in the Paterson Park Precinct.

This is why the implementation of effective stormwater infrastructure solutions with sufficient runoff absorption capacity is critical for the Paterson Park Precinct. Likewise, implementing appropriate forecast-based stormwater infrastructure is critical for other areas of the city, which are already or will become prone to flooding risks in light of climate change.

[1] A 1:100-year flood represents the probability of flood occurrence. It implies there is a 1% probability of flood occurrence in a given year.

Figure 1. Location of Paterson Park and the 1:100-year flood line

Source: City of Johannesburg, 2017

Section 3 provides details about the technical parameters of each stormwater intervention alternative as well as the scope of this SAVi assessment.

3. SAVi Modelling Approach, Assessment Scope, and Parameters

The model used for this SAVi assessment uses the systems thinking and system dynamics methodologies (described in more detail in Appendix C) and includes indicators of physical and monetary natures. These indicators were calculated using information on the size and location of the project, making use of multipliers obtained from both literature and simulation models. Thus, conventional cost positions as well as (co-)benefits (positive externalities) associated with the respective stormwater asset are considered. The cost positions and externalities quantified and valued in monetary terms in this SAVi assessment are defined in the next section.

The underlying dynamics of the Paterson Park stormwater project, including driving forces and key indicators, are summarized in the causal loop diagram (CLD) displayed in Figure 3. The CLD includes the main indicators analyzed during this SAVi assessment, their interconnections with other relevant variables, and the feedback loops they form. Practically, the CLD presents the systemic approach that this SAVi assessment uses to estimate 1) the societal contribution of different stormwater infrastructure options and 2) the environmental, economic, and societal drivers that affect each stormwater infrastructure asset. The CLD was co-created with the City of Johannesburg.

The CLD shows that both the culvert (civil works) and the renaturalization of the river impact government expenditure: there are costs for investment and maintenance, including labour costs related to employment. On the other hand, employment creation leads to income generation, and thus it represents a positive contribution to society.

The outcomes of such investments are many and varied. The direct impact is a reduction in flood risks, which in turn reduces damages to infrastructure and increases property value. Insurance premiums for property and/or real estate owners also decline due to lower flood and related damage risks. When property values increase, government revenue from property taxes will also increase, leading to better value delivered to society via public investment. At the same time, increased property values have a negative impact on inequality. They also may drive populations away from the urban areas as property becomes unavailable.

On the other hand, if the area becomes safer and more desirable, it can expect to draw more population. In this respect, the larger an urban area becomes, the more impervious surfaces expand and vegetation declines. This has an impact on the water absorption capacity and ultimately influences the water runoff stormwater assets will have to deal with. A renaturalized solution increases vegetation and is better suited to coping with increased stormwater runoff volumes due to higher percolation and water uptake.

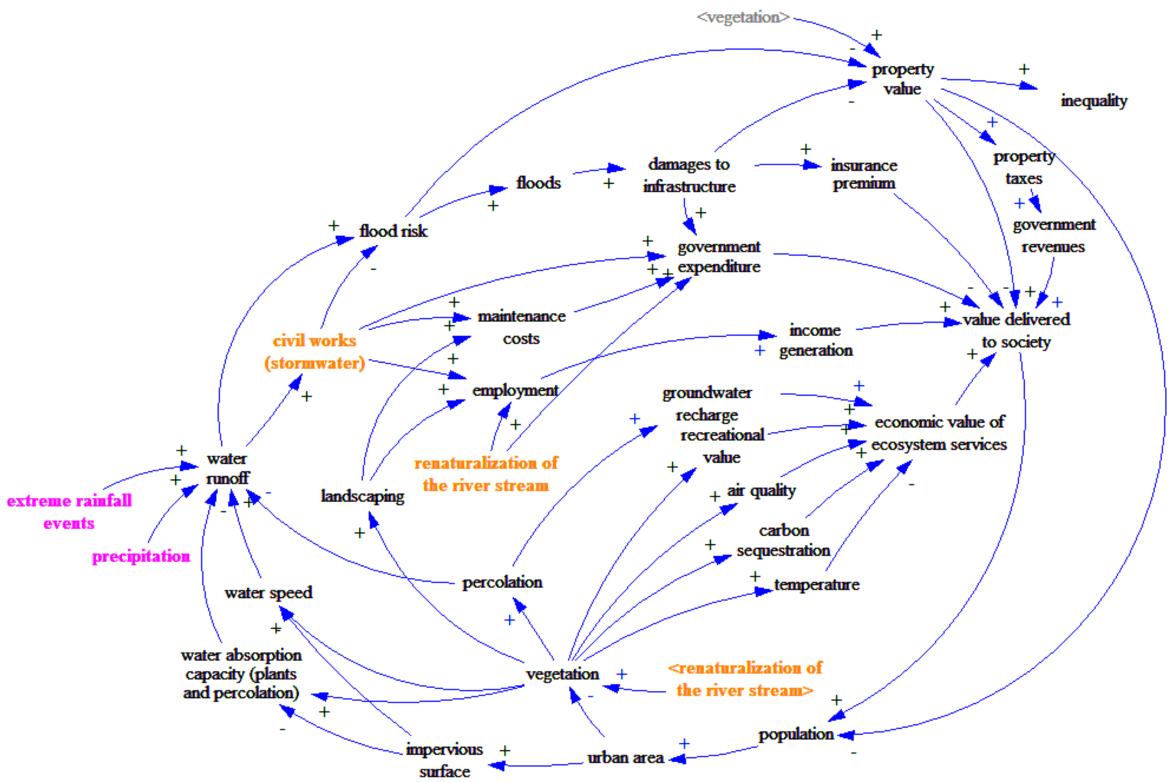
A nature-based solution for stormwater runoff has many other positive benefits that were discussed and included in the CLD:

- **Local air quality improvements,** as vegetation reduces the ambient concentration of air pollutants, which implies positive public health benefits.

- **Local reduction of the urban heat island effect** due to the water stream and surrounding vegetation, which again can imply positive human health impacts.
- **Groundwater recharge and water quality improvements** through percolation and natural self-purification effects in the natural stream and due to tree canopies and other plants, reducing the volume of runoff carrying pollutants and high nutrient loadings.
- **Recreational value** of green spaces, such as the renaturalized stream, because these stimulate citizens to become more physically active and spend time in nature, which has positive effects on public health.
- **Positive local economy effects** due to an increasing number of visitors with spending capacity.

Further, climate parameters (variables in pink) that affect the performance and effectiveness of the different stormwater infrastructure assets are incorporated. The climate-related variables considered for the assessment of climate change impacts on stormwater management capacity are precipitation and extreme rainfall events. Both affect water runoff volume in the assessed city district.

Figure 1. CLD of the systemic analysis performed in this SAVi assessment



3.1 Costs and Benefits Assessed

This SAVi assessment includes the calculation and valuation of cost positions and selected co-benefits (externalities), as well as the implications of climate variables (variations of precipitation rates) on the magnitude of co-benefits associated with three stormwater infrastructure options:

- **Grey stormwater infrastructure:** civil-engineered, concrete culvert.
- **Nature-based stormwater infrastructure:** stream renaturalization
- **Hybrid stormwater infrastructure:** combination of a concrete culvert section and a renaturalized stream section, as implemented in the Paterson Park Precinct.

Available cost data for the infrastructure options stem from a tender document for the Paterson Park Culvert Upgrade (Murray & Dickson, 2015). On the other hand, maintenance cost figures and assumptions for the quantified co-benefits are deduced from international data sources and scientific literature. Quantitative information per stormwater infrastructure option, data sources, assumptions, and respective references are presented in Annex A. The main technical parameters and assumptions for the three stormwater intervention options are presented in Table 1.

Table 1. Main technical parameters and assumptions

Parameter	Unit	Concrete culvert	Renaturalized stream	Hybrid solution
Length	m	756	756	336 (culvert) + 420 (stream)
Operation time	Years	40		
Area at Paterson Park considered for water loads	m^2	21,324		
Fraction of area permeable	%	60	100	80
Infiltration	%	15	50	35
Runoff	%	55	10	30
Evapotranspiration	%	30	30	35
Peak rainfall for flood risks	mm/day	65		

This section provides brief explanations of the main performance parameters analyzed in this SAVi assessment to ease the reading of quantitative results presented in several tables in Section 4.

The SAVi assessment includes the following conventional cost positions and benefits (positive externalities) for the assessed stormwater infrastructure intervention options. Items 1 to 8 are also indicated with respective numbers in the CBA tables to ease the finding of definitions presented below. Data sources and detailed assumptions for each position are indicated in Annex A.

Cost positions

1. **Capital cost:** entails various cost positions associated with the construction and upgrade of the stormwater infrastructure options. All of the following apply to the hybrid solution, while some only apply to the concrete culvert and the renaturalized stream, respectively.
   - 1.1. **Renaturalization of the stream:** site clearance; earthworks; stream lining, ripraps and filters; structural elements and reinforcement elements.
   - 1.2. **Landscaping (for stream):** earthworks, cost of trees and other vegetation, establishment maintenance.
   - 1.3. **Culvert construction:** site clearance, earthworks, concrete walls and other concrete elements, precast concrete, installation of precast culverts, formwork, reinforcement elements, roadworks.
   - 1.4. **Preliminary and general costs:** insurance costs; facilities for construction workers and engineers; security; planning, management, and compliance costs (earmarked for each stormwater infrastructure option in accordance with other capital expenditures).
   - 1.5. **Contingency:** allowance for additional expenses (earmarked for each stormwater infrastructure option in accordance with other capital expenditures).
2. **Maintenance cost:** maintenance expenditures needed to keep each stormwater infrastructure option at full capacity to absorb and channel stormwater. For the concrete culvert, this entails costs for heavy equipment and human resources cost for the excavator and truck driver. For the renaturalized stream, this entails equipment costs and human resources costs for the landscaper and gardener.

Benefits

3. **Avoided flood damages:** Extensive time series data on flood damages in Johannesburg is lacking. Therefore, historical but primarily anecdotal evidence on flood events in Johannesburg (see Section 2) was used to estimate the threshold for a flood indicator and to develop a flood index. This served to estimate damages to properties in a linear way in accordance with increasing water runoff values (see details in Annex A, Table A4, Table A5, and Table A6).

   Differences in flood damages and associated costs between the three stormwater infrastructure options occur as a result of varying water absorption capacities. Vegetated landscapes and permeable soils associated with the renaturalized stream enable temporary detainment of rainwater and enable it to infiltrate and absorb certain ranges of stormwater volumes better than a concrete culvert. If a threshold of 65 mm of runoff per day is surpassed (the threshold identified based on past flood events), the concrete culvert leads to significantly more stormwater runoff (54.8%) compared to the renaturalized stream (10.4%) and the hybrid solution (32.6%). Runoff is then used to determine the flood indicator and to estimate flood damage. The difference in flood damage costs between the three stormwater infrastructure options is accounted for in relative terms, taking the concrete culvert option as a baseline. This enables an estimate of the magnitude of flood damage costs that are avoided by the renaturalized and hybrid stormwater solutions compared to the baseline.

4. **Increased property values:** The renaturalized stream and surrounding vegetation have aesthetic value and enhance the quality of living in proximity to Paterson Park. These green spaces therefore increase the appeal of properties in the vicinity and are expected to have a positive effect on the value of properties in Orange Grove (35 properties), Norwood (2 properties), and Orchard (25 properties) (see details for assumptions in Annex A, Table A6, Figure A1, and Figure A2). Such expected value increases are also supported by studies conducted in other locations (Center for Neighborhood Technology & SB Friedman Development Advisors, 2020; Lategan & Cilliers, 2014; McCord et al., 2014). A one-time 2% value increase is assumed for the identified properties in case the renaturalized stream option or the hybrid stormwater solution is implemented. The calculated property value net changes do not account for potential market-driven, organic appreciation or depreciation of property values in these neighbourhoods over the coming years.

5. **Increased property tax revenues:** The assumed property value increases associated with the renaturalized stream option and the hybrid stormwater solution will lead to additional tax revenues for the city. Given the tax rates in each of the three districts and the assumed properties affected by a value increase, the additional property tax revenues are calculated (see details in Annex A, Table A3).

6. **Income creation:** The annual maintenance work for each of the three stormwater infrastructure options requires human labour, as noted above under position 2. This implies salary and hence income for employed people. This is estimated for the type of employment needed and based on the frequency of maintenance work (see details in Annex A, Table A8 and Table A9).

7. **Avoided cost of carbon:** Four different species of trees will be planted along the renaturalized stream. Each tree species has a specific rate of carbon sequestration, which is estimated and accumulated for the fully renaturalized stream option and the hybrid stormwater solution. Carbon sequestration implies that social costs associated with carbon emissions are being avoided. The social cost of carbon approach is applied to monetize the avoided carbon emissions associated with the renaturalized stream option and the hybrid stormwater solution (see details in Annex A, Table A10). The social cost of carbon is a top-down assessment of the economic cost caused by an additional tonne of carbon dioxide emissions or its equivalent through the carbon cycle (Gaspar et al., 2019; Nordhaus, 2017).

8. **Additional water supply**: The different stormwater infrastructure options allow for varying levels of rainwater infiltration. Renaturalization of the stream and the surface along the stream increases vegetation cover in the park area compared to implementing the concrete culvert. The more natural vegetation cover in an area, the more soil is penetrated by roots. As a consequence, more water can infiltrate the soil, which causes higher percolation rates and hence additional groundwater recharge. It is assumed that 67% of the additional percolation from renaturalizing the area will be available for extraction (= water supply) (see details in Annex A, Table A11). The value of additional water supply associated with the renaturalized stream option and the hybrid stormwater solution is calculated based on the average water sales price (per litre) in Johannesburg, which is ZAR 0.02696 (Fourie, 2017).

3.2 Climate Change Risk Scenarios for the Stormwater Infrastructure Options

A key endeavour of this SAVi assessment was to quantify the impact of physical climate change risks on the performance of the three stormwater infrastructure alternatives. This section outlines the climate change parameters analyzed as well as the climate models and scenarios applied to this assessment. Regional as well as location-specific precipitation data and projections for the City of Johannesburg were sourced from the Copernicus Climate Data Store.[2] For both, historical data (from 2000) and future projections (until 2100) were analyzed. The historical and present-day data are sourced from the Copernicus ECMWF Reanalysis 5th generation (ERA5) database and comprise mean monthly data, and the forecasts use Coupled Model Intercomparison Project Phase 5 (CMIP5) data on mean monthly precipitation flux. More specifically, median projections were used (C3S, 2017). The results are bias-corrected for each month of the year. For this SAVi assessment, results were obtained from an ensemble of nine climate models to determine four climate scenarios associated with common Representative Concentration Pathways (RCPs)[3]:

- **RCP 4.5:** The RCP 4.5 climate scenario assumes that emissions peak in 2040 and begin to decline thereafter. In this SAVi assessment, RCP 4.5 is used as the business -as-usual (BAU) climate scenario.
- **RCP 2.6:** The RCP 2.6 scenario assumes strong international climate action, including negative emissions (i.e., additional carbon sequestration). In this climate scenario, future impacts of GHG emissions on temperature and precipitation are more contained compared to the RCP 4.5 scenario.
- **RCP 6.0:** The RCP 6.0 scenario assumes some climate mitigation actions but lower ambitions than in the RCP 4.5 scenario. The RCP 6.0 scenario could be referred to as the middle ground

[2] The calculated climate change impacts in this SAVi assessment build on modified C3S (2020) data. Neither the European Commission nor the European Centre for Medium-Range Weather Forecasts (ECMWF) is responsible for any use that may be made of the Copernicus information or data it contains.

[3] RCPs describe four possible pathways of GHG emissions and atmospheric concentrations, air pollutant emissions, and land use for the 21st century. These four RCPs serve as inputs for various climate model simulations and are adopted by the Intergovernmental Panel on Climate Change.

between the RCP 4.5 and the RCP 8.5 scenarios in terms of the future impacts of GHG on precipitation and temperature.

- **RCP 8.5:** The RCP 8.5 scenario assumes that fossil fuel-intensive forms of energy generation continue to be used heavily through the remainder of the century.

