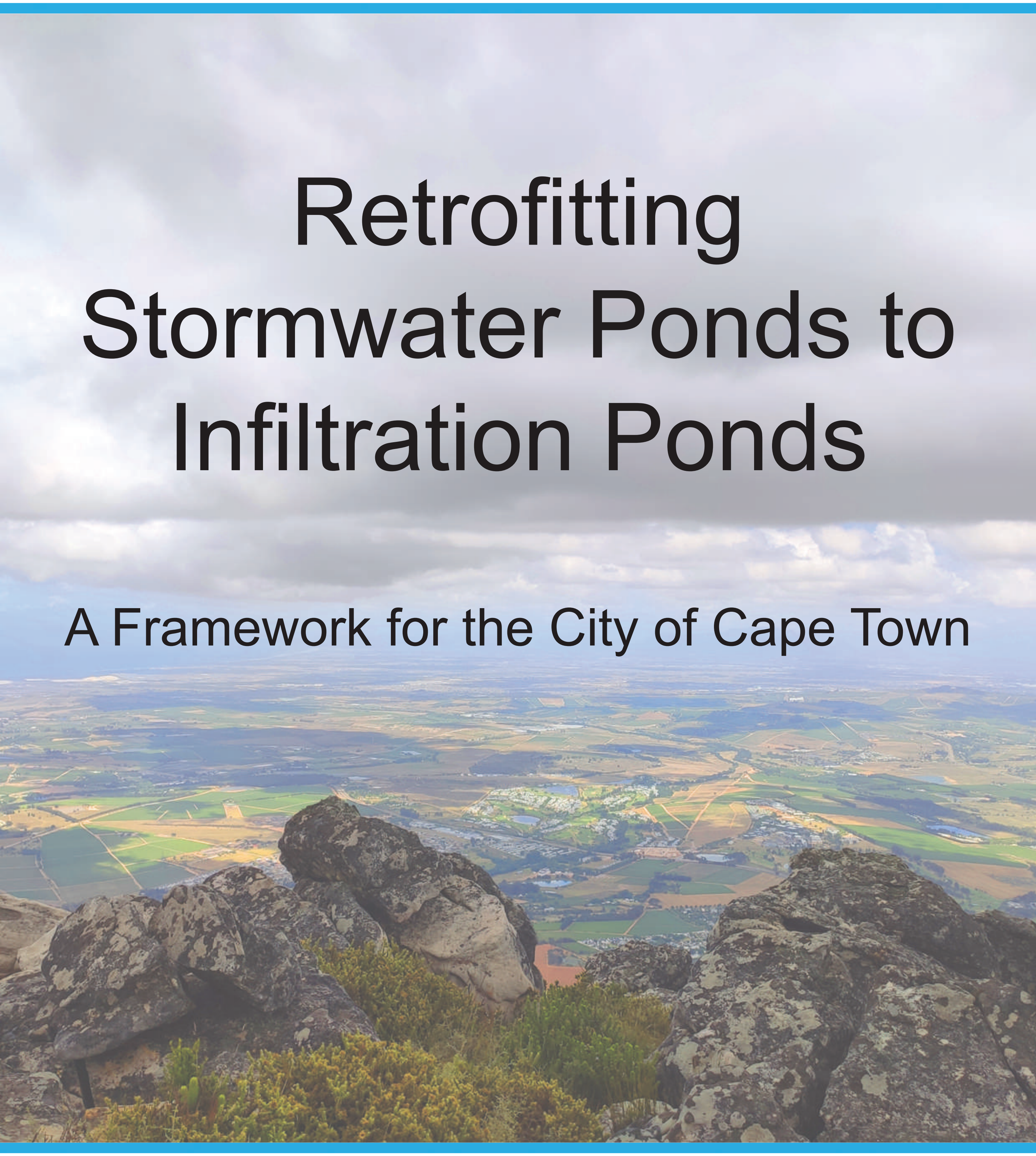
Retrofitting Stormwater Ponds to Infiltration Ponds

A Framework for the City of Cape Town



TU Delft Delft University of Technology

In collaboration with

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A Framework for the City of Cape Town

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Executive Summary

This report is written in response to a request from The Future Water Institute at the University of Cape Town (UCT), which is a 'transdisciplinary research institute addressing issues of water scarcity in South Africa largely through water sensitive design'. One of their research topics is retrofitting existing stormwater ponds into infiltration basins, in order to replenish the groundwater by managed aquifer recharge (MAR). This will contribute to making Cape Town (CT) a more water sensitive city and is the main topic of this report. This effort has been undertaken within the Orange Knowledge Program. The Orange Knowledge Program promotes the collaboration in research between South Africa and the Netherlands.

CT is a city with over four million people and a growing population. Due to three consecutive dry summers as a result of climate change, a growing population and an increased per capita water demand, the city's main water supply was nearly depleted. 'Day Zero', the day CT's taps would need to shut off, was averted due to strict water saving measures and the early onset of rain. The water consumption was reduced by 50% between 2015-2018 through these measures. As a response to the drought and climate change, The Draft Water Strategy was published. The municipality of CT states that its water supply resources need to be diversified. Furthermore the municipality of CT commits itself to become a 'water sensitive city'.

CT depends for 98% on surface water stored in dammed reservoirs, which is replenished by rainfall. Whilst CT's population has grown with 79%, from about 2.4 million to an expected 4.3 million in 2018, dam storage has increased with only 15% over the same period. Additionally, due to climate change, the expectation is that multi-year droughts such as the one that caused the drought in 2018, will occur more frequently for CT in the future.

Precipitation is considered the major source to mitigate the problem of water scarcity. CT's major challenge is the temporal mismatch in water availability and peak demand. The wet winters provide sufficient precipitation, the summers are however too dry. Research has indicated annual rainfall to be the largest flux into the system, larger than the annual water demand. This potential water source is however 'lost' to the ocean via CT's stormwater and the natural river courses. Harvesting the stormwater can be potentially be an additional source of water. CT's urban drainage system has 737 detention ponds, which are used to attenuate flooding in case of heavy rain events. These ponds can be used to harvest the stormwater, and it might be possible to store the stormwater in the Cape Flats aquifer using managed aquifer recharge for seasonal availability.

MAR, using harvested stormwater, requires further research for the context of CT. This research contributes by suggesting a framework consisting of three phases. The three phases can be used separately to respectively assess the suitability of an area for MAR, the suitability of a pond for MAR and lastly to guide the retrofitting process of the existing stormwater ponds to infiltration ponds. The following research objective has been defined:

"Provide an overarching framework that can be applied to determine suitable detention ponds to allow managed aquifer recharge via infiltrating stormwater in Cape Town's context and how to retrofit these detention ponds into infiltration ponds."

In order to answer this question a framework has been constructed, the order of this framework is presented in Figure 1.

The first phase of the framework is the Spatial Assessment. This phase offers a tool to identify suitable areas for the implementation of MAR in order to make CT a more water sensitive city. The objective was to identify suitable locations for the implementation of MAR. In order to do so a Geographical Information System-Multi Criteria Decision Analysis method was used. This desktop study produced a suitability map for MAR areas. It thereby provided an idea of how many of the 737 stormwater ponds present in CT are in a suitable area and can be considered to use as infiltration ponds. The aim of this phase was to provide MAR suitability maps that can guide decision-making for the implementation of MAR.

In order to confirm and obtain site specific information, physical assessment of individual ponds is imperative. The phase Physical Assessment introduces the questions that are investigated, their importance and how these must be examined. A flow chart describes the steps to be followed, based on four different sections, namely; 'hydro-geology', 'hydraulic analysis, 'water quality' and 'risk assessment'. The results of this phase might lead to exclusion of certain ponds or serve as input for the redesign process of the pond. Additionally,

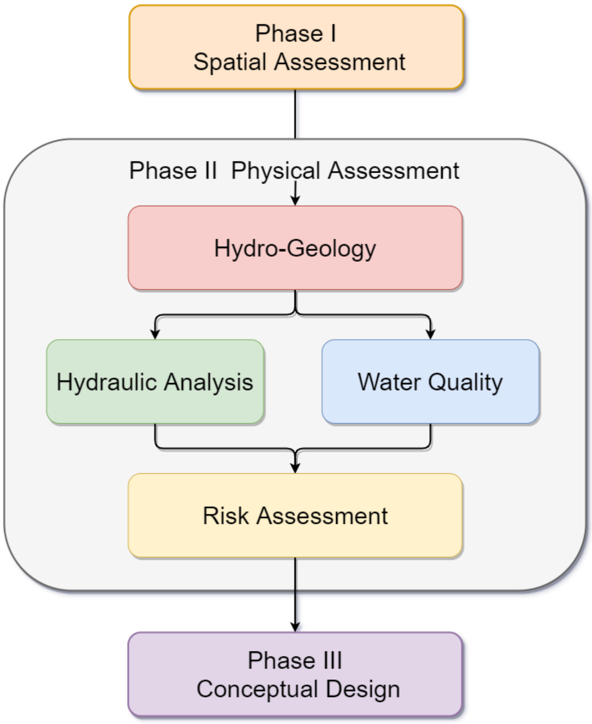

Figure 1: General Flow Chart of the framework

this phase provides a field manual that described the methods to obtain data in the field. A lack of coherent data collection was encountered, this structured manner of data collection is therefore especially interesting for CT to be able to objectively compare the data.

The last phase of the framework is the Conceptual Design phase. Retrofitting of a stormwater pond into an infiltration basin is a complex process. A multitude of factors influence the design criteria and each other. These design criteria are: infiltration rate, yield, flood attenuation, drainage time and water treatment efficiency. Concrete guidance is provided in the process of retrofitting to optimise the design for the design criteria without compromising on the complexity. Firstly, the factors, design criteria and influences on one another have been visualised using a flow chart. A step-wise decision flow chart has been provided to aid the structure of the retrofitting process. Lastly, a model to assess the physical alterations is introduced and explained.

Numerous manuals and design methodologies have been developed for the engineering and construction of infiltration ponds. There are a only few manuals that are aimed specifically at retrofitting existing stormwater attenuation sites into infiltration ponds, and there are none developed particularly for the context of CT. In the course of this multidisciplinary project a new framework was developed tailored to the context of CT. This framework is constructed such that it is highly flexible in usage due to the fact that every phase of the framework can be used separately. Additionally, it is adaptive since the framework can be extended upon by including the socio-economic aspects. This makes the framework both user friendly and readily usable when better data is encountered or other fields of expertise are regarded to be important. Moreover, a field manual that described the methods to obtain data in the field in a coherent way is attributed. This data can consequently be used in the framework itself.

Preface

In 2018 water management in Cape Town (CT) was an important news item worldwide. The effects of climate change on the water resources became painfully visible. After years of relatively little rain the municipality of CT had to announce the projected arrival of Day-zero, the day the water demand would out compete supply to inhabitants. Fortunately, due to a sharp decrease in water consumption by the inhabitants and early rain that year, Day-zero was postponed and eventually called off. This water crisis has attracted global attention towards CT. Especially we as Water Management and Environmental Engineering students were concerned by these developments but also fascinated by this issue. Back then we would have never guessed that we could turn that fascination into participation and have a change to contribute in solving the next crisis before it even occurs.

CT strives to become a climate resilient and specifically a water sensitive city. This has caught the attention of many: it will take engineers, scientist and public officials, not to mention the Capetonians self, to push to reach this goal. One among them is the Future Water Institute, researching water sensitive approaches and design. One of their projects focuses on groundwater replenishment by infiltration of stormwater via the existing stormwater infrastructure. The groundwater promises to serve as additional water source. We have been lucky enough to be granted the possibility to go to CT, cooperate together with this Institute and shed a light on the matter as well. We have personally experienced many challenges within this project, especially trying to define our contribution amongst the many studies and findings of the Institute up to missing essential data necessary to conduct a study ourselves.

With this report, we aim to contribute to the groundwater replenishment project of the Future Water Institute. Thereby hoping to contribute to the wish of CT to become a water sensitive city. To this end, we first provide a background of the current situation and conducted research to define the knowledge gaps, from this our objective is formulated: to develop an assessment and redesign framework. Secondly, we report on the development of the assessment and redesign framework, present the final product, the framework itself together with a partial verification of the framework.

During our time in CT we were met with great hospitality and friendliness. The challenges we faced during our project would have been harder and the goal we set out would have been impossible without the South African deep-seated friendliness, patience and their willingness to help. This not only applies for the ones we had the pleasure to work with but also extends to the people of CT.

We hope to have brought a new perspective into the Future Water Institute project. Moreover, we hope that the assessment and redesign framework, or components of it, will prove itself to be a useful tool for the remainder of the Future Water Institute project. So we can indirectly repay the city and its wonderful people for their kindness and great generosity.

The team,

Ben Bischoff Tulleken, Floor Crispijn, Sebastian Durry, Roos Goedhart, Juliette Kool and Stijn Muntjewerff

Acknowledgements

We would like to express our gratitude to all parties that have contributed to this project. Firstly to our supervisors from the TU Delft Dr. T. Bogaard and Prof. dr. ir. L.C. Rietveld who provided us not only with the opportunity to do this project but also with valuable feedback before, during and in the concluding phase of the project. Deep gratitude also goes to our UCT supervisor Dr. K. Winter for valuable feedback, tips and providing background but also for showing genuine interest in us and the project. You made our stay in South Africa unforgettable.

Our gratitude goes to the University of Cape Town; in particular Future Water Institute and the Department of Environmental Geographical Science for generously welcoming us and providing all necessary facilities to conduct this project. The supporting environment, input and comments of the Future Water Institute team has been of major importance; in particular to Dr. K. Carden Prof. Dr. N.P. Armitage and J. Fell.

We are profoundly grateful to G.T. Tanyanyiwa, Dr. F. Atkins and Dr. J. Okedi for their interest in the project and contribution of data. Also we would like to thank N. Lindenberg and T. Slingsby of the GIS lab at UCT for providing us with shapefiles and assistance with technical problems.

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Nomenclature

AHP	Analytic Hierarchy Process
AWSS	Atlantis Water Supply System
BMP	Best Managment Practice
CFA	Cape Flats Aquifer
CI	Consistency Index
CR	Consistency Ratio
CT	Cape Town
DEM	Digital Elevation Model
DO	Dissolved Oxygen
EC	Electrical Conductivity
GI	Green Infrastructure
GIFMOD	Green Infrastructure Flexible Model
GIS-MCDA	Geographical Information System–Multi-Criteria Decision Analysis
HLC	Hydraulic Loading Cycle
HLR	Hydraulic Loading Rate
IMRaD	Introduction Methodology Results and Discussion and conclusion
LDP	Limiting Design Parameter
LID	Low Impact Development
LIDAR	Light Detection and Ranging
MADM	Multi-Attribute Decision Making
MAR	Managed Aquifer Recharge
MCDA	Multi-Criteria Decision Analysis
MIDS	Minimal Impact Design Standards
MIF	Multi-Influencing Factors
OM	Organic Matter
PCSWMM	Personal Computer Storm Water Management Model
PHA	Philippi Horticultural Area
PRI	Phosphorus Retention Index
RADAR	Radio Detection and Ranging
RCI	Random Consistency Index
SAT	Soil Aquifer Treatment
SBD	Soil Bulk Density
SUDS	Sustainble Urban Drainage Systems

SWH	Stormwater Harvesting
TDS	Total Dissolved Solids
TMG	Table Mountain Group
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
TSS	Total Suspended Solids
UCT	University of Cape Town
UM WMB	Urban Metabolic Water Mass Balance
WLC	Weighted Linear Combination
WSUD	Water Sensitive Urban Design

1

Introduction

Roughly 60% of the world population lives within city boundaries [1]. The prospects are that the world population will grow, as will the percentage that lives in cities [1]. Urban water management practices are being put under stress by this trend and increased per capita water demand and climate change are expected to increase this stress [2, 3]. Many cities around the world are currently sensitive to water shortages [3]. Due to the three above mentioned stresses one out of six large cities is at risk of serious water shortage by 2050 [4]. In 2018, Cape Town has been a striking example of the potential consequences a water shortage may have on a large city [5].

The report at hand is written as a request by The Future Water Institute, a 'transdisciplinary research institute [at the University of Cape Town (UCT),] addressing issues of water scarcity in South Africa largely through water sensitive design' [6]. One of their research topics is the retrofitting of existing stormwater ponds into infiltration ponds, to replenish the groundwater by managed aquifer recharge. This will contribute to making Cape Town a more water sensitive city and is the topic of interest of this report. An extensive background of the problem and our contribution to the ongoing research is explained in the coming sections.

1.1. Water Sensitive Cape Town

Cape Town (CT) is a city with over four million people and a growing population [7]. Due to three consecutive dry summers the city's main water supply was nearly depleted [5]. CT depends for 98% on surface water stored in dammed reservoirs, which is replenished by rainfall [8]. Water can be extracted until the reservoirs are at 13.5% of their capacity [5]. CT's main reservoirs had fallen to a historical minimum of 15% of their capacity. The drought of 2018 was preceded by a rare once in 300-year multi year drought lasting from 2015 until 2018. However, due to human induced climate change the expectation is that such multi-year droughts will occur more frequently for CT in the future. 'Day Zero', the day CT's taps would need to shut off, was averted due to strict water saving measures and the early onset of rain [5]. The water consumption was reduced by 50% between 2015-2018 through these measures [9]. However, inhabitants were limited to 50 litres of water per day, whereas an average Dutch citizen uses 133.4 litres per day [9, 10]. Since urban water resource management is complex pinpointing one cause of the drought is hard. Whilst CT's population has grown with 79%, from about 2.4 million to an expected 4.3 million in 2018, dam storage has increased with only 15% over the same period. This provides at least one cause of the severe water shortage [1, 11]. If no significant change in water supply and demand pattern occurs, a gap of approximately 17% between demand an supply will occur in 2030 [11]. As a response to the drought, The Draft Water Strategy was published. The municipality of CT states that its water supply resources need to be diversified [12]. Furthermore the municipality of CT commits itself to become a 'water sensitive city' [12]. The principle of a water sensitive city is funded on three pillars [13]:

1. Access to a diversity of water sources underpinned by a diversity of centralised and decentralised infrastructure.
2. Provision of ecosystem services for the built and natural environment.