The abovementioned climate scenarios are used to estimate the impacts of climate change variables (precipitation) on the performance of the stormwater infrastructure alternatives considered. Figure 3 illustrates the monthly precipitation projections of the four climate scenarios for the period between 2037 and 2057 in Johannesburg. Figure 4 highlights the absolute difference in precipitation levels of three climate scenarios compared to the RCP 4.5 scenario (BAU) over the same period. This period covers the second half of the stormwater infrastructure lifetime considered in this assessment and was chosen to illustrate the difference in precipitation between the different scenarios. Fewer differences in precipitation levels between the four climate scenarios can be recognized in the first 20 years (2018–2037) of the infrastructure lifetime.

The main performance parameters associated with stormwater infrastructure and altered by varying precipitation projections are:

- Avoided flood damage
- Water supply.

In this SAVi assessment, these two parameters are integrated as benefit parameters—see explanations for benefit parameters 3 and 8 in Section 3.1.

Figure 3. Monthly rainfall projections for Johannesburg under different climate scenarios, 2038–2057

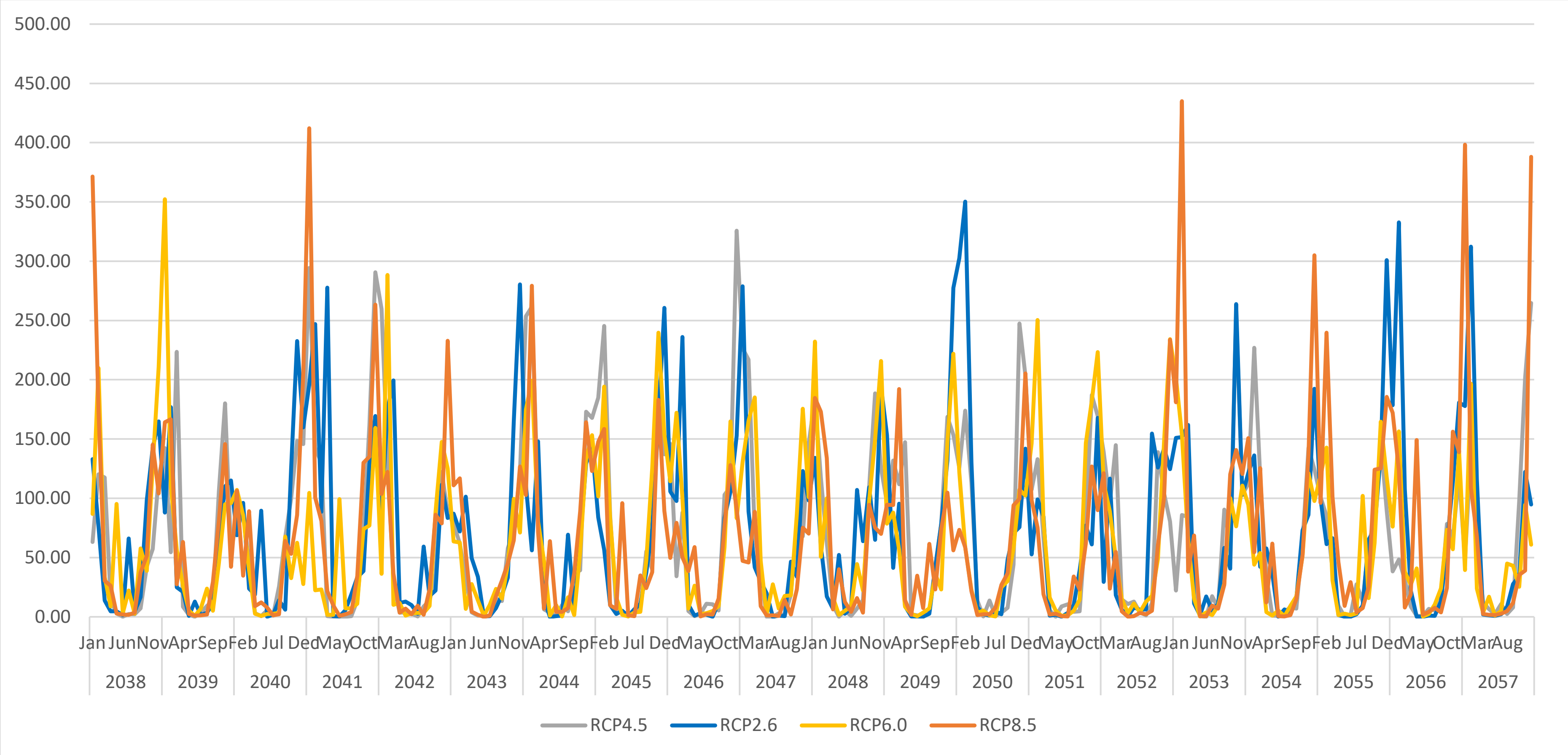
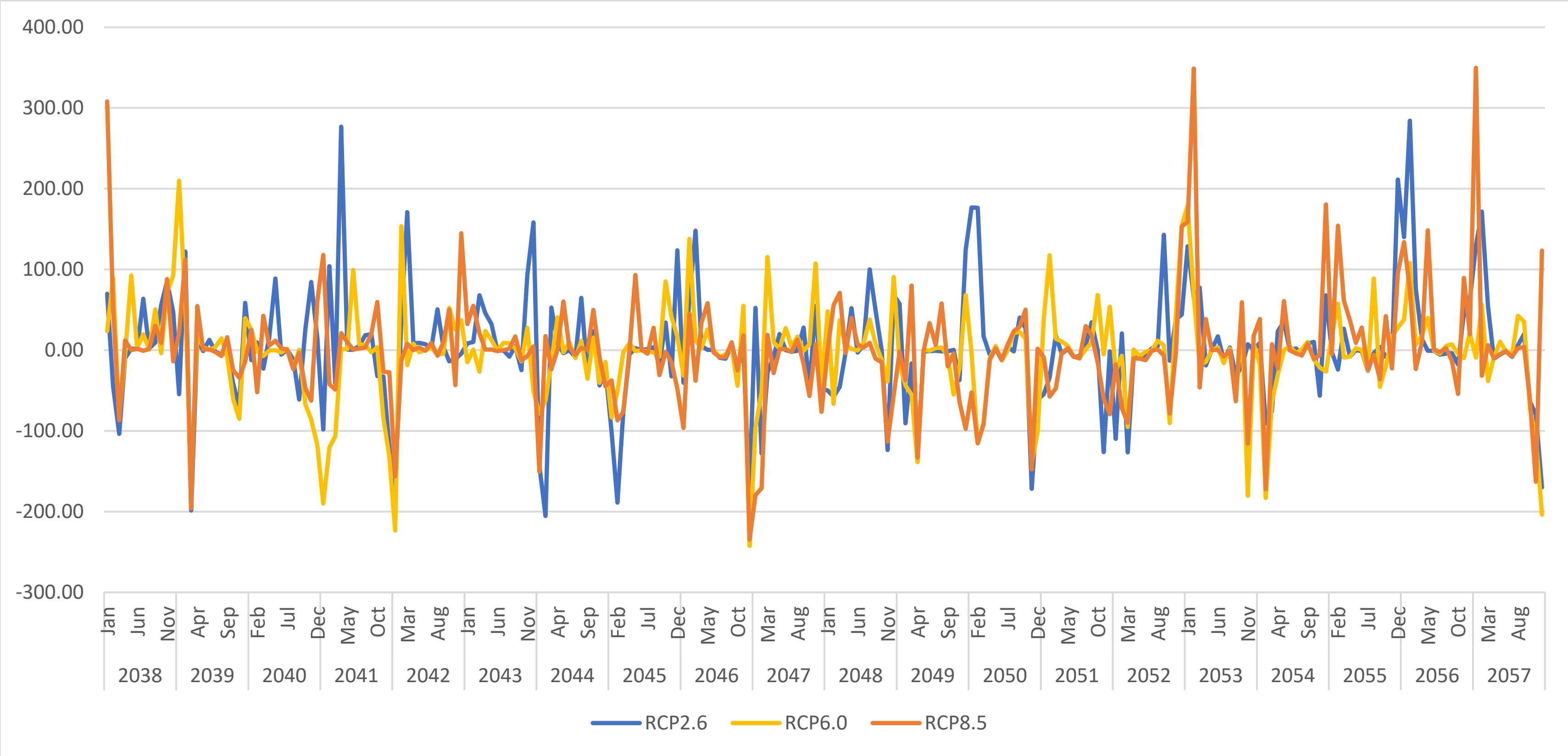


Figure 2. Absolute difference in monthly rainfall projections for Johannesburg under different climate scenarios compared to the RCP 4.5 scenario, 2037–2057



4. Results of the SAVi Assessment

This chapter presents the results of the integrated CBA conducted for the three stormwater infrastructure options:

- **Concrete culvert** (grey stormwater infrastructure)
- **Hybrid solution** (combination of a culvert and a renaturalized stream section, as implemented in the Paterson Park Precinct)
- **Renaturalized stream** (nature-based stormwater infrastructure).

Assumptions for the technical characteristics; capital requirements; and environmental, social, and economic co-benefits of the three alternatives are explained in Section 3 and listed in more detail in Annex A.

Still widely used, the grey culvert option is considered the baseline for analyzing the costs and benefits of the three stormwater infrastructure alternatives. Culverts channel stormwater up to the level of their design capacity. Flooding occurs once rainwater volumes exceed the culverts' capacity. Renaturalization aims at increasing vegetation cover and permeable surfaces, both of which increase water retention and, therefore, increase percolation and reduce flood risk. All avoided costs and benefits in the hybrid and full renaturalization options are assessed by comparing results obtained for the respective option against the results of the concrete culvert scenario.

The calculations of the CBA results are based on the customized SAVi model. Sections 4.1 and 4.2 present the integrated CBA results as well as the CBA results under various climate scenarios. First, the three stormwater infrastructure options are compared under the BAU climate scenario (RCP 4.5). For this purpose, the environmental, social, and economic benefits of each respective alternative are integrated into the CBA (Chapter 4.1). Second, the performance impacts of precipitation variations on the magnitude of (co-)benefits of the three alternatives are presented under four different climate scenarios (Chapter 4.2).

4.1 Results of the Integrated CBA

Table 2 presents the undiscounted CBA results of the three stormwater infrastructure options under a BAU climate scenario (RCP 4.5) over a 20-year period. Table 3 presents the same results when evaluating a 40-year time period. The total costs of the concrete culvert amount to more than ZAR 85 million and are hence the highest among the three options, primarily due to high upfront construction costs. The lowest costs are associated with the renaturalized stream (almost ZAR 45 million), while the hybrid solution ranges in between, given that it consists of a culvert section and a renaturalized stream section. Capital costs for each stormwater infrastructure option remain the same irrespective of the considered time horizon.

Maintenance expenditures over the respective lifetimes are highest for the renaturalized stream due to an assumed higher frequency of maintenance work to keep this green infrastructure in an urban context intact. The maintenance costs for each stormwater infrastructure option are twice as high over a 40-year time horizon compared to a 20-year time horizon.

A range of environmental, social, and economic benefits was assessed for each infrastructure option to provide a more holistic view for urban planning decisions and allow for an evaluation of public stormwater infrastructure alternatives from a societal standpoint.

Benefit estimates indicated in Table 2 and Table 3 demonstrate that the renaturalized stream yields the highest benefits by far over the respective time horizons, followed by the hybrid stormwater solution. The most significant benefit factor, in monetary terms, is the avoidance of flood damages in the case of a renaturalized stream and, to a lower extent, in the case of the hybrid stormwater solution. The renaturalization of the urban stream enhances the infiltration and absorption capacity of the urban landscapes due to increased vegetation cover. The additional absorption capacity temporarily detains rainwater and ultimately reduces runoff volumes and the risk of flooding during extreme rain events. It essentially functions as stormwater management infrastructure that helps to reduce flood events in the Paterson Park Precinct and surrounding neighbourhoods (Orange Grove, Norwood, and Orchard) compared to the baseline stormwater infrastructure scenario (a concrete culvert). A flood event occurs in the precinct when runoff values exceed a threshold of 65 mm per day. The concrete culvert is characterized by a limited stormwater carrying capacity (design capacity) and high runoff values due to the low permeability of surrounding areas. The concrete culvert investment option maintains the status quo, including the occurrence of flood events and damages to properties if the precipitation threshold is exceeded (= zero avoided flood damages), whereas renaturalization and the hybrid option reduce peak runoff values and hence provide more resilience to the neighbourhoods and avoid flood damages. Full renaturalization of the stream avoids approximately ZAR 103 million in flood damage costs over a 20-year time period and more than ZAR 184 million over a 40-year period, respectively. The hybrid solution yields almost ZAR 87 million and ZAR 168 million over the same time horizons.

It should be noted that, among the benefits considered, avoided flood damages make up between 73.6% (renaturalized stream) and 81.3% (hybrid solution), which is considerable. In the hybrid solution, net benefits excluding avoided flood damages would amount to around ZAR 20 million. Without avoided flood damages, the net result for the hybrid solution is indicated at a net cost of ZAR 42.84 million. In the full renaturalization scenario, however, the project still generates net benefits of almost ZAR 37 million, which would be sufficient to cover the indicated capital expenditure. If operation and maintenance costs are considered as well, the net result is a net cost of around ZAR 8 million over the next 20 years.

Table 2. Integrated CBA results (in ZAR million) for three stormwater infrastructure options under the BAU climate scenario (20 years, undiscounted results)

	Concrete culvert (ZAR million)	**Hybrid solution** (ZAR million)	**Renaturalized stream** (ZAR million)
Costs			
(1) Capital cost	**84.67**	**58.62**	**37.78**
(1.1) Renaturalization of the stream	*0.00*	*11.75*	*21.16*
(1.2) Landscaping cost	*0.00*	*2.06*	*3.71*
(1.3) Culvert construction	*55.97*	*24.88*	*0.00*
(1.4) Preliminary and general costs	*17.18*	*11.93*	*7.73*
(1.5) Contingency	*11.52*	*8.00*	*5.18*
(2) Maintenance cost	0.37	4.14	7.15
Total cost	**85.04**	**62.76**	**44.93**
Benefits			
(3) Avoided flood damages	0.00	86.64	102.88
(4) Increased property values	0.00	2.12	2.12
(4.1) Orange Grove	*0.00*	*0.77*	*0.77*
(4.2) Norwood	*0.00*	*0.08*	*0.08*
(4.3) Orchards	*0.00*	*1.27*	*1.27*
(5) Increased property tax revenues	0.00	0.18	0.18
(5.1) Orange Grove	*0.00*	*0.10*	*0.10*
(5.2) Norwood	*0.00*	*0.01*	*0.01*
(5.3) Orchards	*0.00*	*0.07*	*0.07*
(6) Income creation	0.01	2.89	5.20
(7) Avoided cost of carbon	0.00	0.12	0.22
(8) Additional water supply	0.00	14.61	29.23
Total benefits	**0.01**	**106.56**	**139.83**
Net results	**-85.02**	**43.81**	**94.90**
Benefit over cost (ZAR return per ZAR invested)	**–**	**1.7**	**3.1**

The second most considerable benefit factor in monetary terms is the additional water supply resulting from renaturalizing a stream section. The renaturalization increases vegetation cover, which in turn leads to higher percolation rates and hence improved groundwater recharge. A fraction of this becomes available as additional water supply to Johannesburg and surrounding areas. Given that the geology underlying the northern part of Johannesburg is mostly granite with very low storativity, direct recharge of groundwater cannot be assumed. However, the water infiltrated into the soil will later recharge nearby streams and contribute to maintaining the storage volume at dams (and become available for extraction). As the hybrid stormwater option includes a smaller renaturalized stream section (420 m) compared to the full renaturalization option (756 m), the yield of additional water supply and the associated monetary benefits are respectively smaller. The hybrid solution yields additional water supply worth ZAR 14.6 million (20 years) and ZAR 27.8 million (40 years), whereas the renaturalized stream yields additional water supply worth ZAR 29.3 million (20 years) and ZAR 55.5 million (40 years).

Other benefit factors are less significant in absolute terms but still contribute to the improved net results of the hybrid solution and the renaturalized stream. These are, in descending order of magnitude: income creation from regular maintenance work, increased property values in proximity to the renaturalized Paterson Park area, avoided cost of carbon due to the carbon sequestration of planted trees along the stream and increased property tax revenues for the city due to the higher property values in proximity to the renaturalized area. While income generation is listed as a separate benefit, as the labour intensity of the assets differs, labour costs for construction and maintenance are accounted for in the total capital and operation and maintenance costs indicated in the costs section of the table.

In total, the concrete culvert option yields negative net results (ZAR -85 million) over both assessed time periods because this grey infrastructure solution requires high capital expenditures while not delivering any additional environmental, social, or economic benefits—the only exception being some income generation effects due to maintenance work. The hybrid stormwater solution and the renaturalized stream option, on the other hand, both deliver a range of environmental, social, and economic benefits and therefore yield positive net results. This can also be expressed as a benefit over cost indicator or return on investment indicator: implementing the hybrid stormwater solution implies that ZAR 1.7 is generated per ZAR 1 invested when considering a 20-year time frame. This increases to ZAR 3.1 per ZAR 1 invested over a 40-year time horizon. The same return on investment figure is being generated by the full renaturalized stream solution already over a 20-year time frame, while it yields ZAR 4.9 per ZAR 1 invested over a 40-year time horizon.

Similar to the 20-year CBA presented above, avoided flood damages still make up between 72.7% (renaturalized stream) and 82.2% (hybrid solution). While the net result for the hybrid solution would still be negative after 40 years (ZAR -30.63 million), the results for the renaturalized option indicate a net benefit of ZAR 16.75 million, even if avoided flood damages are excluded. The additional percolation resulting from higher permeability in the renaturalized stream option contributes to higher recharge of water reservoirs in surrounding areas. The additional water generates an estimated economic benefit of ZAR 55.52 million, which outweighs the total cost of the project by around ZAR 3.4 million.

Table 3. Integrated CBA results (in ZAR million) for three stormwater infrastructure options under the BAU climate scenario (40 years, undiscounted results)

	Concrete culvert (ZAR million)	**Hybrid solution** (ZAR million)	**Renaturalized stream** (ZAR million)
Costs			
(1) Capital cost	**84.67**	**58.62**	**37.78**
(1.1) Renaturalization of the stream	*0.00*	*11.75*	*21.16*
(1.2) Landscaping cost	*0.00*	*2.06*	*3.71*
(1.3) Culvert construction	*55.97*	*24.88*	*0.00*
(1.4) Preliminary and general costs	*17.18*	*11.93*	*7.73*
(1.5) Contingency	*11.52*	*8.00*	*5.18*
(2) Maintenance cost	0.73	8.27	14.31
Total cost	**85.40**	**66.89**	**52.09**
Benefits			
(3) Avoided flood damages	0.00	167.86	184.10
(4) Increased property values	0.00	2.12	2.12
(4.1) Orange Grove	*0.00*	*0.77*	*0.77*
(4.2) Norwood	*0.00*	*0.08*	*0.08*
(4.3) Orchards	*0.00*	*1.27*	*1.27*
(5) Increased property tax revenues	0.00	0.36	0.36
(5.1) Orange Grove	*0.00*	*0.20*	*0.20*
(5.2) Norwood	*0.00*	*0.02*	*0.02*
(5.3) Orchards	*0.00*	*0.14*	*0.14*
(6) Income creation	0.01	5.77	10.39
(7) Avoided cost of carbon	0.00	0.24	0.43
(8) Additional water supply	0.00	27.76	55.52
Total benefits	0.01	**204.12**	**252.94**
Net results	**-85.37**	**137.23**	**200.85**
Benefit over cost (ZAR return per ZAR invested)	**–**	**3.1**	**4.9**

CBA results have also been calculated under consideration of a discount rate to account for opportunity costs of investment alternatives and the value of time. The CBA results under the condition of a 5% discount factor are presented in Annex B. The overall conclusions and superiority of the renaturalized stream option are not altered when applying a discount factor. However, the net results of the renaturalized stream and the hybrid stormwater solution are significantly lower when applying a discount factor because benefits occur over time, whereas costs occur primarily upfront. Therefore, discounting primarily decreases the magnitude of benefits (that occur in the future), whereas capital costs remain the same (only maintenance costs are affected by discounting). The adverse effect of discounting is most striking when comparing the net results of the renaturalized stream over a 40-year time frame: if not discounted, this nature-based infrastructure option yields a net result of more than ZAR 200 million. If a 5% discount rate is applied, the net result for the same infrastructure option is less than ZAR 78 million (see Table B2 in Annex B).

Finally, it needs to be noted that renaturalizing a stream and increasing associated vegetation in urban areas can unleash more benefit factors than the ones that were quantified and valued in this assessment—benefit positions 3 to 8 indicted in the CBA tables. Additional benefit factors associated with investing in stream renaturalization are:

- **Local air quality improvements,** as vegetation reduces the ambient concentration of air pollutants, which implies positive public health benefits.
- **Local reduction of the urban heat island effect** due to the water stream and surrounding vegetation, which again can imply positive human health impacts.
- **Water quality improvements** through natural self-purification effects in the natural stream and due to tree canopies and other plants reducing the volume of runoff carrying pollutants and high nutrient loadings.
- **Recreational value** of green spaces, such as the renaturalized stream, because these stimulate citizens to become more physically active and spend time in nature, which has positive effects on public health.
- **Positive local economy effects** due to increasing the number of visitors with spending capacity.
- **Lower insurance premiums** for property and/or real estate owners due to lower flood and damage risks.

Due to a lack of local data for quantifying and monetizing these benefit factors in Johannesburg, they were not included in this SAVi assessment and the customized CBA. However, such benefit factors should not be omitted; rather, local data collection and research have to be advanced for improved urban planning and stormwater management that generates the most possible value for the local population and economies.

4.2 Results of the CBA Under Different Climate Scenarios

4.2.1 Three Stormwater Infrastructure Options Under Different Climate Scenarios

For this SAVi assessment, regional as well as location-specific precipitation data and projections for the project area were sourced from the Copernicus Climate Data Store. As introduced in Chapter 3.2, four climate scenarios and associated precipitation variations over time were assessed for each of the three stormwater infrastructure alternatives: RCP 4.5 (BAU), RCP 2.6, RCP 6.0, and RCP 8.5. This section first summarizes the results when comparing the three stormwater infrastructure options under different climate scenarios and then presents the performance results of each stormwater infrastructure alternative in more detail. Tables presenting the quantitative CBA results (undiscounted and discounted results) under the various climate scenarios are included in Annex B.

Figure 6 and Figure 7 present the magnitude of various cost and benefit factors of the three stormwater infrastructure options under the four climate scenarios over 20- and 40-year time horizons, respectively. Result bars indicated with the RCP 4.5 scenario reflect the CBA results presented in Section 4.1, as this is considered the BAU climate scenario. The other three climate scenarios are characterized by precipitation variations compared to the BAU climate scenario.

The overall superior performance (magnitude of benefits over costs) of the renaturalized stream option across the four climate scenarios compared to the performance of the hybrid stormwater solution—and in particular compared to the concrete culvert option—is striking. Under each climate scenario, the renaturalized stream attains the highest magnitude of benefits compared to the benefits of the other two stormwater options. This superiority holds true over the 20- and 40-year time horizons. One needs to recall that the benefits for each option are estimated relative to a baseline scenario, which is characterized by a concrete culvert with limited stormwater design capacity. The capital and maintenance costs remain stable for each stormwater infrastructure option irrespective of the climate scenario, while capital costs are lowest for the renaturalized stream option. Only maintenance costs increase proportionally when comparing the 20- and 40-year time horizons. The fully nature-based stormwater infrastructure solution therefore provides the most value for money and is the most appealing investment choice for addressing stormwater management irrespective of climate variations and associated risks.

Figure 3. Costs and benefits of three stormwater infrastructure solutions under four climate scenarios (20 years, undiscounted)

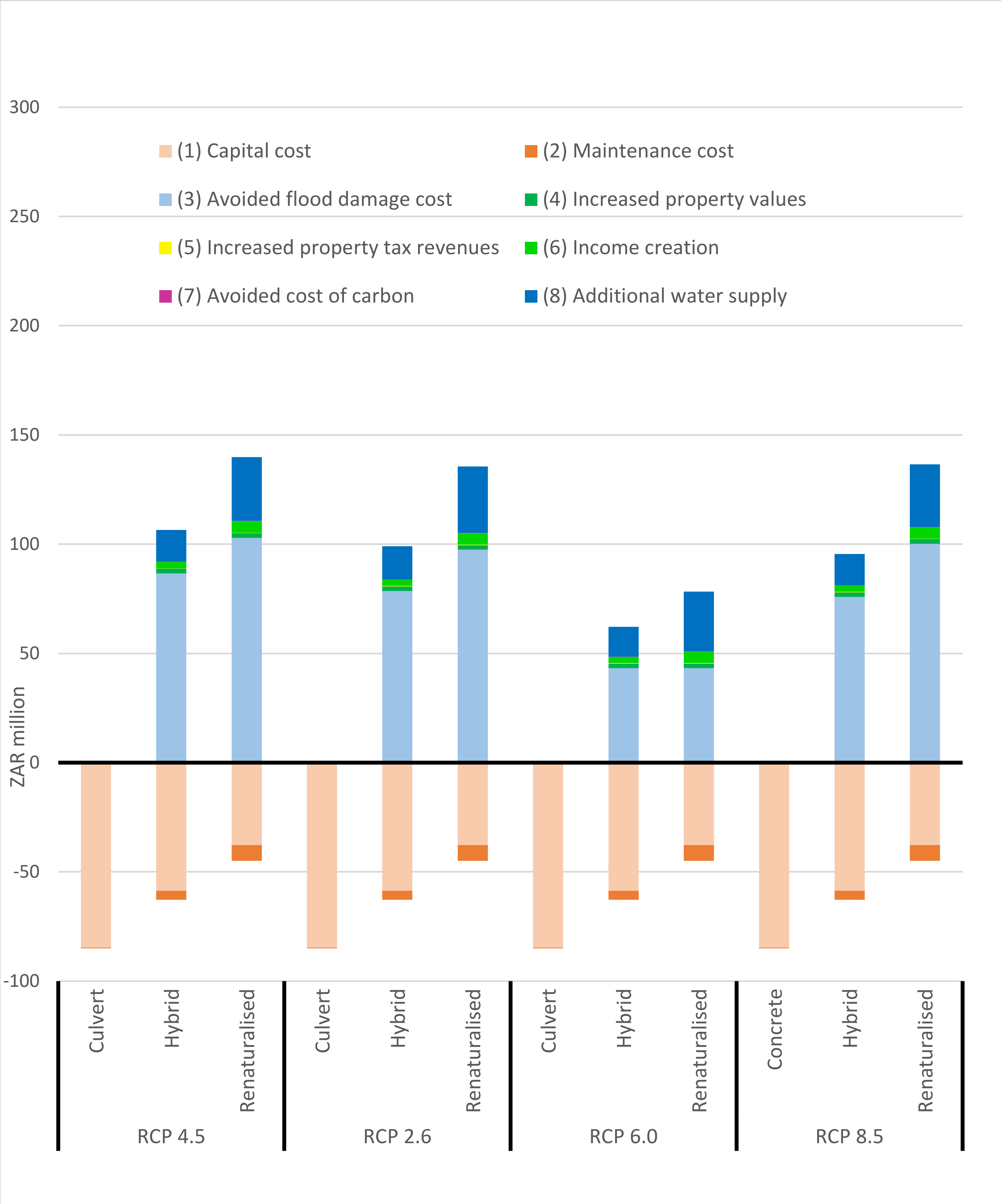
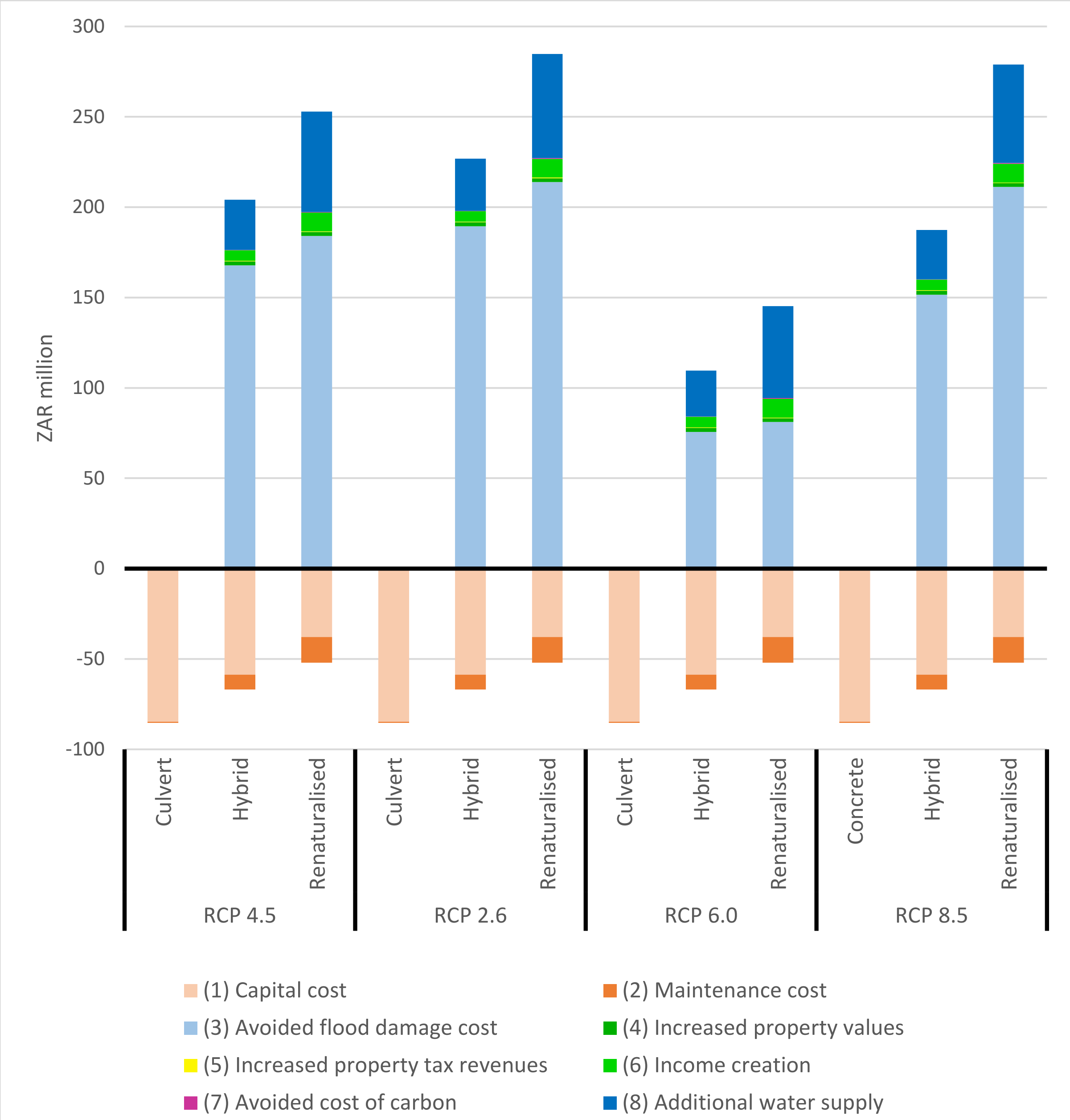


Figure 4. Costs and benefits of three stormwater infrastructure solutions under four climate scenarios (40 years, undiscounted)



4.2.2 Concrete Culvert: Grey stormwater infrastructure

Table 4 presents the CBA results of the concrete culvert option under the four climate scenarios over a 20-year time horizon. It is evident that climate variations under different scenarios have no positive or negative implications for the CBA results of the concrete culvert—the results remain the same across all four scenarios. This, however, does not suggest that the performance of the grey stormwater infrastructure is not affected (adversely) by the impacts of climate change. The constant results indicated in Table 4 are due to the set-up of this assessment and the related lack of sufficient data—for example, how extreme weather events affect maintenance and/or replacement costs for concrete culverts in Johannesburg.

Rather than estimating for each infrastructure alternative the absolute flood damage costs incurred due to prospectively higher frequency of extreme rain events, the CBA provides information about the absolute difference in flood-related damage costs between the three infrastructure options. The assumption is that flood damages can occur if the stormwater absorption capacity of a concrete culvert (baseline) is insufficient. Benefit position 3*, avoided flood damages,* reflects the amount of flood damage costs avoided by each stormwater infrastructure option relative to the baseline due to a given stormwater absorption capacity. Since the concrete culvert is defined as the baseline, this infrastructure option does not avoid additional flood damage costs, indicated with zero under benefit position 3. The same logic applies to benefit position 8, *additional water supply.* Other benefit factors considered in the integrated CBA are simply not provided by a regular concrete culvert, including property value increases, property tax revenue increases, and avoidance of societal costs caused by carbon emissions. Only position 6, *income creation,* is a benefit position that also applies to a concrete culvert due to the maintenance needs.