3. Socio-political capital for sustainability and water sensitive behaviours.

This has been conceptualised into different frameworks around the world, with slightly different names such as Water Sensitive Urban Design (WSUD) in Australia and Sustainable Urban Drainage Systems (SUDS) in the UK. In this report WUDS is used to refer to these set of frameworks. The frameworks give guidance to implement the urban water cycle, which includes stormwater, groundwater, waste water and water supply, in land planning and engineering practices [13].

A WSUD is made for Cape Town, which is provided in this report including the methodology and scientifically reasoning behind it. A WSUD is required to make a paradigm shift in urban water management practices for CT [13].

1.2. WSUD for Cape Town

In order to quantify a city's water sensitivity a Urban Metabolic Water Mass Balance is the most suitable approach [14]. Figure 1.1 [15] shows the UM WMB for CT. Precipitation is considered the major source to mitigate the problem of water scarcity [16]. CT has a Mediterranean climate with dry, warm summers and wetter winters [15]. Figure 1.1 depicts a Sankey Diagram of CT's pre-drought UM WMBM from 2008-2012 . The anthropogenic (brown) and natural (blue) inputs and outputs are average gigalitres per annum. The Surface water inflow represents the natural rivers flowing into CT, Rainfall is the precipitation on the surface area of CT and Surface supply is extracted water from the reservoirs. The Surface supply flow is passed on to the water treatment plant (WTP) and consequently to the waster water treatment works (WWTW) after which it is discharged into the ocean. Loss terms have been included for unaccounted water in the system to satisfy conservation of mass. Lastly, MAR, Managed Aquifer Recharge represents a successful activity that has already been undertaken. Both MAR and the successful MAR activity in CT will be elaborated on in respectively section 1.4 and subsection 1.5.1.

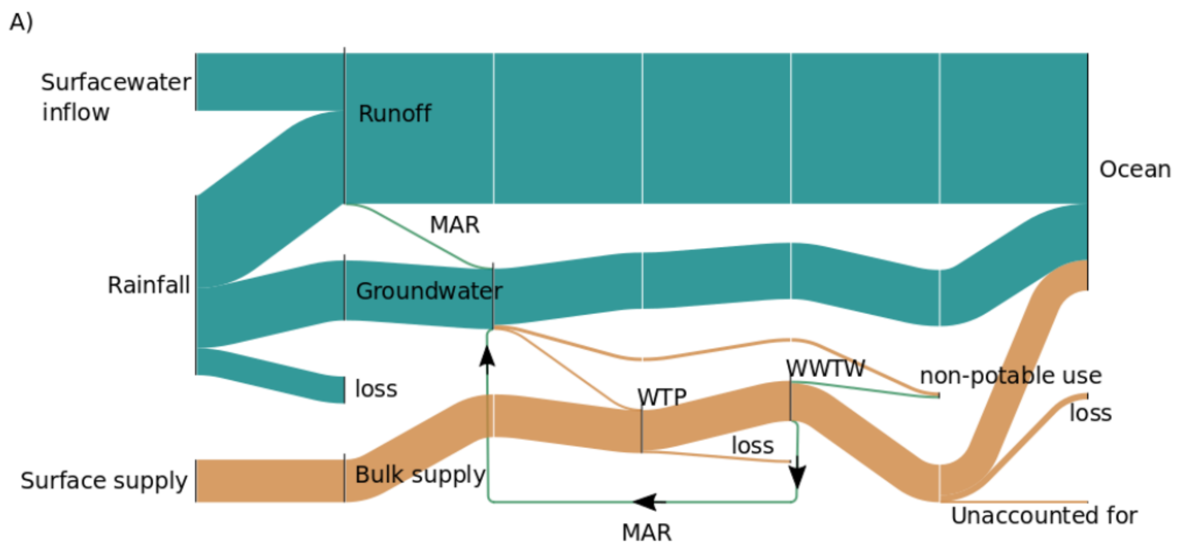

Figure 1.1: Water Mass Balance of Cape Town in 2015 [15].

Figure 1.1 indicates rainfall to be the largest flux into the system. Additionally, the annual runoff within the city boundaries of CT exceeds the annual water supply to CT (Figure 1.1 [15]). This potential water source is however 'lost' to the ocean via CT's separate stormwater and natural river system (Figure 1.1). Harvesting this stormwater can be a potential extra source of water, which can decrease the stress on the surface supply. In this report the potential for stormwater harvesting (SWH) in Cape Town is investigated.

Firstly, the concept of stormwater harvesting will be discussed. Afterwards the concept of managed aquifer recharge is introduced and explained. Lastly, an already existing, successful MAR project in Cape Town and a potential site for MAR are introduced.

1.3. Stormwater Harvesting

Stormwater harvesting is the collection, accumulation, treatment and storing of stormwater for its eventual reuse [17]. To be able to use this potential source of water, a site specific SWH system should be in place [18]. A SWH system is composed of five core components with a multitude of (inter)relations and will be discussed in the order as presented here to stay in line with Philp et al. [19]: end use, collection, treatment, storage and distribution [19].

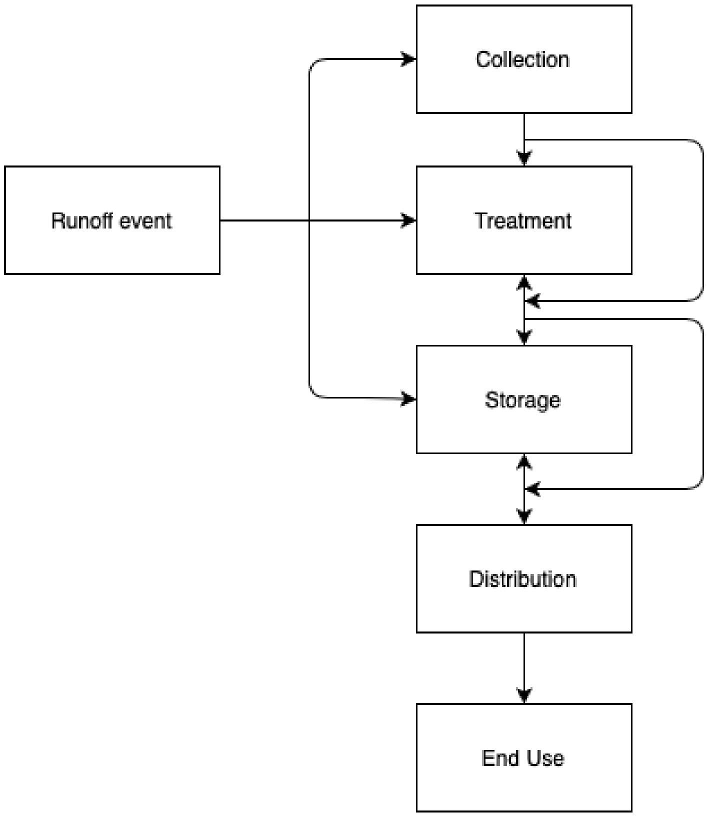

Figure 1.2: Stormwater harvesting core components adapted from [19]

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1.3.1. End Use

SWH systems should be designed and specified to meet the requirements for end use, to determine the appropriate system components. The intended end use of the harvested stormwater in CT has not yet clearly been defined [12] and depends on political decisions. Designing for a particular end-use is outside the scope of this research.

1.3.2. Collection

The stormwater system comprises of both constructed infrastructure (pipes, culverts, canals and detention ponds) and natural features (rivers, vleis, wetlands and ponds). At peakflow, the stormwater system's detention ponds function as stormwater attenuation facilities. The pipe network discharges runoff through the landscaped depression. The inlet and outlet pipes are configured to drain into the downstream watercourse at a predetermined rate (within 24 - 72 hours) [20]. Hereby these ponds attenuate peak flows and regulate water levels downstream. There are 737 registered stormwater ponds distributed over the city which are currently temporarily storing stormwater [21].

1.3.3. Treatment

Urban stormwater is often polluted [22]. One of the major hurdles in using stormwater is the lack of reliable and affordable treatment techniques [19]. The level of treatment needed depends on the catchment properties, the end use and legislation concerning the storage method [19]. Detention ponds are at the end of the

WSUD treatment train, which requires on-site treatment [18]. Depending on the end use, further treatment might be necessary. This is however not part of the WUSD anymore.

1.3.4. Storage

The ponds are designed to detain the stormwater for 24-72 hours, after which it is released downstream. This ensures the functionality of the detention pond in its purpose of flood attenuation. To be able to use the stormwater and to overcome the seasonality in precipitation, it should however be stored for a longer time. CT partly overlies the Cape Flat Aquifer (CFA) . The benefits of using a aquifer for storage are that little space is required and it is cost effective [19]. It however also bears disadvantages such as the requirement of suitable geology and has the potential to pollute groundwater [19]. It is essential that the storage capacity suffices the needs of intended end use by means of water supply reliability [19]. One method to be able to control and increase infiltration is MAR [12, 18]. This will be discussed more extensively in the next section as will the storage capacity of the aquifer.

1.3.5. Distribution

The system for distributing the stormwater is mainly depending on the end use of the water. Since this is not determined yet, it is out of scope for this research.