Undiscounted CBA results over a 40-year time horizon only differ slightly for the concrete culvert, as solely maintenance costs (2) and income creation (6) increase proportionally with time; other results remain constant. Likewise, the discounted CBA results over a 20-year time horizon are only slightly lower compared to the undiscounted 20-year time horizon because the bulk of expenses occur at the beginning of the lifetime and are hence not affected by discounting. Again, solely maintenance costs (position 2) and income creation (position 6) are affected because these occur over the lifetime of the concrete culvert and are hence affected by a discount rate, implying that the discounted results are slightly lower than the undiscounted CBA results. The same logic applies to results over a 40-year time horizon.

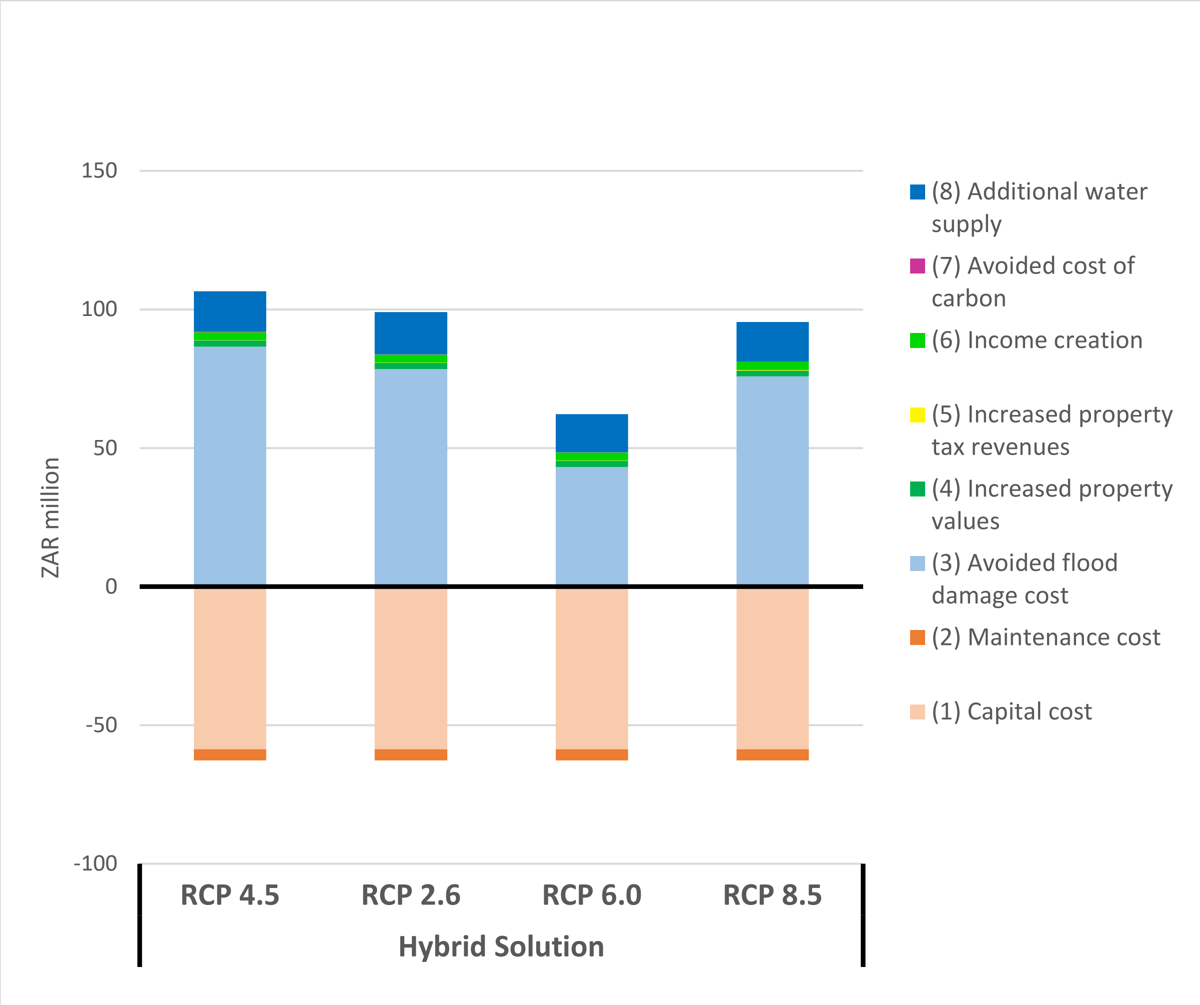
Table 4. CBA results (in ZAR million) for the concrete culvert under different climate scenario (20 years, undiscounted results)

Concrete culvert	**RCP 4.5 (BAU)**	**RCP 2.6**	**RCP 6.0**	**RCP 8.5**
Costs				
(1) Capital cost	84,672,230	84,672,230	84,672,230	84,672,230
(1.1) Renaturalization of the stream	*0*	*0*	*0*	*0*
(1.2) Landscaping cost	*0*	*0*	*0*	*0*
(1.3) Culvert construction	*55,973,510*	*55,973,510*	*55,973,510*	*55,973,510*
(1.4) Preliminary and general costs	*17,178,720*	*17,178,720*	*17,178,720*	*17,178,720*
(1.5) Contingency	*11,520,000*	*11,520,000*	*11,520,000*	*11,520,000*
(2) Maintenance cost	366,174	366,174	366,174	366,174
Total cost	**85,038,404**	**85,038,404**	**85,038,404**	**85,038,404**
Benefits				
(3) Avoided flood damages	0	0	0	0
(4) Increased property values	0	0	0	0
(5) Increased property tax revenues	0	0	0	0
(6) Income creation	6,943	6,943	6,943	6,943
(7) Avoided cost of carbon	0	0	0	0
(8) Additional water supply	0	0	0	0
Total benefits	**19,202**	**19,202**	**19,202**	**19,202**
Net results	**- 85,019,202**	**- 85,019,202**	**- 85,019,202**	**- 85,019,202**
Benefit over cost (ZAR return per ZAR invested)	**–**	**–**	**–**	**–**

4.2.3 Hybrid Stormwater Infrastructure Solution

Figure 7 illustrates the magnitude of various cost and benefit factors of the hybrid stormwater infrastructure solution under four climate scenarios over a 20-year time horizon relative to the baseline stormwater management capacity. While the capital and maintenance expenditures do not vary across the four climate scenarios, variations for two benefit factors can be observed. The most significant variations can be noticed for the avoided flood damages (light blue bar). When comparing the four climate scenarios, by far the lowest amount of avoided flood damages is forecasted for the RCP 6.0 scenario. In this climate scenario, precipitation events above the flood threshold are more frequent compared to the other climate scenarios, which leads to greater flood damages and hence reductions in damages avoided from floods relative to the baseline situation.

Figure 7. Costs and benefits of a hybrid stormwater solution under four climate scenarios (20 years, undiscounted)



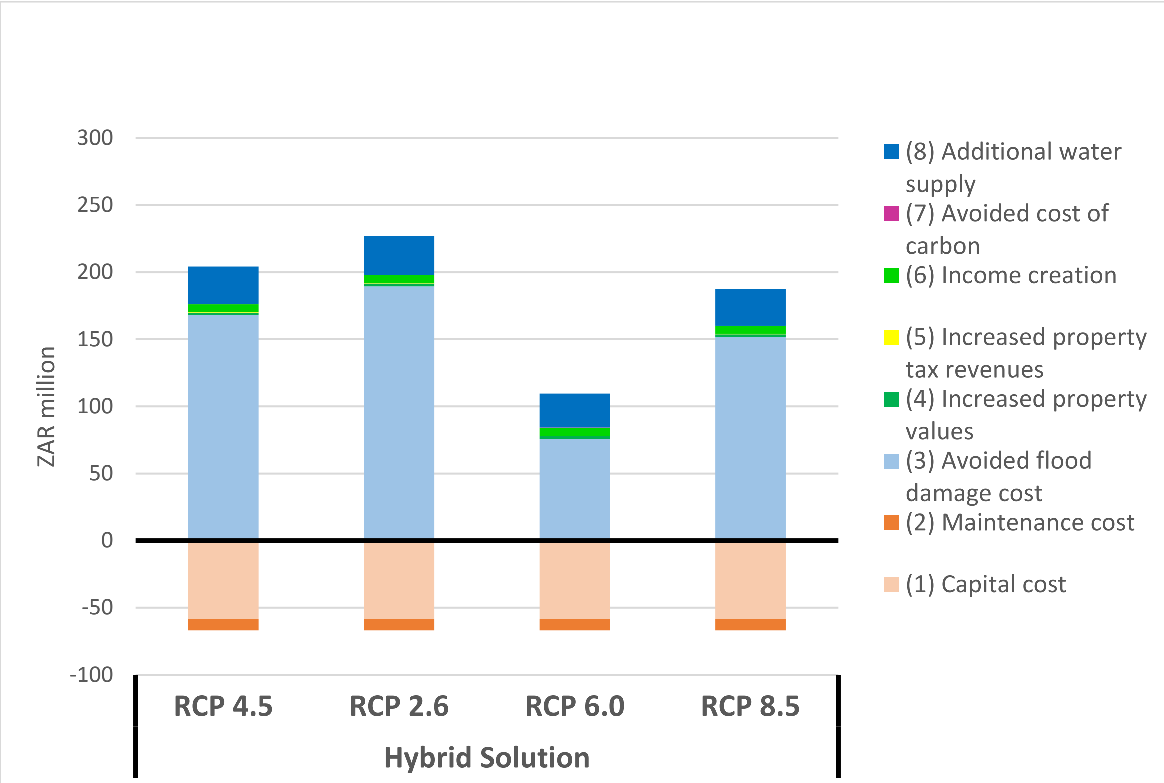
The other variation applies to the benefit factor "additional water supply." The variations are less pronounced across the climate scenarios and hence can hardly be observed in Figure 7, but results in Table 5 indicate the percentage deviation of each climate scenario compared to the BAU climate scenario (RCP 4.5) for this benefit factor. One can recognize that the RCP 2.6 scenario yields the highest additional water supply over a 20-year time horizon, while both the RCP 8.5 and the RCP 6.0 yield less additional water supply compared to the BAU climate scenario. This indicates that (i) the total water volume in the RCP 2.6 scenario is higher compared to the RCP 4.5 scenario while extreme events are more frequent (more additional water supply, less avoided flood damages), as opposed to (ii) a decline in total water volume compared to the RCP 4.5 scenario and a higher frequency of extreme events observed in the RCP 6.0 and RCP 8.5 scenarios.

Table 5. Selected benefits and net results of a hybrid stormwater solution under four climate scenarios (20 years, undiscounted)

Hybrid solution	**RCP 4.5 (BAU)**	**RCP 2.6**	**RCP 6.0**	**RCP 8.5**
Benefits	Absolute value	Percentage change compared to BAU		
(3) Avoided flood damages	ZAR 86.6 m	-9.4%	-50.1%	-12.5%
(8) Additional water supply	ZAR 14.6 m	3.8%	-6.3%	-1.9%
Net results (in ZAR million)	**43.81**	**36.24**	**-0.54**	**32.70**

In total, the highest net result for the hybrid stormwater solution over a 20-year time horizon is attained under the RCP 4.5 scenario (ZAR 43.8 million), followed by the net results under the RCP 2.6 and RCP 8.5 scenarios. Only the materialization of the RCP 6.0 climate scenario would imply negative net results for the hybrid stormwater solution over a 20-year time horizon.

Figure 8. Costs and benefits of a hybrid stormwater infrastructure solution under four climate scenarios (40 years, undiscounted)



The net results for the hybrid stormwater solution differ when evaluating a 40-year time horizon, as illustrated in Figure 8 and Table 6. The RCP 2.6 scenario yields the highest net results, as the hybrid stormwater solution would avoid more flood damages and enable higher levels of "additional water supply" under the climate projections of this climate scenario compared to the other three climate scenarios. This is the case because, as opposed to the results of the 20-year period described above, the overall frequency of extreme precipitation events over a 40-year period is lower under the RCP 2.6 climate scenario (compared to the RCP 4.5 scenario). The overall total precipitation remains higher under the RCP 2.6 climate scenario. The hybrid stormwater solution can avoid certain flooding events that would otherwise occur in the baseline situation during heavy precipitation events (> 65 mm per day). But the hybrid solution itself has a limited capacity for absorbing stormwater and cannot handle each rainfall severity level. Flooding and the associated damages can still occur—which can be observed under the RCP 4.5 and RCP 8.5 scenarios and even more in the RCP 6.0 scenario. The absorption capacity of the hybrid stormwater solution is comparatively less often surpassed under the RCP 2.6 scenario when evaluating the 40-year time horizon.

The RCP 4.5 climate scenario yields the second-highest net results, followed by the RCP 8.5 scenario and the RCP 6.0 scenario. While the RCP 6.0 scenario yields by far the lowest net results, the 40-year time horizon is still sufficiently long for generating more benefits in monetary terms compared to the costs needed for implementing and maintaining the hybrid stormwater solution (as opposed to the 20-year time horizon, which does not yield more benefits than costs—see net results in Table 6).

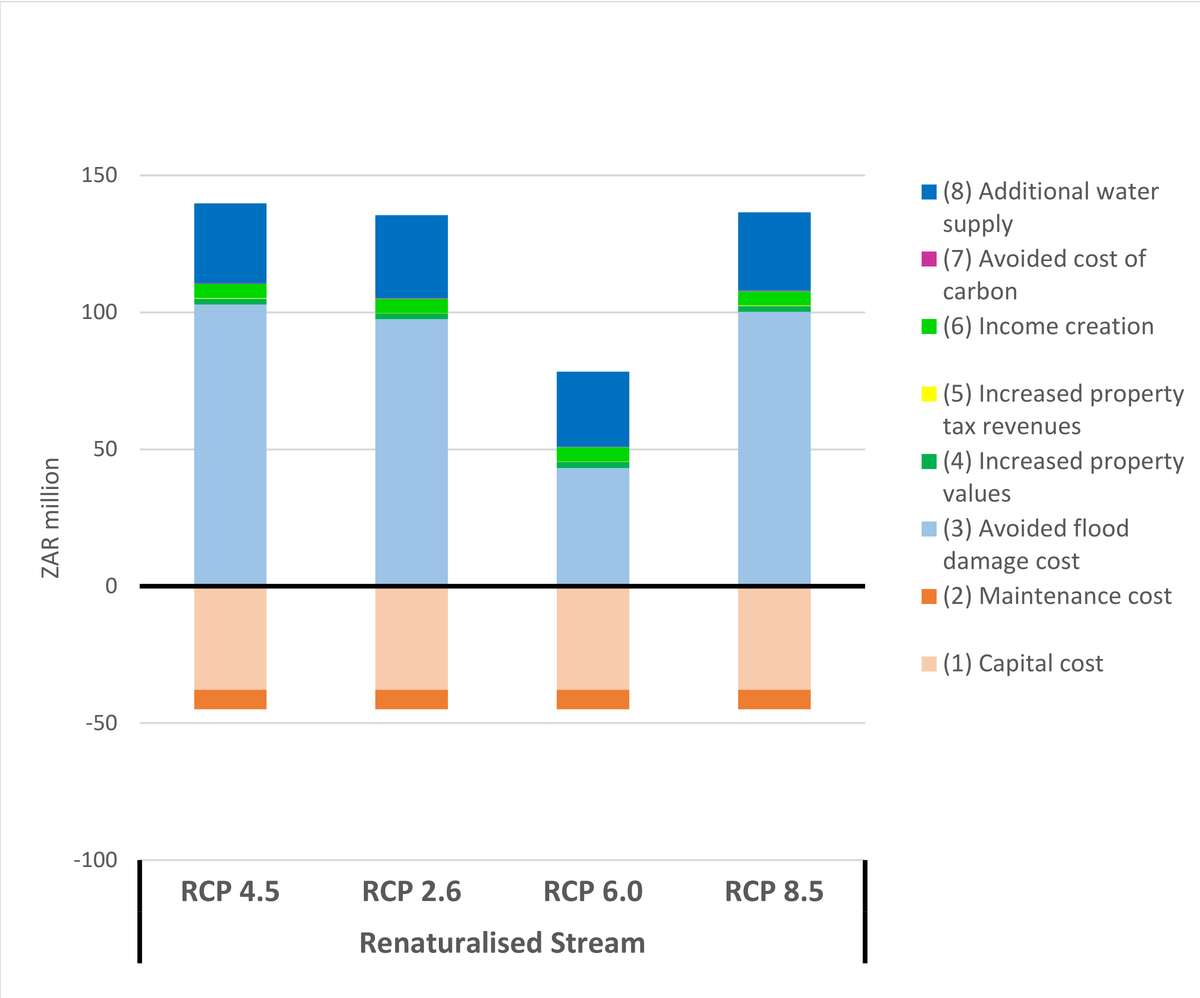
Table 6. Selected benefits and net results of a hybrid stormwater solution under four climate scenarios (40 years, undiscounted)

Hybrid solution	**RCP 4.5 (BAU)**	**RCP 2.6**	**RCP 6.0**	**RCP 8.5**
Benefits	Absolute value	Percentage change compared to BAU		
(3) Avoided flood damages	ZAR 167.9 m	12.9%	-54.9%	-9.7%
(8) Additional water supply	ZAR 27.8 m	3.6%	-8.3%	-1.9%
Net results (in ZAR million)	**137.23**	**159.90**	**42.75**	**120.46**

4.2.4 Renaturalized Stream: Nature-based stormwater infrastructure

Figure 9 illustrates the magnitude of various cost and benefit factors of the renaturalized stream option under four climate scenarios over a 20-year time horizon. While the capital and maintenance expenditures do not vary across the four climate scenarios, variations for two benefit factors can be observed—as is the case for the hybrid stormwater solution. The most significant variations can be noticed for the avoided flood damages (light blue bar). When comparing the four climate scenarios, by far the lowest amount of avoided flood damages is provided under the RCP 6.0 scenario. In fact, over a 20-year time horizon, exactly the same amount of avoided flood damage cost (ZAR 43.2 million) is provided by the renaturalized stream option and the hybrid stormwater solution under the RCP 6.0 scenario (see results under RCP 6.0 indicated in Figure 5 at the beginning of Section 4.2). This suggests that the more severe precipitation events under this climate scenario cause floods and damages irrespective of whether a hybrid or a fully renaturalized stream solution is implemented. Under all other climate scenarios, the renaturalized stream option avoids a higher amount of flood damages compared to the hybrid solution because the threshold for flood damages of the hybrid stormwater solution is more often surpassed than the threshold level of the renaturalized stream.

Figure 9. Costs and benefits of a renaturalized stream under four climate scenarios (20 years, undiscounted)



Furthermore, one can observe that over a 20-year time horizon, the renaturalized stream yields very similar amounts of flood damage avoidance across the RCP 4.5, RCP 2.6, and RCP 8.5 scenarios. This suggests that while precipitation volumes and patterns are different when comparing the scenarios, overall, the frequency of triggered flood events over a 20-year time horizon is similar. A stronger variation can be recognized when considering a 40-year time horizon (see Figure 10). Avoided flood damages vary strongly across the four climate scenarios, whereas the largest amounts are avoided under the RCP 2.6 and RCP 8.5 scenarios. Under the RCP 4.5 scenario there are more extreme rainfall events, leading to more flood damages.

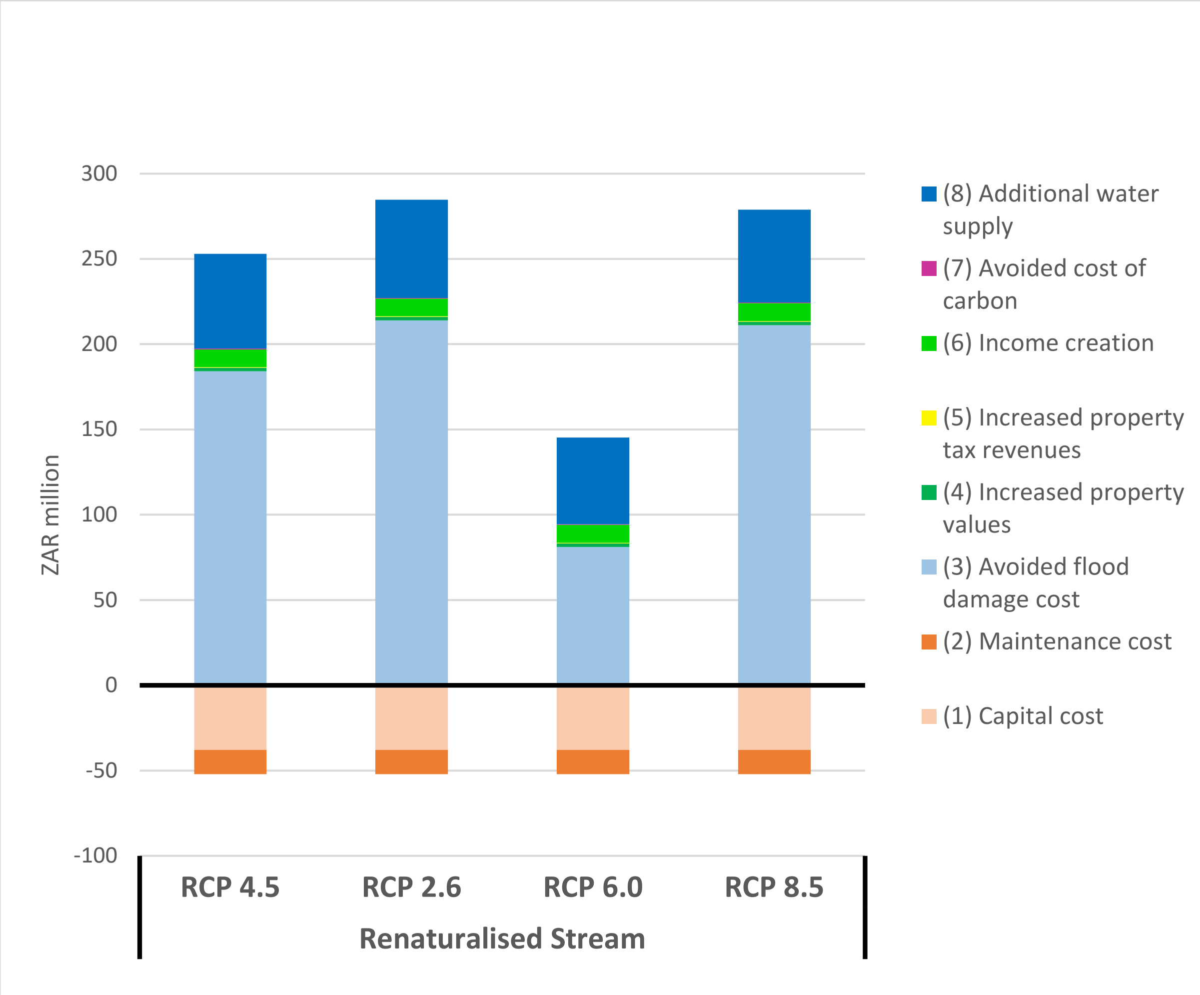
Table 7. Selected benefits and net results of a renaturalized stream under four climate scenarios (20 years, undiscounted)

Renaturalized stream	**RCP 4.5 (BAU)**	**RCP 2.6**	**RCP 6.0**	**RCP 8.5**
Benefits	Absolute value	Percentage change compared to BAU		
(3) Avoided flood damages	ZAR 102.88m	-5.3%	-58.0%	-2.6%
(8) Additional water supply	ZAR 29.23m	3.8%	-6.3%	-1.9%
Net results (in ZAR million)	**94.90**	**90.59**	**33.38**	**91.63**

The second benefit factor characterized by some variations in magnitude across the four climate scenarios is “additional water supply.” The variations are not very strong but can be recognized in Table 7, which highlights the percentage of deviation of each climate scenario compared to the BAU climate scenario (RCP 4.5). One can recognize that the RCP 2.6 scenario yields the highest additional water supply over a 20-year time horizon while the RCP 6.0 yields the lowest volume. This is due to the difference in rainfall volume between the climate scenarios.

The net results of the renaturalized stream options remain relatively constant across the RCP 4.5, RCP 2.6, and RCP 8.5 scenarios. Under the RCP 6.0 scenario, the net results are significantly lower because the overall volumes of total rainfall are lower, resulting in comparatively lower net benefits under that scenario.

Figure 10. Costs and benefits of a renaturalized stream under four climate scenarios (40 years, undiscounted)



Over a 40-year time horizon, the renaturalized stream option ensures a higher amount of flood damage avoidance under each climate scenario compared to the hybrid solution. When comparing the performance results of the renaturalized stream across the four climate scenarios over a 40-year time horizon, similar insights apply as for the 20-year time horizon: benefits, and hence net results, are lowest under the RCP 6.0 scenario.

However, one difference is that the renaturalized stream option generates higher benefits and higher net results under both the RCP2.6 and the RCP8.5 scenarios compared to the results generated under an RCP4.5 scenario. This can primarily be explained with the overall lower frequency of extreme precipitation events over a 40-year period under the RCP 2.6 and the RCP 8.5 climate scenarios (compared to the RCP 4.5 scenario). This implies that under those two scenarios, more flood damages can be avoided relative to the baseline (concrete culvert), as opposed to the magnitude of flood damages that can be avoided under the RCP 4.5 climate scenario.

Table 8: Selected benefits and net results of a renaturalized stream under four climate scenarios (40 years, undiscounted)

Renaturalized stream	**RCP 4.5 (BAU)**	**RCP 2.6**	**RCP 6.0**	**RCP 8.5**
Benefits	Absolute value	Percentage change compared to BAU		
(3) Avoided flood damages	ZAR 184.10m	16.2%	-55.9%	14.7%
(8) Additional water supply	ZAR 55.52m	3.6%	-8.3%	-1.9%
Net results (in ZAR million)	**200.90**	**232.66**	**93.23**	**226.90**

The renaturalized stream option attains overall superior performance results (magnitude of benefits over costs) across the four climate scenarios compared to the performance of the other two stormwater options. This holds true under each climate scenario and irrespective of the time horizon analyzed. The fully nature-based infrastructure solution for stormwater management therefore provides the most value for money and is the most appealing investment choice for addressing stormwater management irrespective of climate variations and associated risks.

5. Conclusions and Recommendations

The SAVi methodology was customized and applied to assess different stormwater infrastructure options for the City of Johannesburg, South Africa. These options were derived from an earlier stormwater infrastructure upgrade in the Paterson Park Precinct, an urban development zone. The assessment scope and objectives were determined together with the city's Development Planning Department. Accordingly, this SAVi assessment served to analyze the following three stormwater infrastructure alternatives:

- **Grey stormwater infrastructure:** civil-engineered, concrete culvert.
- **Nature-based stormwater infrastructure:** stream renaturalization
- **Hybrid stormwater infrastructure:** combination of a concrete culvert section and a renaturalized stream section, as implemented in the Paterson Park Precinct in 2018.

The integration of environmental, social, and economic benefit factors into a performance analysis of each infrastructure option enables a more holistic and society-oriented view for urban stormwater planning decisions. Moreover, infrastructure resilience to climate change impacts, including variations in precipitation patterns and the increasing frequency of extreme rainfall events, is crucial for delivering effective stormwater management services to urban populations and hence making cost-effective public investment decisions.

Therefore, this SAVi assessment was composed of the following:

- **Comparative Integrated CBA:** The project costs and the social, environmental, and economic (co-) benefits of the three stormwater infrastructure options were assessed and valued in monetary terms over 20- and 40-year time horizons.
- **Climate Change Scenario Analysis:** The CBA performance of the three infrastructure options was assessed under four different climate scenarios over the 20- and 40-year time horizons.

The SAVi assessment draws a clear conclusion. The nature-based infrastructure solution is the most value-generating and most climate-resilient infrastructure solution for stormwater management in Johannesburg. Compared to constructing a concrete culvert (baseline) and a hybrid solution, the full renaturalization of a stream yields higher benefits under each assessed climate scenario and requires the lowest public spending overall. Therefore, it provides the most value for money and is the most appealing investment choice for addressing stormwater management in Johannesburg. If space in an urban setting is available and if planning and construction costs for implementing a stream renaturalization are in the range of cost estimates for this assessment, it is clearly the infrastructure solution to opt for.

Most noticeable is the superior performance of the renaturalized stream regarding the avoidance of floods and associated damages due to the better absorption and infiltration capacity, resulting in lower volumes of runoff compared to a concrete culvert or a hybrid solution (which would be composed of a smaller renaturalized stream section). This superior performance holds true over the 20- and 40-year time horizons under all climate scenarios, with the only exception being the 20-year horizon under the RCP 6.0 scenario. In the latter constellation, the hybrid solution yields the same amount of avoided flood damage costs as the fully renaturalized stream. It should further be reiterated that the economic value of additional water supply in the renaturalized stream option exceeds total project-related costs after 40 years. This indicates that, even if flood damages would be avoided, the economic value of the systemic benefit generated by increasing the permeability and water infiltration outweighs the economic costs of the project.

The RCP 6.0 scenario is also the one that implies the poorest performance results for all assessed stormwater infrastructure options due to a higher frequency of extreme rainfall events. While the renaturalized stream still attains comparatively the best results among the three options, the RCP 6.0 scenario also provides evidence that nature-based stormwater solutions are vulnerable to climate extremes, and their performance depends on which climate scenario materializes.

Moreover, one can recognize that the avoided flood damage costs are by far the most significant benefit factor provided by both the renaturalized stream and the hybrid solution. As this is calculated based on avoided damages to properties, one can conclude that it is most beneficial to implement nature-based stormwater solutions in proximity to high-value properties and built infrastructure because it would deliver the most protective value there. This might pose a challenge to urban planners because these areas might not provide sufficient unsealed space for implementing nature-based solutions to a larger extent. However, it is worthwhile to at least opt for hybrid (i.e., combined) solutions where viable or to integrate nature-based solutions early on when urban planning and redevelopment strategies are being developed.

This makes even more sense in the South African context, where urban areas are increasingly facing drinking water shortages during the summer months. This SAVi assessment clearly indicates that water supply due to groundwater recharging effects—provided by both the hybrid and the full renaturalized stream solutions—is the second-highest benefit position in monetary terms. The renaturalized stream yields significantly more water supply. While the magnitude of this benefit factor again varies depending on which climate scenario materializes, the variations are less pronounced compared to the variations concerning avoided flood damage costs. This is positive news for urban planners because, irrespective of which climate and associated precipitation scenario materializes, a renaturalized stream—and to a lesser extent, a hybrid solution—will yield additional water supply. The more extensive the renaturalized area, the higher the permeability of the surface and the higher the percolation and, consequently, the groundwater recharge. Given these compelling benefits, renaturalizing river streams addresses the recommendation of the City of Johannesburg’s Climate Action Plan to establish a decentralized water provisioning system to diversify the city’s water resources as a means to increase freshwater system resilience (City of Johannesburg, 2020a).

Whether additional drinking water supply for the city could also be provided by a concrete culvert depends on where the stormwater is channelled, whether it then can be treated, and if so, at what cost. In this SAVi assessment, it was assumed that a concrete culvert would not deliver additional water supply for the city.

The city's Climate Action Plan identifies the establishment of a decentralized water provisioning system as a key action. It aims to achieve an increased proportion of water used from alternative sources by 25%, which increases water system resilience.

The SAVi assessment pointed to further benefit factors that are delivered if nature-based stormwater infrastructure solutions are implemented in urban settings, including increases in property values in proximity to areas that benefited from the renaturalization. Linked to that, cities would also be able to generate respectively higher property tax revenues. Moreover, green spaces also provide carbon sequestration benefits and hence contribute to climate change mitigation and a lower social cost of carbon. Lastly, a renaturalized area is expected to require more maintenance expenditures compared to a concrete culvert. While this is a more significant cost position for the renaturalized and hybrid solutions, it is a labour-intensive activity that implies that these two stormwater infrastructure solutions also yield more employment and income generation effects. While the scale of additional employment opportunities is not very compelling when only considering a small renaturalized area, a more widespread implementation of nature-based solutions for stormwater management could provide a more decisive number of additional jobs. This is a benefit factor that should not be ignored in a South African urban context.

Finally, this SAVi assessment did not account for all benefit factors that will be provided by nature-based stormwater solutions, including lower insurance premiums associated with lower flooding risks and positive effects for local economies due to higher visitor numbers with spending capacity. Moreover, renaturalized areas can deliver public health benefits due to local air quality improvements, local reduction of the urban heat island effect, freshwater quality improvements in urban streams, and the recreational value of green spaces in urban settings. It is recommended that urban planners collect data for these parameters in order to quantify and value them in monetary terms to further strengthen the business case for investing in nature-based infrastructure solutions for urban stormwater management.