1.4. Managed Aquifer Recharge

"*MAR is the purposeful recharge of water to aquifers for subsequent recovery or environmental benefit*" [23]. The term 'managed' relates to human interventions for recharging the aquifer by techniques such as infiltration basins and injection wells. This is contrary to unintentional natural recharge, which occurs for example by infiltration of rainfall in permeable soils and/or by deep-rooted vegetation [24]. Seasonal storage is the main driver of applying MAR; infiltrating water when there is plenty, in order to use it in times of scarcity [25]. Careful planning and consideration of the constraints of MAR should be assessed before implementing a MAR project. Numerous MAR projects without adequate pre-assessment studies have been known to fail [26].

Only when all questions in Figure 1.3 can be answered with 'Yes' it is sensible to continue with a MAR project. More specifically, the main constraints for MAR are water availability, infiltration methods, hydro-geology and health concerns [27]. The water availability, or water shortage, has already been determined to be a driver for SWH and consequently MAR, rather than a constraint.

The detention ponds in CT provide surface area for infiltration. Infiltration ponds are shallow impounded areas designed to temporarily store, infiltrate, and treat water [28]. The detention ponds are however only designed to temporarily store and not to infiltrate or treat the stormwater. Therefore, these detention ponds must be re-designed in order to meet the requirements for MAR. The suitability of an MAR system depends for the most part on the local hydro-geological characteristics [29]. MAR with a infiltration pond requires the following conditions: the unsaturated zone must allow water to infiltrate to the aquifer, the aquifer must be unconfined and the aquifer must be able to store the infiltrated water [27]. The CFA is a sand covered coastal plain, specifically calcareous sand unconfined aquifer [30]. Sand is very suitable soil type regarding infiltration, with infiltration rates ranging from 13 to 25 mm/hour [31]. However, the sand of the CFA contains lenses of clay, calcrete and shale which do not promote infiltration. The storage capacity is among other dependent on the thickness and area of the aquifer. The CFA compromises a area of 620 km^2 with an average depth of 20 m [30]. The last major constraint raised is health and environmental risks. Stormwater can contain high levels of pathogens and metals which may lead to both health and environmental issues [32]. Besides that, oxygen demanding substances and nutrients in the stormwater can alter the soil conditions and have adverse effects on ecosystems, which emphasise the need for treatment of the stormwater [33, 34].

1.5. Case Studies in Cape Town

Within CT one successful MAR project is in operation, the Atlantis Water Supply System (AWSS) and a potential site for MAR is presented, the Philippi Horticultural Area (PHA) . A short description of both projects will be provided below.

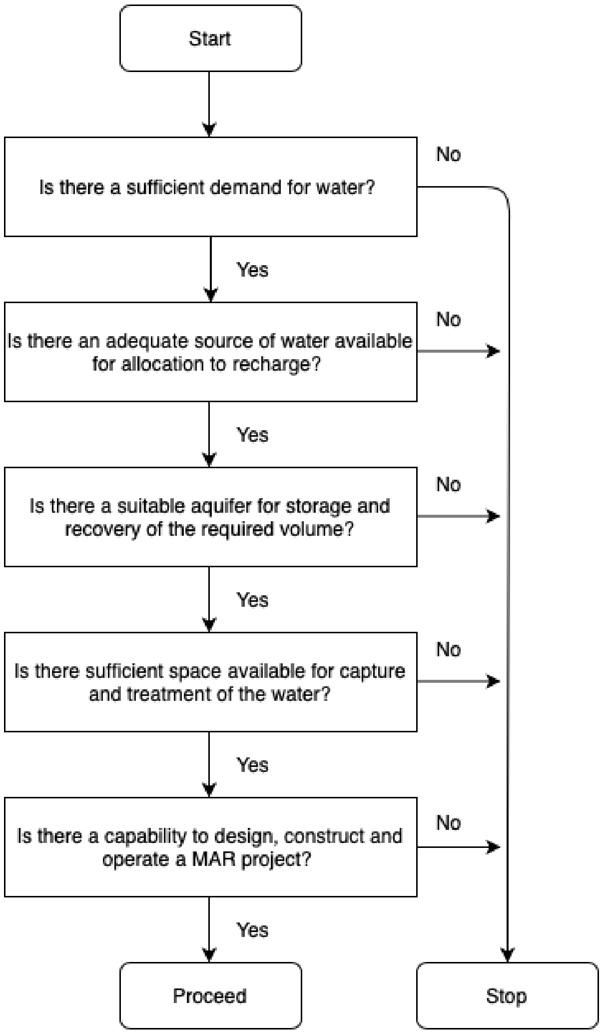

Figure 1.3: A checklist whether to undertake a managed aquifer recharge project adapted from [23].

1.5.1. Atlantis Water Supply System

In Atlantis, a town 40 km north from Cape Town, the 67,000 inhabitants are all supplied by groundwater coming from the Atlantis Aquifer. It is a local successful example on how recharging the aquifer with stormwater and wastewater effluent is used as an alternative water source [35]. The system is cost-effective and functions properly when combined with good management [25]. Historic data revealed some limitations that are important to take into account when designing a similar system for Cape Town. The first lesson is that monitoring and controlling the groundwater levels are crucial, to ensure proper treatment by the unsaturated soil. Critically maintaining and updating the monitoring programme for volume, water quality, evaporation and transpiration are crucial for ensuring a well balanced water system. Another advice is to develop a groundwater protection plan for the aquifer. The last recommendation is to set up a 'risk management and assessment plan' to reduce health risks [25]. These lessons are important to take into account when designing a stormwater harvest system for CT. The situation in CT is however different, since Atlantis was a planned town with separated industrial and residential areas. Additionally the soil type is different, there is less climate variability and different social aspects play a role [25].

1.5.2. Philippi Horticultural Area

The PHA is a rural land which is mainly focused on horticulture, situated on the densely populated area of the Cape Flats [36]. The PHA is a vital component of the CT food system [36] and the main user of groundwater from the CFA. Groundwater is pumped into dammed reservoir from where it is pumped through the irrigation system [37]. The CFA is locally recharged by both the enhanced recharge from the dams and irrigation return flow [37]. The sustainability of the PHA is threatened by deteriorating water quality due to increased salinity, pesticides and nutrients [37]. The implementation of MAR is expected to alleviate these problems such that the PHA can continue to be a productive horticultural area [37].

1.6. Knowledge Gaps

The SWH core components and the constraints posed for MAR have not been researched for the CT context and therefore show the gaps in knowledge for the implementation of MAR using detention ponds with stormwater as a source for CT. The gaps in knowledge have turned out to be extensive. Although MAR is a widely researched topic and the potential of the CFA for storage seems promising, little information is available about re-purposing stormwater detention ponds for MAR and with that a good estimation for its potential is lacking. It is valuable to obtain an impression whether or not it can make a significant contribution to CT's water supply system in order to proceed with the project. Consequently, a quantification of CT's water sensitivity should be conducted. One approach was an urban metabolism [14]. The urban metabolism quantifies flows into, within, and out of the urban area [38]. Other gaps in knowledge that have been identified and require further investigation are the end use of the water that can be obtained via SWH through MAR. The data on the stormwater collection network in place needs to be revised, since it is both lacking data and some data seems to be inconsistent. The treatment train as proposed in WSUD are ending in the stormwater ponds. More research needs to be conducted in the different components of the urban drainage system before the stormwater flows into the stormwater ponds. The WSUD includes alternatives for these components. This will elevate the chances of success for MAR in infiltration ponds using SWH. Lastly, it seems that quite a bit of data is around. The difficulty is however to obtain the data since most of the data is not open source nor easily shared.

The first step in overcoming most of these gaps is finding a structured method how to determine if the current stormwater system in CT has potential for infiltration. This leads to a better understanding of the systems, which helps for quantification, determining the best end use, and will result in a uniform data collection.

1.7. Objective

The Project covered a period of 12 weeks and was part of a bigger Future Water Institute Project aiming to answer the following research question:

"What is the potential for re purposing existing flood control infrastructure (stormwater ponds) in Cape Town to allow for the harvesting and treatment for contaminated surface runoff through managed aquifer recharge and recovery at basin/settlement scale?"

In consultation with our local supervisor Kevin Winter affiliated with the Future Water Institute the general objective of the project was established and was formulated as:

"Provide an overarching framework that can be applied to determine suitable detention ponds to allow managed aquifer recharge via infiltrating stormwater in CT's context and how to retrofit these detention ponds into infiltration ponds."

Firstly, a method to assess the suitability of areas for MAR using a Geographical Information System–Multi-Criteria Decision Analysis (GIS-MCDA) was provided. This resulted in a suitability map. Thereafter, a method was proposed to obtain site -specific suitability data using set criteria for the individual ponds. A guidance in retrofitting the stormwater ponds in the form of a conceptual design method was provided in the last phase.

1.8. Scope

Provided with a limited project duration and resources available to complete the objective, the decision was made to focus on the physical aspects of site or stormwater pond suitability and redesign. Therefore the framework will be of physical nature. Moreover, the framework will not include a maintenance aspect. The research acknowledges the need to determine the socio-economics aspects for site suitability as well [18].

1.9. Relevance

CT has expressed its ambition to become a water sensitive city. A water mass balance has already been constructed based on the ambition of CT. It is important to verify if this ambition can be turned into reality. This framework will attribute in obtaining a sense of the potential for MAR using stormwater ponds in CT to become a water sensitive city. It can be used to determine which ponds are most suitable for MAR and which steps of redesign the pond has to go through. This research has been conducted within an overarching 3-year research programme into the potential of stormwater as an alternative water resource for Cape Town led by the Future Water Institute. The Future Water Institute is a interdisciplinary and transdisciplinary research group of the University of Cape Town around water. The ambition of CT to become a water sensitive city can not be borne by investigating infiltration basins and optimising their pre-treatment and infiltration capacity alone. The WUSD provides a holistic framework. Infiltration basins are part of that framework, but not solely.

1.10. Framework and Outline

The framework starts by setting out to determine suitable areas for MAR. Secondly, the framework assists in assessing the stormwater ponds located in the suitable areas to determine the feasibility of retrofitting them into infiltration ponds. Thirdly, the frameworks aids in retrofitting existing stormwater ponds into infiltration ponds. Meaning the framework consists of three phases or three sub-frameworks: I. Suitability mapping, II. Physical assessment of suitability and III. Conceptual redesign. Each phase contains a part of the overall framework. Every phase is self-contained and can be seen and conducted separately from the other phases.

The report is divided into three parts presenting the three phases of the framework. The report starts with the GIS-MCDA based screening approach to identify the most suitable areas for infiltration (Phase 1). The following part (Phase 2) provides the physical assessment of the detention ponds. Consisting of a hydro-geology, hydraulic, water quality and risk assessment. The last part of the report (Phase 3) provides a retrofitting framework for stormwater ponds deemed suitable for infiltration.

In this three-legged report every part reports on the creation of the specific sub-framework via the IMRaD, Introduction Methodology, Results and Discussion/Conclusion, chapter format as requested by the client. The report then follows with a chapter that summarises the conclusions and provides recommendations.

More specifically, this report consists of 14 chapters. Chapter 1 (this one) provides an introduction including a background, objective, scope and relevance. Chapter 2 to 5 are devoted to Phase 1. Chapter 2 introduces the MCDA-GIS based screening methodology. Chapter 3 explains the methodology and how it is applied to CT context. Chapter 4, results, presents the infiltration suitability map. Chapter 5 presents the preliminary conclusions of Phase 1. Chapter 6 to 9 are devote to Phase 2. Chapter 6 introduces the Phase 2 and its four components; hydro-geology, hydraulic analysis, water quality and risk assessment. Chapter 7 describes the general approach to obtain the framework to assess the suitability detention ponds based on the 4 components. Chapter 8 presents four flow charts, one per component. Chapter 9 presents the preliminary conclusions of Phase 2. Chapter 10 to 13 are devoted to Phase 3. Chapter 10 introduces the design criteria and indicators. Chapter 11 discusses the retrofitting options and how they relate to each other. Chapter 12 presents the retrofit flow chart. Chapter 13 presents the preliminary conclusions of Phase 3. Chapter 14 presents the overall conclusion and recommendations of the report. A reference list and appendices are provided at the end of this report.

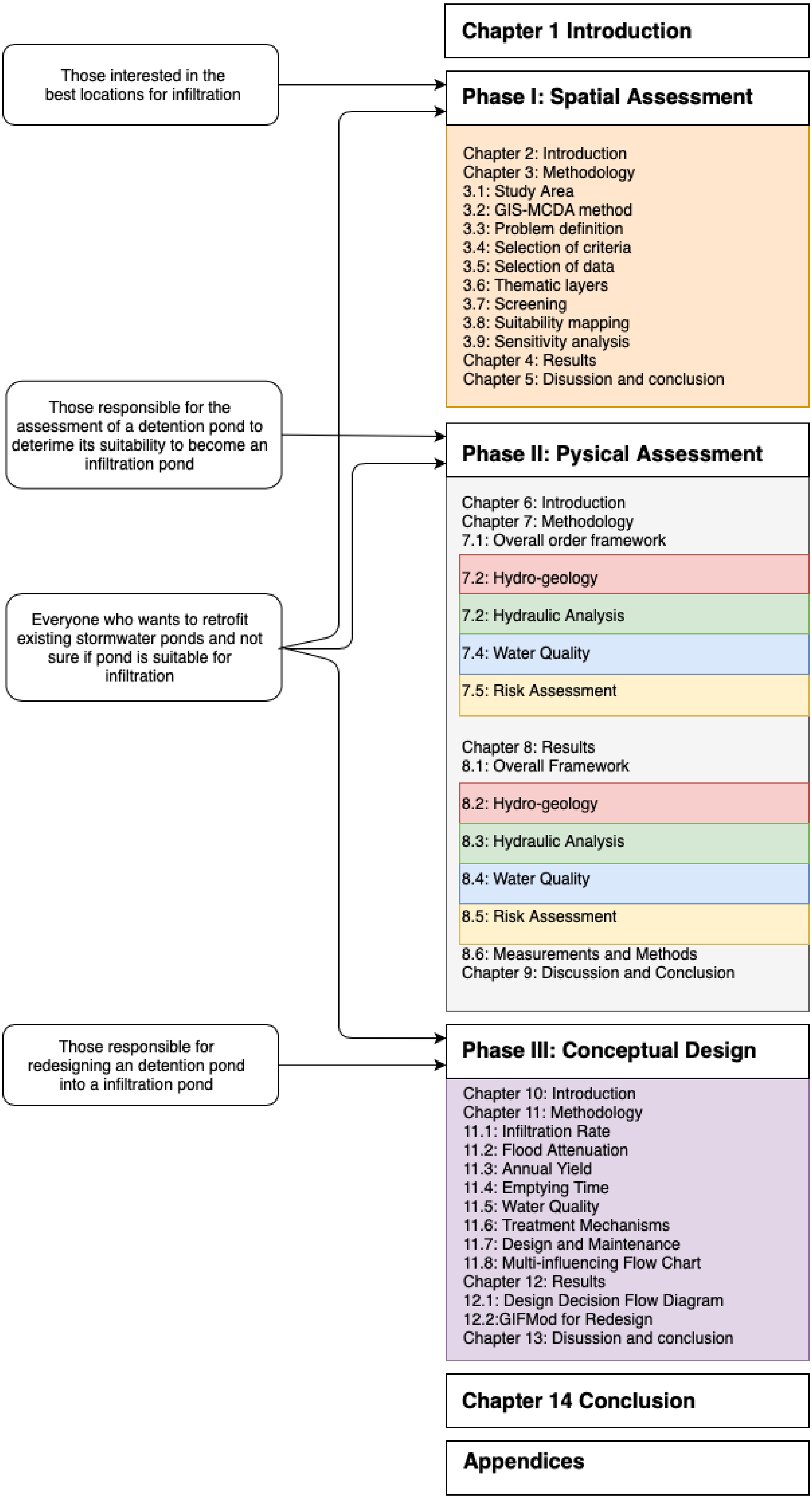

Figure 1.4: Reading Guide of phases and chapters

I

Spatial Assessment

2 Introduction

Sustainable urban drainage is considered a possible solution to Cape Towns water problems as stated in the general introduction. Improving infiltration as a means of MAR can help to restore the natural hydrological cycle and diversify Cape Town's water supply. In order to achieve this, selection and redesigning existing stormwater ponds into infiltration basins is needed [39]. MAR suitability studies are needed to assess the feasibility of this proposition. Among other sustainable urban drainage, suitable infiltration sites (stormwater ponds) should be located and aquifer suitability should be assessed.

Former studies have investigated the capacity of the Cape Flats Aquifer to assess the potential contribution of MAR to the current water supply [40, 41]. Cape Town has 737 known and mapped stormwater ponds [21]. Simulations of SWH via MAR using stormwater ponds as infiltration ponds for the Zeekoeivlei, a catchment area in CT, resulted in an infiltration increase of 47-120% and therefore indirectly demonstrates a significant potential in increasing aquifer recharge [11]. What is left uninvestigated is selecting suitable stormwater ponds for re-purposing to recharge the aquifer. The selection of suitable sites is generally based on the judgement of decision makers, and selection of locations is often made on opportunistic basis [42]. There is a need for a city wide screening tool/framework to identify potentially suitable stormwater ponds for further investigation.

GIS combined with MCDA has been recognised as a useful tool for supporting the identification of stormwater infiltration sites. Selecting potentially suitable sites for infiltration involves integrating several complex parameters, which necessitates the use of GIS in combination with a MCDA [43]. Several studies have assessed the most suitable areas for artificial groundwater recharge using a MCDA in GIS programs [43, 44, 45]. The MAR suitability maps created combined with the stormwater pond location map will indicate the potentially suitable stormwater ponds for infiltration.

GIS-MCDA based site suitability mapping for infiltration sites has not yet been performed for South Africa [46, 47, 48]. Therefore a method to determine the best sites for MAR using the existing stormwater ponds is much needed. Currently, CT does not have any comparable guidance in their attempts to select suitable sites.