References

Al Jazeera. (2016). *Fatal flash floods hit Johannesburg.* https://www.aljazeera.com/news/2016/11/11/fatal-flash-floods-hit-johannesburg

Bassi, A. (2009). *An integrated approach to support energy policy formulation and evaluation* [PhD dissertation, University of Bergen]. https://core.ac.uk/download/pdf/30896832.pdf

Bassi, A., Bechauf, R., Casier, L., Lago, S., Pallaske, G., Perera, O., Perrette, M., Uzsoki, D., & Wuennenberg, L. (2020). *The integration of climate data into the SAVi model* (2019/C3S_428h_IISD-EU/SC1). Copernicus Climate Change. https://www.iisd.org/publications/integration-climate-data-savi-model

Center for Neighborhood Technology & SB Friedman Development Advisors. (2020). *Green stormwater infrastructure impact on property values.* https://www.cnt.org/sites/default/files/publications/GSI-Impact-on-Property-Values.pdf

Christiansen, C., Filer, A., Landi, M., O'Shaughnessy, E., Palmer, M., & Schwartz, T. (2014). *Cost-benefit analysis of stream-simulation culverts*. Wisconsin Department of Natural Resources. https://lafollette.wisc.edu/images/publications/cba/2014-culvert.pdf

City of Bremerton. (2019). *Stormwater facility maintenance manual for municipal and private stormwater facilities*. (2015 ed., 2019 edit). https://www.bremertonwa.gov/DocumentCenter/View/2744/Stormwater-Facility-Maintenance-Manual-PDF

City of Johannesburg. (2017). *Special Development Zones – Orange Grove Precinct Stormwater Master Plan.* GIBB Ltd.

City of Johannesburg. (2020a). *Climate Action Plan.*

City of Johannesburg. (2020b). *Environmental Sustainability Strategy and Action Plan.* Institute of Natural Resources & ICLEI Africa.

Copernicus Climate Change Service (C3S). (2017). *ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate.* Copernicus Climate Change Service Climate Data Store. https://cds.climate.copernicus.eu/cdsapp#!/home

Copernicus Climate Change Service. (2020). *Climate Data Store.* https://cds.climate.copernicus.eu/cdsapp#!/home

European Centre for Medium-Range Weather (ECMWF). (2017). *ECMWF Newsletter No. 151 – Spring 2017.* https://www.ecmwf.int/en/elibrary/17181-newsletter-no-151-spring-2017

Floodlist. (2020). *South Africa – Floods cause havoc in Johannesburg and Gauteng.* *http://floodlist.com/africa/south-africa-floods-johannesburg-gauteng-february-2020*

Forrester, J. W. (1961). *Industrial dynamics*. The MIT Press.

Fourie, C. (2017). *How much water do you really use?* Randburg Sun. https://randburgsun.co.za/328517/how-much-water-do-you-really-use/

Gaspar, V., Mauro, P., Parry, I., & Pattillo, C. (2019). *Fiscal policies to curb climate change* [IMFBlog]. https://blogs.imf.org/2019/10/10/fiscal-policies-to-curb-climate-change/

Johannesburg Road Agency. (2014, March 19). *Joburg's extensive plans to repair flood damage and upgrade road infrastructure.* https://www.jra.org.za/documents/pressrelease/Flood_repairs_19_2014.pdf

Kenton, W. (2019). *Externality*. Investopedia. https://www.investopedia.com/terms/e/externality.asp

Lategan, L. G. & Cilliers, E. J. (2014). The value of public green spaces and the effects of South Africa's informal backyard rental sector. *The Sustainable City, 9, 1*, 427–238. https://www.witpress.com/Secure/elibrary/papers/SC14/SC14036FU1.pdf

LookSeek Knowledge Base. (2020). *Weeping willow tree.* http://knowledgebase.lookseek.com/Weeping-Willow-Salix-babylonica.html

McCord, J., McCord, M., McCluskey, W., Davis, P. T., McIlhatton, D., & Haran, M. (2014). Effect of public green space on residential property values in Belfast metropolitan area. *Journal of Financial Management of Property and Construction, 19*(2), 117–137. https://doi.org/10.1108/JFMPC-04-2013-0008

Murray & Dickson. (2015). *Paterson Park Culvert Upgrade – 2455477. Schedule of Quantities for Tender.*

Nemry, F. & Demirel, H. (2012). *Impacts of climate change on transport: A focus on road and rail transport infrastructures* (JRC Working Papers JRC72217). Joint Research Centre (Seville). https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/impacts-climate-change-transport-focus-road-and-rail-transport-infrastructures

Nordhaus, W. (2017). Revisiting the social cost of carbon. *PNAS, 11*(7), 1518–1523.

OANDA. (2020). Currency Converter: USD/ZAR exchange rate from 30 October 2020. https://www1.oanda.com/currency/converter/

PayScale. (2020a). *Average heavy truck driver hourly pay in South Africa.* https://www.payscale.com/research/ZA/Job=Heavy_Truck_Driver/Hourly_Rate

PaySCale. (2020b). *Average excavator operator hourly pay in South Africa.* https://www.payscale.com/research/ZA/Job=Excavator_Operator/Hourly_Rate

PayScale. (2020c). *Average gardener hourly pay in South Africa.* https://www.payscale.com/research/ZA/Job=Gardener/Hourly_Rate

PayScale. (2020d). *Average landscaper hourly pay in South Africa.* https://www.payscale.com/research/ZA/Job=Landscaper/Hourly_Rate

Pittock, J., Dumaresq, D., & Bassi, A. (2016). Modeling the hydropower-food nexus in large river basins: A Mekong case study. *Water, 8*(10), 425. https://doi.org/10.3390/w8100425

Property24. (2020a). *Orange Grove property trends and statistics.* https://www.property24.com/johannesburg/orange-grove/property-trends/4365

Property24. (2020b). *Norwood property trends and statistics.* https://www.property24.com/johannesburg/norwood/property-trends/4363

Property24. (2020c). *Orchards Grove property trends and statistics.* https://www.property24.com/johannesburg/orchards/property-trends/4366

Roberts, N., Andersen, D., Deal, R., Garet, M., & Shaffer, W. (1983). *Introduction to computer simulation. The system dynamics approach*. Addison-Wesley.

The Economics of Ecosystems and Biodiversity (TEEB). (2018). *TEEB for agriculture & food: Scientific and economic foundations*. UN Environment. http://teebweb.org/agrifood/wp-content/uploads/2018/10/TEEB_Foundations_October13.pdf

United Nations Economic Commission for Africa. (2018). *Socioeconomic benefits of climate information service for disaster risk reduction in Africa.* https://archive.uneca.org/sites/default/files/images/annex_a1.1.1_-_seb_and_vfm_frameworks_application_in_drr_en.pdf

United Nations Environment Programme (UNEP). (2014). *Using models for green economy policymaking*. http://www.un-page.org/files/public/content-page/unep_models_ge_for_web.pdf

U.S. Environmental Protection Agency (EPA). (2008). *Reducing urban heat islands: Compendium of strategies. Urban heat island basics.* https://www.epa.gov/sites/production/files/2017-05/documents/reducing_urban_heat_islands_ch_1.pdf

U.S. Environmental Protection Agency. (2020). *Greenhouse gases equivalencies calculator – Calculations and references: Number of urban tree seedlings grown for 10 years.* https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references

Annex A. Data Sources and Assumptions

Table A1. Technical data and cost figures for the concrete culvert

Parameter	Unit	Concrete Culvert	Data Source/Comment
Culvert length	metre	756	Assumption. Based on Paterson Park stormwater project and assuming the entire upgrade would be a concrete culvert.
Culvert construction	ZAR/metre	74,039	Based on cost figures indicated in Murray & Dickson (2015)
Contingency	ZAR/metre	15,238	Based on cost figures and total cost shares (culvert compared to renaturalized stream) indicated in Murray & Dickson (2015)
Preliminary and general costs	ZAR/metre	22,723	Based on cost figures and total cost shares (culvert compared to renaturalized stream) indicated in Murray & Dickson (2015)
Maintenance cost (annual)	ZAR/metre/ year	24	Cost per maintenance exercise for equipment and working hours deduced from Christiansen et al. (2014); South African labour costs for truck driver and excavator operator sourced from PayScale (2020a, 2020b)
Maintenance frequency	times/year	1	Assumption to estimate annual maintenance cost. Deduced from City of Bremerton (2019)
Exchange rate	ZAR per USD	16.378	Exchange rate from October 30, 2020, accessed via OANDA (2020)

Table A2. Technical data and cost figures for the renaturalized stream

Parameter	Unit	Renaturalized stream	Data Source/Comment
Stream length	metre	756	Assumption. Based on Paterson Park stormwater project and assuming the entire upgrade would be a renaturalized.
Renaturalization of stream	ZAR/metre	27,983	Based on cost figures indicated in Murray & Dickson (2015)
Landscaping cost	ZAR/metre	4,905	Based on cost figures indicated in Murray & Dickson (2015)
Contingency	ZAR/metre	6,857	Based on cost figures and total cost shares (culvert compared to renaturalized stream) indicated in Murray & Dickson (2015)
Preliminary & general costs	ZAR/metre	10,225	Based on cost figures and total cost shares (culvert compared to renaturalized stream) indicated in Murray & Dickson (2015)
Maintenance cost (annual)	ZAR/metre/ year	473	Based on cost figures indicated for "cleaning of site" and "mowing/trimming" under "Rehab Landscaping" and section "Establishment Maintenance" in Murray & Dickson (2015)
Maintenance frequency: cleaning of site	times/year	4	Assumption to estimate annual maintenance cost
Maintenance frequency: mowing and trimming	times/year	26	Assumption to estimate annual maintenance cost

Table A3. Technical data and cost figures for the hybrid stormwater solution

Parameter	Unit	Value	Data Source/Comment
Culvert length	metre	336	Based on Paterson Park stormwater project: length of culvert upgrade
Stream length	metre	420	Based on Paterson Park stormwater project: length of renaturalized stream section
Cost items			All cost parameters according to indicated values in Table A 1 and Table A 2. The values expressed in "ZAR/Metre" apply to the culvert section and the stream section of the hybrid solution, respectively.

Table A4. Rainfall, permeable area, and infiltration

Parameter	Unit	Value	Data Source/Comment
Total renaturalized area considered for water loads	m^2	21,324	Based on m^2 figures indicated for "Rehab Landscaping" in Murray & Dickson (2015)
Peak rainfall for flood risks	mm/day	65	Estimated based on precipitation data and the anecdotal evidence of when floods occurred (Al Jazeera, 2016; Floodlist, 2020). This parameter was calibrated to generate floods during years where floods have occurred. Runoff values were estimated using water balance information on runoff, infiltration and evapotranspiration (see percentage below, sourced from U.S. Environmental Protection Agency [EPA], 2008) and an assumption on total permeable and impermeable surface for the three different asset type scenarios.
Infiltration and runoff: Water balance			U.S. EPA (2008)
Concrete Culvert			
Infiltration	*%*	*15*	
Runoff	*%*	*55*	
Evapotranspiration	*%*	*30*	
Naturalized only			
Infiltration	*%*	*50*	
Runoff	*%*	*10*	
Evapotranspiration	*%*	*40*	
Fraction of area permeable			
Concrete culvert	*%*	*60*	*Assumption*
Combined option	*%*	*80*	*Assumption*
Renaturalized stream (full)	*%*	*100*	*Assumption*

Table A5. Flood damages

Parameter	Unit	Value	Data Source/Comment
Flood indicator	Dimensionless	Flood damage costs expressed as % of property value	Varies depending on precipitation, permeable area and respective infiltration, runoff and evapotranspiration fractions provided in Table A4. Estimated based on precipitation and runoff value using Nemry & Demirel (2012) as a reference for calibrating floods.
No flood	% of property value (flood damage)	0	Flood indicator value = 1
Flood intensity 1	% of property value (flood damage)	5	Flood indicator value = 1.01
Flood intensity 2	% of property value (flood damage)	7.5	Flood indicator value = 1.1
Flood intensity 3	% of property value (flood damage)	10	Flood indicator value = 1.25
Flood intensity 4	% of property value (flood damage)	12.5	Flood indicator value = 1.5
Flood intensity 5	% of property value (flood damage)	15	Flood indicator value = 1.75
Flood intensity 6	% of property value (flood damage)	20	Flood indicator value = 1.85
Flood intensity 7	% of property value (flood damage)	25	Flood indicator value = 2
Flood intensity 8	% of property value (flood damage)	50	Flood indicator value = 3

Note: A flood indicator is used to determine the share of property value that suffers from flood damages. The underlying assumption here is that the stronger the floods (= the higher the flood indicator value above value "1"), the higher the likelihood that more severe damages occur. This was calibrated according to flood indicator values obtained based on peak rainfall threshold and anecdotal evidence (Al Jazeera, 2016; Floodlist 2020). The chosen flood indicator values are informed by climate impact data from the Copernicus Climate Data Store (CDS).

Table A6. Property values

Parameter	Unit	Value	Data Source/Comment
Property value by district			
Orange Grove	ZAR/property	1,105,923	Average sales price: Property24 (2020a)
Norwood	ZAR/property	2,063,333	Average sales price: Property24 (2020b)
Orchards	ZAR/property	2,533,571	Average sales price: Property24 (2020c)
Number of affected properties			
Orange Grove	properties	35	Estimated number of properties per district at risk to flood damages based on 1:1000 year flood line (City of Johannesburg, 2017), see Figure 2, Figure A1, and Figure A2. Assumption that these number of properties at risk remains constant over time.
Norwood	properties	2	
Orchards	properties	25	
Property value increase (one-time) -> Applies to renaturalized stream and the hybrid stormwater option as both increase green space.	%	2	Assumed magnitude of property value increase was approved by Development Planning Department of Johannesburg. The positive effect of green spaces on property values is supported by scientific studies: Center for Neighborhood Technology & SB Friedman Development Advisors (2020); Lategan & Cilliers (2014); McCord et al. (2014). The 2% one-time increase is applied to the number of affected properties in Orange Grove, Norwood and Orchard according to the average sales price (year 2020) in the respective neighbourhood.

Note: The property values in proximity to the Paterson Park serve to estimate various benefit parameters associated with investing in a renaturalized stream section: avoided flood damages (to properties), property value increase, property tax revenue increases.