To address the challenge, this phase of the project presented a GIS-MCDA based screening methodology to identify potentially suitable infiltration locations. The main objective of this phase was to set up and present a GIS-MCDA based methodology and to demonstrate this methodology for the City of Cape Town. Firstly a suitable GIS-MCDA methodology has been chosen. Secondly relevant parameters/criteria affecting infiltration has been determined, after which the relevant data was obtained. Finally, the various chosen parameters/criteria were standardised and weighted in order to compose the suitability maps.

The innovation presented in this phase is the development and application of a framework. This framework serves as a basic screening tool to identify potentially suitable locations for further detailed investigation. The applied approach can easily be supplemented with additional data.

3
Methodology

3.1. Study Area

The study area is the municipal area of CT. CT is situated in the South West of South Africa sided by the Atlantic and Indian Ocean. The study area can roughly be separated in two distinct areas; the renowned Table Mountain relief and the Cape Flats area. The Table Mountain area has a shallow soil after which bedrock is encountered. The Table Mountain Group (TMG) consists of sand, silt and mud lithified by pressure. The Cape Flats is a (calcareous) sand covered coastal plain. Both are situated on top of the Malmesbury Formation [49]. Due to erosion by fluctuating sea levels the TMG is completely removed from the Cape Flats [49]. The same sea level fluctuations sedimented sand depositions and within the sand layer impervious calcrete-cemented dune sands layers on the Cape Flats [49]. This has created a unconfined sand aquifer, with an estimated surface area of 620 kilometres^2 [30]. On average the aquifer is 20 metres deep with a maximum depth of 50 metres [30].

3.2. GIS-MCDA Method

Geographical Information System (GIS) is a tool for gathering, managing, analysing and visualising data. GIS is recognised as 'a decision support system involving the integration of spatially referenced data in a problem solving environment' [50]. Benefits of using GIS are, amongst others, cost savings resulting from greater efficiency and improved communication by visualisation in maps [51] Multi-Criteria Decision Analysis (MCDA) is concerned with structuring and solving decision and planning problems involving multiple criteria [51]. MCDA entails a collections of techniques and procedures that help structuring decision problems and design, evaluate and prioritise alternative decisions. Structuring complex problems well and considering multiple criteria explicitly leads to more informed and better decisions [52]. GIS-MCDA can be used to rank the GIS data based on decision rules that define how the standardised criteria are integrated [52]. The two separate areas of research, GIS and MCDA, integrated is more comprehensive and cost effective in ranking potential MAR sites than using them separately. GIS-MCDA has proven its use in determining potential MAR sites globally. [52].

A general process to assess site suitability for MAR based on [53] is: problem definition, the selection of criteria, classification of thematic layers and suitability mapping. The suitability mapping includes standardisation, weighing of criteria, overlaying layers and a sensitivity analysis.

3.3. Problem Definition

Recognition of the decision problem is the first step in the GIS-MCDA process for MAR [53]. For a successful implementation of MAR a suitable site allocation for infiltration is a primary requirement [44, 26]. The problem definition is therefore: *What are the suitable areas in CT to implement MAR?*

3.4. Selection of Criteria

In order to produce MAR suitability maps, criteria related to MAR have to be used. These criteria can be divided into different groups as visible in Figure 3.1 [46].

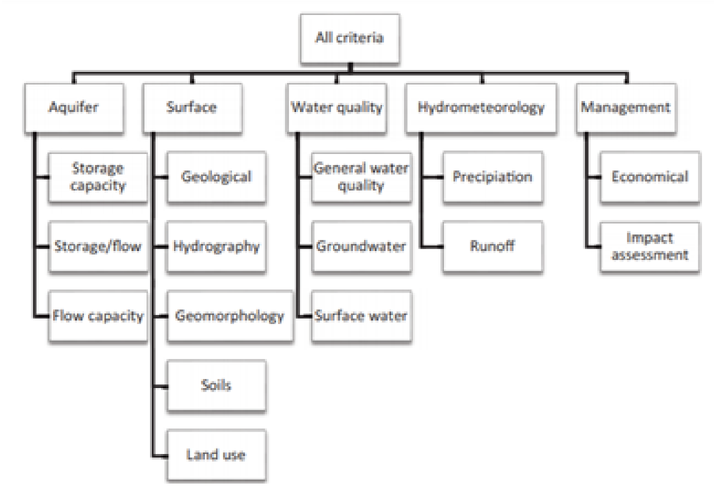

Figure 3.1: Groups of criteria for MAR used in geographic information system – multi-criteria decision analysis studies [46].

A literature research resulted in the following criteria: slope, hydro-geological aptitude, land use, land cover, drainage network density, top soil, peak flow, groundwater depth and flood plains are such criteria [44, 54, 16, 43]. For the purpose of suitability mapping in CT not all categories and criteria provided in Figure 3.1 are thought to be relevant and/or necessary. On the other hand some criteria were thought to be missing and where added. This will also be explained below. The category 'aquifer' is replaced by hydro-geological aptitude as defined in Bonilla Valverde et al. [44]. It includes the geological criteria of category surface. Groundwater depth is added since it has been found to be to inhibit infiltration if it is within 1 metre below the ground [55]. The category 'surface' consist of five criteria of which geological, soils and land use will be used. Hydrography is excluded due to the fact that CT is an urban area where run off is a very fast process, transported towards the SWH sites via the urban drainage system. Geomorphology's most important criterion is slope [46]. Most of the water entering the detention ponds will come from the urban drainage system, therefore slope has been removed [44] [56]. Flood plains is a criteria thought to be missing in Figure 3.1 and is therefore added. The initial purpose of the ponds is flood attenuation, the location of the ponds is consequently in flood prone areas. Infiltration facilities increase groundwater levels and can therefore contribute to more severe flooding in flood plains [55]. This defeats the purpose of flood attenuation. So areas located in flood plains are added. Additionally, the choice was made to use both soils and land use and disregard land cover. The land cover is mostly used in GIS analyses to obtain runoff calculations. This is omitted for this phase, the assumption is made that sufficient stormwater will reach the stormwater ponds through the urban drainage system. This had to be based on expert knowledge of UCT since the stormwater ponds are connected to the urban drainage system of CT. The problem that arised here was that no complete data on the urban drainage system, location and dimensions of pipe system, was available within UCT. Therefore it was not possible to make a own calculation. A simple rationale method was considered, but eventually not conducted since this would not represent the runoff for CT well enough. The category water quality is chosen to be excluded for this phase since no proper proxy for water quality was encountered in literature. The hydro-meteorological category is not common practice for MAR suitability mapping with stormwater ponds and as such has been neglected [46]. The category management is disregarded because this is not within the scope of this research.

3.5. Selection of Data

The department of Water and Sanitation of South Africa has an online resource centre including a database of GIS files. Since the maps cover all of South Africa, the resolution is very low when zooming in on the metropolitan area of the city of Cape Town. After making an account on the website www.wr2010.co.za, the required GIS files are loaded into QGIS. The spatial data obtained via the resource centre are country and city boundaries, watercourses, groundwater level (1x1 km resolution) and geology. Additional GIS data sets are obtained through a ArcGisMapServer connection in QGIS to access the open data portal of the City of Cape Town (http://odp.capetown.gov.za/). The spatial data obtained via the resource centre are high resolution aerial imagery (8cm) and a map of all identified waterbodies. Lastly GIS maps on sensitive information such as the location of informal settlements and the stormwater reticulation system are obtained via the Engineering and Built Environment at the UCT library (EBE). These data sets are not published by the city of Cape Town. The data is obtained via email correspondence and meetings with GIS specialist Nicholas Lindenberg at the EBE. Detailed maps on groundwater, landuse and flood lines are not encountered, the WR2010 data files are therefore used.

3.6. Thematic Layers

The data obtained for the criteria in the previous steps are transformed into thematic maps using GIS. The following maps are produced with the appropriate data:

- Risk analysis: Land use, stormwater ponds, CT's municipal boundary
- Hydro-geological aptitude: geology, aquifer boundary, CT's municipal boundary
- Topsoil: soil, CT's municipal boundary
- Flood prone areas: Flood lines, open water bodies, digital elevation model (DEM), CT's municipal boundary
- Groundwater depth: Groundwater depth, DEM, CT's municipal boundary

The first layer, Risk analysis, was a special request of the client. The risk is the risk of damage to the nearby area with both flooding and site instability. Land use has been used to provide a sense of which areas have the most risk. Hydro-geological aptitude provides the aquifer type, extent and depth. Topsoil indicates the infiltration capacity of areas, certain soils are more suitable than others. This will be elaborated on in chapter 4. The flood prone areas layer consists of the flood lines, DEM and open water bodies since as explained, the stormwater ponds should continue their flood attenuation purpose. An increased groundwater level due to MAR in flood prone areas could increase flooding. Groundwater depth is constructed using the the groundwater depth and DEM. The DEM might not be necessary, but is expected to provide an insight in the spatial pattern of the groundwater depth. A comprehensive explanation of the construction of the thematic layers in GIS is provided in A

3.7. Screening

Screening comprises the elimination of non-suitable areas for MAR application [46]. Areas are excluded by applying Boolean logic if decisive criteria thresholds for the suitability of MAR application are not met [43]. This study uses hydro-geological aptitude and groundwater depth as decisive criteria. Hydro-geological aptitude is assigned a value of 1 if the area is above the CFA and thus suitable or 0 if the area is not above the aquifer and thus non-suitable.Groundwater depth should have its maximum level at 1 metre below the ground to be suitable. The areas that are suitable are assigned a value of 1, if the water level is above the threshold the areas are assigned a value of 0. [55]. In order to obtain 1 for a grid both criteria should be 1, this is the 'AND' Boolean approach.

3.8. Suitability Mapping

The suitability mapping consists of three consecutive steps that will be discussed in the following order: weighted linear combination, standardisation and weight assignment.

3.8.1. Weighted Linear Combination

In GIS-MCDA the decision rule is a fundamental part of suitability mapping. A weighted linear combination (WLC) is a decision rule used when dealing with multi-attribute decision making (MADM) . MADM, a component of MCDA, is data oriented [57]. "*An attribute is a concrete descriptive value, a measurable characteristic of an entity, including inter-entity relationships*" [57]. Weighted linear combination (WLC) is a widely used as decision rule in GIS-MCDA [58, 53]. The first step is to provide a grid over all the thematic layers. Then the scales of the different attributes are standardised subsection 3.8.2. Consequently, a weight is given to the different thematic layers subsection 3.8.3. This finally results in a suitability map which is provided in chapter 4. The WLC formula to calculate the suitability score S [59]:

$$S = \sum w_i x_i \times \prod c_j \tag{3.1}$$

Where:

S is the suitability score
w_i is the weight assigned to the thematic layer i
x_i is the index of the thematic layer at the cell considered i
c_j is the value of the constraint factor j
$\sum$ is the sum of weighted factor criteria
$\prod$ is the product of constraint criteria (1=suitable; 0=unsuitable)

Note, if a screening phase, applying a Boolean approach, is already included it is not necessary to include a constraint factor, c_j, and product of constraint factor, $\prod$, again. This will simplify the equation.

3.8.2. Standardisation

Standardisation is the process of implementing and developing technical standards which are based upon literature or expertise. The attributes of the five thematic layers need to be standardised to be able to compare these distinct layers via the WLC rule. Both step-wise and linear function are accepted methods of standardisation [53]. A step-wise function was used for soil, hydro-geological aptitude and land use. The attributes of soil, hydro-geological aptitude and land use are each categorised and valued on a scale ranging from 0 till 1. A linear function was used to standardise flood prone areas and groundwater depth and consequently also standardised on a scale ranging from 0 til 1. The calculations are provided in Appendix A.

3.8.3. Weight Assignment

The last step in WLC is the weight assignment. The weights of the criteria describe the relative importance of one criteria over the others [46]. This is necessary since the criteria bear a different degree of influence [60]. Four methods to weigh assignment exist: ranking, rating, pairwise comparison and entropy based criterion weights [58]. Common practice in similar research is the analytic hierarchy process (AHP) pairwise comparison and multi-influencing factors (MIF) to set a weight for the suitability mapping [16, 58, 44]. The reason not to use ranking and rating is that these are rather simple methods that provide less information [58]. MIF is a method whereby factors/attributes that influence the other factors, besides the criterion, are given more weight [45]. This method is however only valid when all criteria can also influence each other, this is not the case for the criteria of this research. The AHP method compares the different criteria within a set of reciprocal matrices. A ranking from 1-9 is assigned to a criteria in comparison to another criteria with respect to their significance for MAR suitability. This ranking is done with expert knowledge. The Consistency Ratio (CR) is consequently introduced to check the consistency of the assigned weights.

$$CR = \frac{CI}{RCI} \tag{3.2}$$

The CI is calculated as follows:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{3.3}$$

Where:

RCI is Random Consistency Index
CI is the Consistency Index
λ_{max} is principal eigenvalue
n is the number of criteria

The CR value should be less than 0.1. If this condition is not met, the weights assigned should be adjusted to account for consistency [61]. See Appendix A for a more detailed approach for the weight assignments performed for this study.

3.9. Sensitivity Analysis

In the real world data, and consequently information, bears uncertainty [62]. Solving that problem is outside the scope of this report, however addressing the uncertainty with an sensitivity analysis already provides a more robust approach to determine MAR [56]. A sensitivity analysis is "*The study of how the uncertainty in the output of a model (numerical or otherwise) can be apportioned to different sources of uncertainty in the model input*" [62]. The effect of the weights to the criteria assigned by different decision makers or experts on the suitability maps can be displayed and assessed [58]. Several methods exist to perform a sensitivity analysis [62]. The'one-at-the time' and 'variance-method', among others, are applicable for MCDA research [58]. The variance-method will be described below, since it has been encountered most often in comparable research [46]. In the variance-method the weight assigned to a criteria in the AHP is slightly changed. It is essential to make the weight difference not too large, since this might alter the CR value. The effect of this small change can consequently be studied on the spatial pattern of the suitability map [58].

4
Results

An intermediate result is the suitability of a thematic layer without the overlay of the other thematic layers as displayed in Figure 4.1. The soil abbreviations, Sa, Lm and Cl are respectively Sand, Loam and Clay. The suitability of the different colour range from red; least suitable, to dark green; most suitable. A clear distinction between suitability can be obtained.

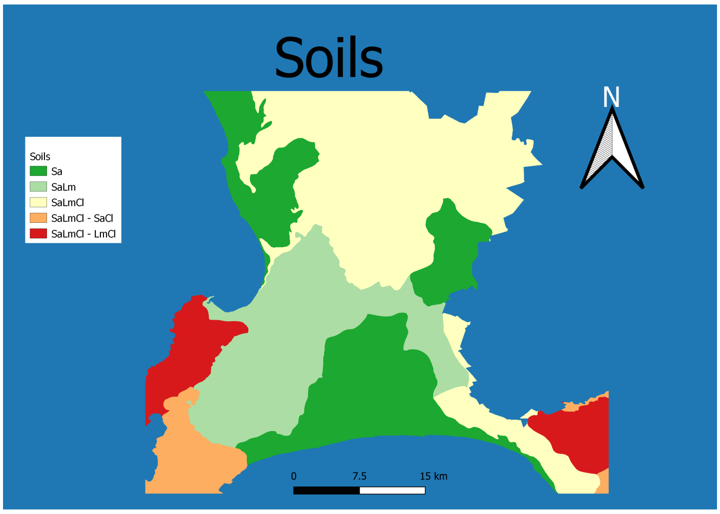

Figure 4.1: Suitability for soil map

Next, the criteria are standardised. Flood plains are standardised according to the return period of the flood lines. The greater the flood frequency, the less suitable the area is thought to be. The data available contains only one return period flood line so the following standardisation could not be performed entirely . The standardisation function proposed is linear. A once in half a-year flood is given 0, once in 5-year flood 0.2, once in 10-year flood 0.4 and once in 50 or above 1.

For the risk analysis, the land uses have been classified as being opposed to most risk. Risk is defined as: a flood event induced by a infiltration basin, the likelihood of occurrence of the event and the negative effect that the occurrence would have. The land use with the most economic value and the highest likelihood of losing this value due to the flood events is ranked least suitable and vice versa. Standardisation of risk analysis: urban 0, agriculture 0.25, rural 0.5, mountain 1 [63].

The soil type is divided into four classes to standardise. The first class consists of sand, secondly sandy loamy soils are most suitable. Then sandy loamy clay that contain clay to a minor extent, sandy loamy clay with mostly sandy clay and lastly sandy loamy clay with mostly loamy sand. The assigned step-wise standardised values are respectively 1, 0.75, 0.5, 0.25 and 0 [44].

The groundwater level needs to be at least one metre below the surface for an area to not be excluded. However, due to the fact that the main soil type is sand, infiltration rates are high and the groundwater level can be locally elevated, called mounding, which can reduces the groundwater level to less than one metre below the surface. Therefore groundwater levels of with the threshold value of one metre below the surface obtain a low suitability, 0.1. From -50 metres and lower, the groundwater table will not increase the suitability for MAR [64]. A linear standardisation is applied between – 1 to -50 metres [64] The standardised plots of all the criteria are provided in Figure 4.2.

The hydro-geological aptitude is standardised step-wise based on the information provided in section 3.1. The TMG formation is unsuitable for managed aquifer recharge using infiltration basins and therefore obtains a value of 0. The sand deposition North of the Cape Flats are more compacted and therefore less suitable than the sand deposition on the Cape Flats itself ([30]. Thus the respective values are; 0.5 and 1.

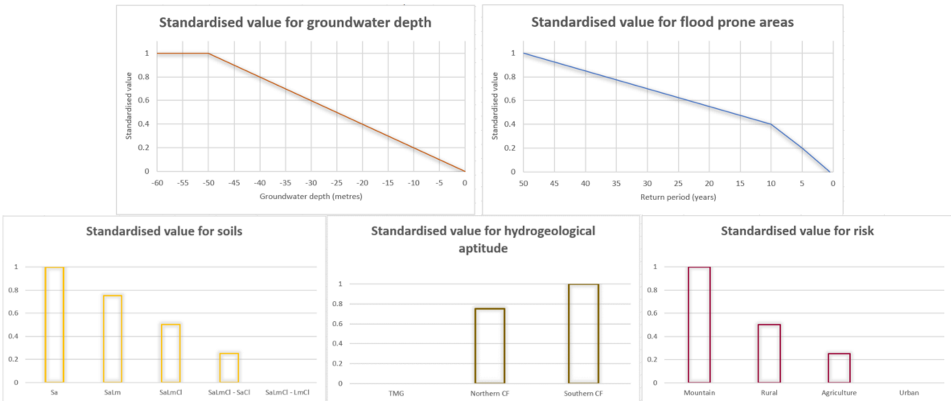

Figure 4.2: Standardised values for the criteria

The five thematic layer are overlain with the assigned corresponding weight. The result is a suitability map presented in Figure 4.3.