Figure A1. Properties at flood risk in Orange Grove

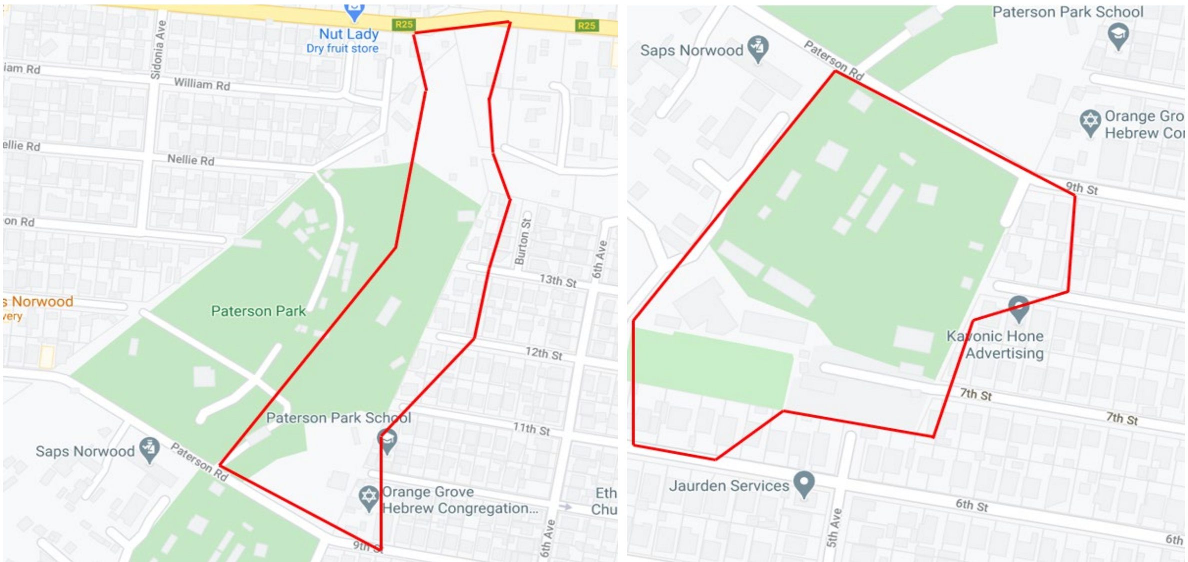


Figure A2. Properties at flood risk in Norwood and Orchard

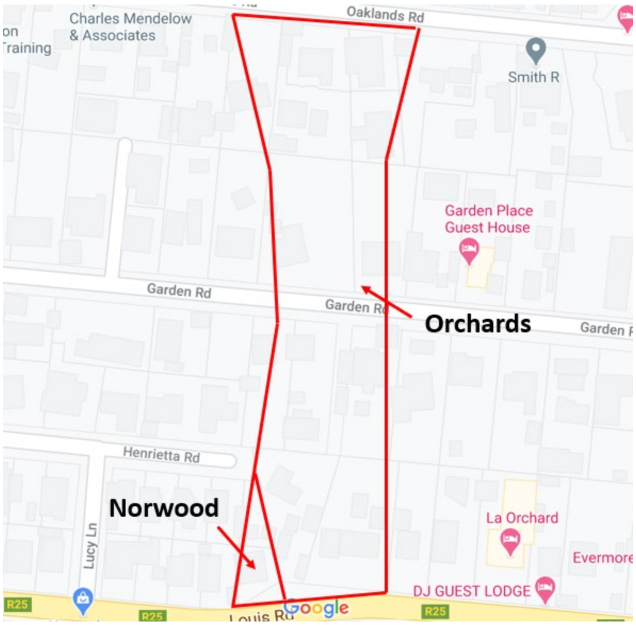


Table A7. Property tax revenue increase

Parameter	Unit	Value	Data Source/Comment
Tax payments			
Orange Grove	ZAR/year	7,200	Values for Orange Grove and Norwood provided by the Development Planning Department, City of Johannesburg. Assumption that tax payments for properties in Orchard are in line with tax payments in Orange Grove.
Norwood	ZAR/year	9,800	
Orchards	ZAR/year	7,200	
Tax rate			
Orange Grove	% of property value/year	0.65	Tax rates are calculated based on absolute tax payment and average property sales prices (2020) per district. Tax rates are applied to the increased property values (see Table A1) to estimate the additional property tax revenues for the city in scenarios where either the hybrid stormwater solution or the (fully) renaturalized stream option is implemented.
Norwood	% of property value/year	0.47	
Orchards	% of property value/year	0.28	

Table A7. Income creation – maintenance of concrete culvert

Parameter	Unit	Value	Data Source/Comment
Income truck driver	ZAR/hour	47.58	PayScale (2020a)
Income excavator operator	ZAR/hour	39.21	PayScale (2020c)
Duration per maintenance event	hours	4	Christiansen et al. (2014)
Maintenance frequency	#/year	1	City of Bremerton (2014)

Table A8. Income creation – maintenance of renaturalized stream area (fully renaturalized and hybrid option)

Parameter	Unit	Value	Data Source/Comment
Income gardener	ZAR/hour	25	PayScale (2020c)
Income landscaper	ZAR/hour	27.85	PayScale (2020d)
Share of gardener for maintenance work	%	65	Assumes mainly conventional gardening work, without major need for equipment or tree care
Share of landscaper for maintenance work	%	35	
Renaturalized area (fully renaturalized stream)	m^2	21,324	Based on m^2 figures indicated for "Rehab Landscaping" in Murray & Dickson (2015)
Employment multiplier for renaturalized area	FTE/m^2/year	0.000249	Confirmed by Wolfram Reinhard, Green Space Office, City of Offenburg (Germany)
Gardener: full-time equivalent (FTE) needed	person/year	3.5	Both values calculated based on the type of work needed (share) for the renaturalized area, employment multiplier, and assumption that FTE equals 1,880 hours of work per year.
Landscaper: FTE needed	person/year	1.9	
Fully renaturalized stream: share of renaturalized area to be maintained	%	100	Renaturalized area associated with the full length of the renaturalized stream: 756m
Hybrid option: Share of renaturalized area to be maintained	%	56	Calculated as share of the renaturalized stream (420m) over total length of stormwater infrastructure (756m) for the hybrid option.

Table A9. Avoided cost of carbon from carbon sequestration

Parameter	Unit	Value	Data Source/Comment
Carbon sequestration per tree type			
Salix babylonica	tonne/tree	0.080	LookSeek Knowledge Base (2020)
Acacia caffra	tonne/tree	0.063	U.S. EPA (2020)
Combretum erythrophyllum	tonne/tree	0.063	
Searcia lancea	tonne/tree	0.063	
Hybrid stormwater option: Type and # of trees			
Salix babylonica	trees	15	Quantities of trees per type indicated in the tender document for the Paterson Park Culvert Upgrade: Murray & Dickson (2015)
Acacia caffra	trees	15	
Combretum erythrophyllum	trees	25	
Searcia lancea	trees	25	
Renaturalized stream: Type and # of trees			
Salix babylonica	trees	27.0	Proportionally more trees relative to the area increase of renaturalized space
Acacia caffra	trees	27.0	
Combretum erythrophyllum	trees	45.0	
Searcia lancea	trees	45.0	
Carbon price	USD/tonne CO_2	75	Assumption, based on Gaspar et al. (2019)

Table A10. Additional water supply

Parameter	Unit	Value	Data Source/Comment
Difference in infiltration (litre/day) compared to concrete culvert (baseline)	%	Hybrid: +19.7 Renaturalized : +39.4	Absolute infiltration varies by month for each stormwater infrastructure option based on precipitation levels. But the hybrid and fully renaturalized stormwater options achieve consistently higher infiltration rates than the concrete culvert. This is indicated by the positive percentage values.
Additional infiltration available for extraction (= supply)	%	66.6	Assumption
Price per litre of water (tap)	ZAR/Litre	0.02696	Price of tap water in Johannesburg, based on Fourie (2017)

Note: Added water supply is obtained from the increase in permeable area as a consequence of renaturalizing the stream and surrounding area of the Paterson Park. The "concrete culvert only" scenario serves as baseline for comparison to the hybrid and fully renaturalized stream alternatives. The difference in permeable area leads to a difference in infiltration for the latter two stormwater infrastructure options, which leads to groundwater recharge that could potentially be extracted. The additional water supply is equivalent to the difference in infiltration per day, multiplied by the days per year and the assumed fraction of water supply that will be available for extraction.

Annex B. SAVi Results

Table B1. Integrated CBA results (in ZAR million) for three stormwater infrastructure options under the BAU climate scenario, 20 years, discount factor: 5%

Costs and benefits (in ZAR million)	Concrete culvert	Hybrid solution	Renaturalized stream
Costs			
(1) Capital cost	84.672	58.620	37.778
(1.1) Renaturalization of the stream	*0.000*	*11.753*	*21.155*
(1.2) Landscaping cost	*0.000*	*2.060*	*3.708*
(1.3) Culvert construction	*55.974*	*24.877*	*0.000*
(1.4) Preliminary and general costs	*17.179*	*11.930*	*7.730*
(1.5) Contingency	*11.520*	*8.000*	*5.184*
(2) Maintenance cost	0.228	2.578	4.458
Total cost	**84.900**	**61.198**	**42.236**
Benefits			
(3) Avoided flood damages	0.000	56.863	68.233
(4) Increased property values	0.000	2.022	2.022
(4.1) Orange Grove	*0.000*	*0.737*	*0.737*
(4.2) Norwood	*0.000*	*0.079*	*0.079*
(4.3) Orchards	*0.000*	*1.206*	*1.206*
(5) Increased property tax revenues	0.000	0.113	0.113
(5.1) Orange Grove	*0.000*	*0.063*	*0.063*
(5.2) Norwood	*0.000*	*0.005*	*0.005*
(5.3) Orchards	*0.000*	*0.045*	*0.045*
(6) Income creation	0.004	1.799	3.238
(7) Avoided cost of carbon	0.000	0.079	0.141
(8) Additional water supply	0.000	9.424	18.848
Total benefits	**0.004**	**70.299**	**92.596**
Net results	**-84.896**	**9.101**	**50.360**
Benefit over cost (ZAR return per ZAR invested)	**0.0**	**1.1**	**2.2**

Table B2. Integrated CBA results (in ZAR million) for three stormwater infrastructure options under the BAU climate scenario, 40 years, discount factor: 5%

Costs and benefits (in ZAR million)	**Concrete culvert**	**Hybrid solution**	**Renaturalized stream**
Costs			
(1) Capital cost	**84.672**	**58.620**	**37.778**
(1.1) Renaturalization of the stream	*0.000*	*11.753*	*21.155*
(1.2) Landscaping cost	*0.000*	*2.060*	*3.708*
(1.3) Culvert construction	*55.974*	*24.877*	*0.000*
(1.4) Preliminary and general costs	*17.179*	*11.930*	*7.730*
(1.5) Contingency	*11.520*	*8.000*	*5.184*
(2) Maintenance cost	0.314	3.549	6.138
Total cost	84.986	62.170	43.916
Benefits			
(3) Avoided flood damages	0.000	78.273	89.644
(4) Increased property values	0.000	2.022	2.022
(4.1) Orange Grove	*0.000*	*0.737*	*0.737*
(4.2) Norwood	*0.000*	*0.079*	*0.079*
(4.3) Orchards	*0.000*	*1.206*	*1.206*
(5) Increased property tax revenues	0.000	0.155	0.155
(5.1) Orange Grove	*0.000*	*0.086*	*0.086*
(5.2) Norwood	*0.000*	*0.007*	*0.007*
(5.3) Orchards	*0.000*	*0.062*	*0.062*
(6) Income creation	0.006	2.477	4.458
(7) Avoided cost of carbon	0.000	0.106	0.191
(8) Additional water supply	0.000	12.548	25.096
Total benefits	0.006	95.581	121.566
Net results	-84.980	33.412	77.650
Benefit over cost (ZAR return per ZAR invested)	**0.0**	**1.5**	**2.8**

Table B3. Integrated CBA results (in ZAR million) for three stormwater infrastructure options under the RCP 2.6 climate scenario, 20 years, undiscounted

Costs and benefits (in ZAR million)	**Concrete culvert** (ZAR million)	**Hybrid solution** (ZAR million)	**Renaturalized stream** (ZAR million)
Costs			
(1) Capital cost	**84.67**	**58.62**	**37.78**
(1.1) Renaturalization of the stream	0.00	11.75	21.16
(1.2) Landscaping cost	0.00	2.06	3.71
(1.3) Culvert construction	55.97	24.88	0.00
(1.4) Preliminary and general costs	17.18	11.93	7.73
(1.5) Contingency	11.52	8.00	5.18
(2) Maintenance cost	0.37	4.14	7.15
Total cost	**85.04**	**62.76**	**44.93**
Benefits			
(3) Avoided flood damages	0.00	78.52	97.47
(4) Increased property values	0.00	2.12	2.12
(4.1) Orange Grove	0.00	0.77	0.77
(4.2) Norwood	0.00	0.08	0.08
(4.3) Orchards	0.00	1.27	1.27
(5) Increased property tax revenues	0.00	0.18	0.18
(5.1) Orange Grove	0.00	0.10	0.10
(5.2) Norwood	0.00	0.01	0.01
(5.3) Orchards	0.00	0.07	0.07
(6) Income creation	0.01	2.89	5.20
(7) Avoided cost of carbon	0.00	0.12	0.22
(8) Additional water supply	0.00	15.17	30.34
Total benefits	**0.01**	**99.00**	**135.53**
Net results	**-85.03**	**36.24**	**90.59**
Benefit over cost (ZAR return per ZAR invested)	**0.0**	**1.6**	**3.0**

Table B4. Integrated CBA results (in ZAR million) for three stormwater infrastructure options under the RCP 2.6 climate scenario, 40 years, undiscounted

Costs and benefits (in ZAR million)	**Concrete culvert** (ZAR million)	**Hybrid solution** (ZAR million)	**Renaturalized stream** (ZAR million)
Costs			
(1) Capital cost	**84.67**	**58.62**	**37.78**
(1.1) Renaturalization of the stream	0.00	11.75	21.16
(1.2) Landscaping cost	0.00	2.06	3.71
(1.3) Culvert construction	55.97	24.88	0.00
(1.4) Preliminary and general costs	17.18	11.93	7.73
(1.5) Contingency	11.52	8.00	5.18
(2) Maintenance cost	0.73	8.27	14.31
Total cost	**85.40**	**66.89**	**52.09**
Benefits			
(3) Avoided flood damages	0.00	189.52	213.89
(4) Increased property values	0.00	2.12	2.12
(4.1) Orange Grove	0.00	0.77	0.77
(4.2) Norwood	0.00	0.08	0.08
(4.3) Orchards	0.00	1.27	1.27
(5) Increased property tax revenues	0.00	0.36	0.36
(5.1) Orange Grove	0.00	0.20	0.20
(5.2) Norwood	0.00	0.02	0.02
(5.3) Orchards	0.00	0.14	0.14
(6) Income creation	0.01	5.77	10.39
(7) Avoided cost of carbon	0.00	0.24	0.43
(8) Additional water supply	0.00	28.77	57.55
Total benefits	**0.01**	**226.79**	**284.74**
Net results	**-85.39**	**159.90**	**232.66**
Benefit over cost (ZAR return per ZAR invested)	**0.0**	**3.4**	**5.5**

Table B5. Integrated CBA results (in ZAR million) for three stormwater infrastructure options under the RCP 2.6 climate scenario, 20 years, discount factor: 5%

Costs and benefits (in ZAR million)	**Concrete culvert** (ZAR million)	**Hybrid solution** (ZAR million)	**Renaturalized stream** (ZAR million)
Costs			
(1) Capital cost	84.672	58.620	37.778
(1.1) Renaturalization of the stream	0.000	11.753	21.155
(1.2) Landscaping cost	0.000	2.060	3.708
(1.3) Culvert construction	55.974	24.877	0.000
(1.4) Preliminary and general costs	17.179	11.930	7.730
(1.5) Contingency	11.520	8.000	5.184
(2) Maintenance cost	0.228	2.578	4.458
Total cost	84.900	61.198	42.236
Benefits			
(3) Avoided flood damages	0.000	61.017	76.609
(4) Increased property values	0.000	2.022	2.022
(4.1) Orange Grove	0.000	0.737	0.737
(4.2) Norwood	0.000	0.079	0.079
(4.3) Orchards	0.000	1.206	1.206
(5) Increased property tax revenues	0.000	0.113	0.113
(5.1) Orange Grove	0.000	0.063	0.063
(5.2) Norwood	0.000	0.005	0.005
(5.3) Orchards	0.000	0.045	0.045
(6) Income creation	0.004	1.799	3.238
(7) Avoided cost of carbon	0.000	0.079	0.141
(8) Additional water supply	0.000	9.963	19.926
Total benefits	0.004	74.993	102.050
Net results	-84.896	13.795	59.814
Benefit over cost (ZAR return per ZAR invested)	**0.0**	**1.2**	**2.4**

Table B6. Integrated CBA results (in ZAR million) for three stormwater infrastructure options under the RCP 2.6 climate scenario, 40 years, discount factor: 5%

Costs and benefits (in ZAR million)	**Concrete culvert** (ZAR million)	**Hybrid solution** (ZAR million)	**Renaturalized stream** (ZAR million)
Costs			
(1) Capital cost	**84.672**	**58.620**	**37.778**
(1.1) Renaturalization of the stream	0.000	11.753	21.155
(1.2) Landscaping cost	0.000	2.060	3.708
(1.3) Culvert construction	55.974	24.877	0.000
(1.4) Preliminary and general costs	17.179	11.930	7.730
(1.5) Contingency	11.520	8.000	5.184
(2) Maintenance cost	0.314	3.549	6.138
Total cost	84.986	62.170	43.916
Benefits			
(3) Avoided flood damages	0.000	85.685	102.413
(4) Increased property values	0.000	2.022	2.022
(4.1) Orange Grove	0.000	0.737	0.737
(4.2) Norwood	0.000	0.079	0.079
(4.3) Orchards	0.000	1.206	1.206
(5) Increased property tax revenues	0.000	0.155	0.155
(5.1) Orange Grove	0.000	0.086	0.086
(5.2) Norwood	0.000	0.007	0.007
(5.3) Orchards	0.000	0.062	0.062
(6) Income creation	0.006	2.477	4.458
(7) Avoided cost of carbon	0.000	0.106	0.191
(8) Additional water supply	0.000	13.154	26.309
Total benefits	0.006	103.600	135.548
Net results	-84.980	41.430	91.632
Benefit over cost (ZAR return per ZAR invested)	**0.0**	**1.7**	**3.1**

Table B7. Integrated CBA results (in ZAR million) for three stormwater infrastructure options under the RCP 6.0 climate scenario, 20 years, undiscounted

Costs and benefits (in ZAR million)	**Concrete culvert** (ZAR million)	**Hybrid solution** (ZAR million)	**Renaturalized stream** (ZAR million)
Costs			
(1) Capital cost	**84.67**	**58.62**	**37.78**
(1.1) Renaturalization of the stream	0.00	11.75	21.16
(1.2) Landscaping cost	0.00	2.06	3.71
(1.3) Culvert construction	55.97	24.88	0.00
(1.4) Preliminary and general costs	17.18	11.93	7.73
(1.5) Contingency	11.52	8.00	5.18
(2) Maintenance cost	0.37	4.14	7.15
Total cost	**85.04**	**62.76**	**44.93**
Benefits			
(3) Avoided flood damages	0.00	43.21	43.21
(4) Increased property values	0.00	2.12	2.12
(4.1) Orange Grove	0.00	0.77	0.77
(4.2) Norwood	0.00	0.08	0.08
(4.3) Orchards	0.00	1.27	1.27
(5) Increased property tax revenues	0.00	0.18	0.18
(5.1) Orange Grove	0.00	0.10	0.10
(5.2) Norwood	0.00	0.01	0.01
(5.3) Orchards	0.00	0.07	0.07
(6) Income creation	0.01	2.89	5.20
(7) Avoided cost of carbon	0.00	0.12	0.22
(8) Additional water supply	0.00	13.69	27.38
Total benefits	**0.01**	**62.22**	**78.31**
Net results	**-85.03**	**-0.54**	**33.38**
Benefit over cost (ZAR return per ZAR invested)	**0.0**	**1.0**	**1.7**

Table B8. Integrated CBA results (in ZAR million) for three stormwater infrastructure options under the RCP 6.0 climate scenario, 40 years, undiscounted

Costs and benefits (in ZAR million)	**Concrete culvert** (ZAR million)	**Hybrid solution** (ZAR million)	**Renaturalized stream** (ZAR million)
Costs			
(1) Capital cost	**84.67**	**58.62**	**37.78**
(1.1) Renaturalization of the stream	0.00	11.75	21.16
(1.2) Landscaping cost	0.00	2.06	3.71
(1.3) Culvert construction	55.97	24.88	0.00
(1.4) Preliminary and general costs	17.18	11.93	7.73
(1.5) Contingency	11.52	8.00	5.18
(2) Maintenance cost	0.73	8.27	14.31
Total cost	**85.40**	**66.89**	**52.09**
Benefits			
(3) Avoided flood damages	0.00	75.70	81.12
(4) Increased property values	0.00	2.12	2.12
(4.1) Orange Grove	0.00	0.77	0.77
(4.2) Norwood	0.00	0.08	0.08
(4.3) Orchards	0.00	1.27	1.27
(5) Increased property tax revenues	0.00	0.36	0.36
(5.1) Orange Grove	0.00	0.20	0.20
(5.2) Norwood	0.00	0.02	0.02
(5.3) Orchards	0.00	0.14	0.14
(6) Income creation	0.01	5.77	10.39
(7) Avoided cost of carbon	0.00	0.24	0.43
(8) Additional water supply	0.00	25.45	50.89
Total benefits	**0.01**	**109.65**	**145.32**
Net results	**-85.39**	**42.75**	**93.23**
Benefit over cost (ZAR return per ZAR invested)	**0.0**	**1.6**	**2.8**

Table B9. Integrated CBA results (in ZAR million) for three stormwater infrastructure options under the RCP 6.0 climate scenario, 20 years, discount factor: 5%

Costs and benefits (in ZAR million)	**Concrete culvert** (ZAR million)	**Hybrid solution** (ZAR million)	**Renaturalized stream** (ZAR million)
Costs			
(1) Capital cost	84.672	58.620	37.778
(1.1) Renaturalization of the stream	0.000	11.753	21.155
(1.2) Landscaping cost	0.000	2.060	3.708
(1.3) Culvert construction	55.974	24.877	0.000
(1.4) Preliminary & general costs	17.179	11.930	7.730
(1.5) Contingency	11.520	8.000	5.184
(2) Maintenance cost	0.228	2.578	4.458
Total cost	84.900	61.198	42.236
Benefits			
(3) Avoided flood damages	0.000	28.716	28.716
(4) Increased property values	0.000	2.022	2.022
(4.1) Orange Grove	0.000	0.737	0.737
(4.2) Norwood	0.000	0.079	0.079
(4.3) Orchards	0.000	1.206	1.206
(5) Increased property tax revenues	0.000	0.113	0.113
(5.1) Orange Grove	0.000	0.063	0.063
(5.2) Norwood	0.000	0.005	0.005
(5.3) Orchards	0.000	0.045	0.045
(6) Income creation	0.004	1.799	3.238
(7) Avoided cost of carbon	0.000	0.079	0.141
(8) Additional water supply	0.000	8.749	17.498
Total benefits	0.004	41.477	51.728
Net results	-84.896	-19.721	9.492
Benefit over cost (ZAR return per ZAR invested)	**0.0**	**0.7**	**1.2**

Table B10. Integrated CBA results (in ZAR million) for three stormwater infrastructure options under the RC P6.0 climate scenario, 40 years, discount factor: 5%

Costs and benefits (in ZAR million)	**Concrete culvert** (ZAR million)	**Hybrid solution** (ZAR million)	**Renaturalized stream** (ZAR million)
Costs			
(1) Capital cost	**84.672**	**58.620**	**37.778**
(1.1) Renaturalization of the stream	0.000	11.753	21.155
(1.2) Landscaping cost	0.000	2.060	3.708
(1.3) Culvert construction	55.974	24.877	0.000
(1.4) Preliminary & general costs	17.179	11.930	7.730
(1.5) Contingency	11.520	8.000	5.184
(2) Maintenance cost	0.314	3.549	6.138
Total cost	84.986	62.170	43.916
Benefits			
(3) Avoided flood damages	0.000	37.713	39.657
(4) Increased property values	0.000	2.022	2.022
(4.1) Orange Grove	0.000	0.737	0.737
(4.2) Norwood	0.000	0.079	0.079
(4.3) Orchards	0.000	1.206	1.206
(5) Increased property tax revenues	0.000	0.155	0.155
(5.1) Orange Grove	0.000	0.086	0.086
(5.2) Norwood	0.000	0.007	0.007
(5.3) Orchards	0.000	0.062	0.062
(6) Income creation	0.006	2.477	4.458
(7) Avoided cost of carbon	0.000	0.106	0.191
(8) Additional water supply	0.000	11.513	23.026
Total benefits	0.006	53.986	69.509
Net results	-84.980	-8.183	25.593
Benefit over cost (ZAR return per ZAR invested)	**0.0**	**0.9**	**1.6**

Table B11. Integrated CBA results (in ZAR million) for three stormwater infrastructure options under the RCP 8.5 climate scenario, 20 years, undiscounted

Costs and benefits (in ZAR million)	**Concrete culvert** (ZAR million)	**Hybrid solution** (ZAR million)	**Renaturalized stream** (ZAR million)
Costs			
(1) Capital cost	**84.67**	**58.62**	**37.78**
(1.1) Renaturalization of the stream	0.00	11.75	21.16
(1.2) Landscaping cost	0.00	2.06	3.71
(1.3) Culvert construction	55.97	24.88	0.00
(1.4) Preliminary and general costs	17.18	11.93	7.73
(1.5) Contingency	11.52	8.00	5.18
(2) Maintenance cost	0.37	4.14	7.15
Total cost	**85.04**	**62.76**	**44.93**
Benefits			
(3) Avoided flood damages	0.00	75.81	100.17
(4) Increased property values	0.00	2.12	2.12
(4.1) Orange Grove	0.00	0.77	0.77
(4.2) Norwood	0.00	0.08	0.08
(4.3) Orchards	0.00	1.27	1.27
(5) Increased property tax revenues	0.00	0.18	0.18
(5.1) Orange Grove	0.00	0.10	0.10
(5.2) Norwood	0.00	0.01	0.01
(5.3) Orchards	0.00	0.07	0.07
(6) Income creation	0.01	2.89	5.20
(7) Avoided cost of carbon	0.00	0.12	0.22
(8) Additional water supply	0.00	14.33	28.66
Total benefits	**0.01**	**95.45**	**136.56**
Net results	**-85.03**	**32.70**	**91.63**
Benefit over cost (ZAR return per ZAR invested)	**0.0**	**1.5**	**3.0**

Table B12. Integrated CBA results (in ZAR million) for three stormwater infrastructure options under the RCP 8.5 climate scenario, 40 years, undiscounted

Costs and benefits (in ZAR million)	**Concrete culvert** (ZAR million)	**Hybrid solution** (ZAR million)	**Renaturalized stream** (ZAR million)
Costs			
(1) Capital cost	**84.67**	**58.62**	**37.78**
(1.1) Renaturalization of the stream	0.00	11.75	21.16
(1.2) Landscaping cost	0.00	2.06	3.71
(1.3) Culvert construction	55.97	24.88	0.00
(1.4) Preliminary and general costs	17.18	11.93	7.73
(1.5) Contingency	11.52	8.00	5.18
(2) Maintenance cost	0.73	8.27	14.31
Total cost	**85.40**	**66.89**	**52.09**
Benefits			
(3) Avoided flood damages	0.00	151.62	211.18
(4) Increased property values	0.00	2.12	2.12
(4.1) Orange Grove	0.00	0.77	0.77
(4.2) Norwood	0.00	0.08	0.08
(4.3) Orchards	0.00	1.27	1.27
(5) Increased property tax revenues	0.00	0.36	0.36
(5.1) Orange Grove	0.00	0.20	0.20
(5.2) Norwood	0.00	0.02	0.02
(5.3) Orchards	0.00	0.14	0.14
(6) Income creation	0.01	5.77	10.39
(7) Avoided cost of carbon	0.00	0.24	0.43
(8) Additional water supply	0.00	27.24	54.48
Total benefits	**0.01**	**187.36**	**278.97**
Net results	**-85.39**	**120.46**	**226.89**
Benefit over cost (ZAR return per ZAR invested)	**0.0**	**2.8**	**5.4**

Table B13. Integrated CBA results (in ZAR million) for three stormwater infrastructure options under the RCP 8.5 climate scenario, 20 years, discount factor: 5%

Costs and benefits (in ZAR million)	**Concrete culvert** (ZAR million)	**Hybrid solution** (ZAR million)	**Renaturalized stream** (ZAR million)
Costs			
(1) Capital cost	84.672	58.620	37.778
(1.1) Renaturalization of the stream	0.000	11.753	21.155
(1.2) Landscaping cost	0.000	2.060	3.708
(1.3) Culvert construction	55.974	24.877	0.000
(1.4) Preliminary and general costs	17.179	11.930	7.730
(1.5) Contingency	11.520	8.000	5.184
(2) Maintenance cost	0.228	2.578	4.458
Total cost	84.900	61.198	42.236
Benefits			
(3) Avoided flood damages	0.000	41.910	54.095
(4) Increased property values	0.000	2.022	2.022
(4.1) Orange Grove	0.000	0.737	0.737
(4.2) Norwood	0.000	0.079	0.079
(4.3) Orchards	0.000	1.206	1.206
(5) Increased property tax revenues	0.000	0.113	0.113
(5.1) Orange Grove	0.000	0.063	0.063
(5.2) Norwood	0.000	0.005	0.005
(5.3) Orchards	0.000	0.045	0.045
(6) Income creation	0.004	1.799	3.238
(7) Avoided cost of carbon	0.000	0.079	0.141
(8) Additional water supply	0.000	8.944	17.888
Total benefits	0.004	54.866	77.497
Net results	-84.896	-6.332	35.261
Benefit over cost (ZAR return per ZAR invested)	**0.0**	**0.9**	**1.8**

Table B14. Integrated CBA results (in ZAR million) for three stormwater infrastructure options under the RCP 8.5 climate scenario, 40 years, discount factor: 5%

Costs and benefits (in ZAR million)	**Concrete culvert** (ZAR million)	**Hybrid solution** (ZAR million)	**Renaturalized stream** (ZAR million)
Costs			
(1) Capital cost	**84.672**	**58.620**	**37.778**
(1.1) Renaturalization of the stream	0.000	11.753	21.155
(1.2) Landscaping cost	0.000	2.060	3.708
(1.3) Culvert construction	55.974	24.877	0.000
(1.4) Preliminary and general costs	17.179	11.930	7.730
(1.5) Contingency	11.520	8.000	5.184
(2) Maintenance cost	0.314	3.549	6.138
Total cost	84.986	62.170	43.916
Benefits			
(3) Avoided flood damages	0.000	58.006	77.221
(4) Increased property values	0.000	2.022	2.022
(4.1) Orange Grove	0.000	0.737	0.737
(4.2) Norwood	0.000	0.079	0.079
(4.3) Orchards	0.000	1.206	1.206
(5) Increased property tax revenues	0.000	0.155	0.155
(5.1) Orange Grove	0.000	0.086	0.086
(5.2) Norwood	0.000	0.007	0.007
(5.3) Orchards	0.000	0.062	0.062
(6) Income creation	0.006	2.477	4.458
(7) Avoided cost of carbon	0.000	0.106	0.191
(8) Additional water supply	0.000	11.929	23.857
Total benefits	0.006	74.695	107.905
Net results	-84.980	12.525	63.989
Benefit over cost (ZAR return per ZAR invested)	**0.0**	**1.2**	**2.5**

Annex C. The SAVi Methodology

Systems Thinking and System Dynamics

The Sustainable Asset Valuation (SAVi) model for this stormwater infrastructure assessment is based on systems thinking and elements of the system dynamics methodology. The SAVi model has been developed based on global literature, customized with local stakeholder input, and parametrized with local, accessible data. The model simulates the period 2018 to 2060. There are two main reasons for using this specific time frame: (i) being causal-descriptive, SAVi needs to be validated against historical data (hence the simulation of the model from 2018 onwards); (ii) being focused on infrastructure and long-term interventions (and their costs and outcomes), SAVi needs to forecast the impacts of interventions after they have been implemented and are fully operational. The stormwater infrastructure assets assessed in this SAVi assessment have an assumed lifetime of 40 years.

The customized SAVi model is applied to assess and monetize the impacts climate change has on the different stormwater infrastructure assets, as well as the environmental, social, and economic (co-)benefits and costs caused by each of the assessed infrastructure options.

System Dynamics Overview

A customized causal loop diagram (CLD) was developed together with the Development Planning Department of the City of Johannesburg to scope out the main parameters of this assessment and capture important dynamics of stormwater infrastructure in an urban setting. The CLD is displayed in Figure 2 in the main body of this report. Designing a CLD for a project helps to combine and integrate a team's knowledge, ideas, and concepts and define the scope of the analysis and important performance indicators. Moreover, an interactive CLD design and verification process with key stakeholders of a project ensures that these stakeholders have a common understanding of the analysis being undertaken, both in terms of its overarching scope and its underlying factors. This co-development process contributes to improved learning about dynamics at play and enables these stakeholders to improve internal communication and make better use of analysis results (Pittock et al., 2016; TEEB, 2018). In this regard, CLDs show the overarching dynamics where the root causes of a problem lie, as well as the variables of a system that could, with the appropriate technical or policy interventions, be targeted to develop solutions (United Nations Economic Commission for Africa, 2018).

To design solution-oriented and effective interventions, CLDs need to capture the causal relations of a system correctly. Therefore, CLDs establish causal links between variables by linking them with arrows and attributing a sign to the arrow (either + or −) that indicates whether a change in one variable generates a positive or negative change in the other.

Table C1. Causal relations and polarity

Variable A	Variable B	Sign
↑	↑	+
↓	↓	+
↑	↓	-
↓	↑	-

As noted by Bassi (2009):

- "A causal link from variable A to variable B is positive if a change in A produces a change in B in the same direction.
- A causal link from variable A to variable B is negative if a change in A produces a change in B in the opposite direction."

Copernicus Climate Change Service