Figure 4.3: Suitability map Cape Town

The suitability of areas is ranked from dark green; most suitable, to lighter green and lastly red; unsuitable. The most suitable area has almost the same extent of the CFA. The southern stripe of the Cape Flats shows lighter green and the waterbodies show red.

5

Discussion and Conclusion

A suitability map for MAR by SWH is developed. The data in the GIS-layers which were used to generate the suitability map was too coarse to create a detailed map. It is recommended to create a new suitability map with refined data using the method described in chapter 3. The GIS layer of flood plains that was used consists of 1 polygon per water course. Preferably this would be several polygons, representing the different return periods of a flood event to happen. Additionally, the meta-data does not show what the return period of the flood plain is. The soil coverage data used is not contain sufficient detail. However, higher quality GIS layers have been encountered on a website with a GIS interface. This data is produced by the Western Cape government, however it was not possible to extract the data from this website [65]. Additionally, although a GIS layer containing stormwater ponds is available, whether the map is complete is not certain [21]. Lastly, the GIS data for the groundwater levels has a resolution of 1 by 1 km. This is coarse, but is thought to suffice for the current application. Higher resolution data was not available. Therefore, the choice was made to produce the suitability map using the available data, to test if the method works. The method proved to work since it produced a suitability map indicating that the area of the around and above the CFA is the most suitable area for MAR using SWH (dark green area in Figure 4.3). This is in line with literature reporting about the location of the CFA. Other areas such as the North West and Centre East appear to be promising areas as well. A difficulty encountered using the INOWAS tool was that the INOWAS website could not process large data files, such as the raster files used in this phase. The resulting suitability maps of INOWAS and the method in this phase are the same except that the constraints in the INOWAS tool appear as a red colour instead of excluding those grids. An important note it that the output of the INOWAS tool is not a GIS file but a PNG file. It is therefore recommended to use INOWAS to assist in the weighting step, since it has a build in software for AHP weighting. Apart from that, the choice has been made to continue to use INOWAS because of the open source aspect.

Phase I has proved to be a framework to spatially assess the suitability of areas for MAR using SWH. Both the INOWAS tool as an analysis in GIS are described to produce a suitability map.

II

Physical Assessment

6 Introduction

From phase I an overview of ponds that are considered suitable regarding their location is provided. The next step is the physical assessment, in which individual ponds are examined. The spatial assessment is helpful in minimising the amount of ponds needed to investigate in the physical assessment. Phase II can be used on its own when for e.g. data required for phase I is not available. The physical assessment can be used as a guide for the field measurements, the ponds must be properly investigated to assure the requirements for infiltration are met. This investigation and assessment will lay the foundation for redesign measures that need to be taken in order to meet these requirements.

The design of a conventional infiltration pond normally follows a pre-determined design process. For retrofitting existing detention ponds into infiltration ponds the design process is slightly different. Parameters such as location and dimensions are fixed, which will change the procedure of designing the pond. Therefore a generalised and objective methodology to investigate, assess and monitor the potential of existing ponds for infiltration is required and produced in this phase. The methodology is tailored to suit the context of CT. The goal is assessing individual stormwater detention ponds on its suitability for retrofitting into an infiltration pond. It will lead to design criteria needed to achieve infiltration, or it might eliminate a pond if it can not be retrofitted.

The framework is divided in four different parts; hydro-geology, hydraulic analysis, water quality and risk assessment. Phase II is organised as follows: the first section is the methodology. In this chapter the general approach to obtain the physical assessment of the framework is described, along with guiding questions that are to be answered. Hereafter, the methodology is subdivided in four parts, in line with the four parts of the framework mentioned before. The methodology for each of the parts consists of an explanation of the general approach taken to construct the physical assessment of the framework. Furthermore, the methodology also contains a justification for the methods used, data obtained and decisions made to obtain the final result. The result of phase II is a framework on how to physically assess a existing stormwater pond on it's potential for retrofitting. The measurement and calculation techniques required in the methodology are further described. The outputs from the framework will be used in the conceptual design in phase III. Finally, the discussion and conclusion contains important findings and main recommendations of this phase.

7

Methodology

In this chapter the methodology of building the part of the framework responsible for assessing the suitability of the stormwater ponds is explained. Several manuals and studies on designing and assessing Sustainable Urban Drainage Systems (SUDS) [55, 20, 66, 67, 68, 69, 70, 71] along with specific requests and local knowledge from the client are used to build up the overarching questions that must be answered to assess a pond's suitability. The questions are divided in the four parts as described in the introduction. They are all assigned a different color, such that the reader always knows to which part a certain topic belongs while reading this phase.

1: Hydro-geology

- What is the maximum groundwater level beneath the pond?
- Is the soil contaminated and until what depth?
- What is the infiltration capacity of the pond's soil?

2: Hydraulic Analysis

- What is the maximum surface runoff volume the pond should be able to drain given its dimensions?
- What is the current and potential annual yield, infiltrated water, of the stormwater pond?

3: Water Quality

- Is the groundwater contaminated?
- Is the influent water contaminated?

4: Risk Assessment

- Is there a risk of groundwater flooding in or near the pond?
- Is there a risk of subsidence or other forms of soil instability due to infiltrating water?
- Are there risks associated with infiltrating water in proximity to existing structures?

The methodology for each of the separate parts describes the relevance, overall approach and the data collection, along with the reasoning behind the chosen parameters and tools that are suggested. The methodology how the stated questions above are answered in the framework are described in the different sections.

7.1. Overall Order Physical Assessment

For a smooth and efficient assessment, the order of the measurements is of importance. The reasoning behind the order in the physical assessment of the framework is to place the determinative and relative simple steps first when possible. If a certain measurement determines if a pond is eliminated or not independently of other factors, such a measurement should be executed in the beginning of the assessment. Another reason for the chosen order is that some calculations require inputs obtained by another measurement. This approach will prevent one from taking unnecessary measures that are labour intensive and may lead to high costs. A final overview of the order is presented in the result chapter, for the methodology the hydro-geology is discussed first, followed by hydraulic analysis, water quality and finally the risk assessment.

7.2. Hydro-geology

Various factors determine if a detention ponds is suitable for retrofitting for MAR via infiltration. The hydro-geological factors to be considered are depth and fluctuation of the groundwater table, the soil characteristics, contamination and infiltration rate of the site [55][70]. This chapter briefly discusses what is already known about the geology of the area based on previous studies. Afterwards, the hydro-geological factors and the preferable method to asses them are discussed.

7.2.1. Desktop Study

Several studies have identified the subsurface of the Cape Flats in order to asses its hydro-geological suitability for aquifer development and management [30, 72, 73]. These studies indicate that the CFA consists of a sand covered coastal plain referred to as the Sandveld Group [74, 73]. The various lithologies of the Sandveld Group form a heterogeneous, stratified, unconfined aquifer that is suitable for MAR via infiltration [30, 40]. Areas within the region that are less suitable for infiltration due to their corresponding infiltration rates are parts of the shallow coastal sands that are covered by limestone deposits and calcareous sands [75, 76] and small inland vleis that deposited marine, silcrete clays and bottom sediments [77]. The ground water level in the region is positioned within a few meters from the surface level (around 3.4 m on average) [30, 40]. The geology of the Cape Flats is described in detail by Henzen and Vandoolaeghe. Based on these extensive studies and open GIS data, non-suitable areas can be excluded based on there hydro-geological characteristics via a desktop study. Areas that show infiltration potential can also be determined in this way. Site specific conditions may differ and hence a field assessment is necessarily to evaluate the site specific potential[70]. The methodology of the field assessment and the parameters to be obtained are tailored to the context of CT and the local geology. Therefore it is important to be aware of the geological background before the start of the second. phase.

7.2.2. Groundwater Level

One important parameter to determine if a detention pond is suitable for MAR it the maximum groundwater level. The depth between the infiltration base and the groundwater level should be at least 1 m above the seasonal high water table, according to the constraints stated by Woods et al. This, to maintain the performance of the infiltration process by ensuring a certain depth of unsaturated material through which the water can flow and to protect the groundwater from contaminants from the surface runoff [55]. The maximum groundwater table is reached by the end of winter, after the groundwater is (naturally) recharged by rainfall [40]. In order to answer the following question: *What is the maximum groundwater level beneath the pond.* It is necessary to obtain a measurement during wintertime. The minimum groundwater level will be reached in the beginning of March [78]. To understand the depth and the fluctuations of the subsurface it is needed to monitor the groundwater level on a regular base. A bore hole at the lowest point is required to obtain the maximum groundwater table. A well at the inlet and a well at the outlet of the pond is needed to understand the hydraulic gradient of the pond. These wells are also used for quality sampling.

7.2.3. Soil Characteristics

Woods et al. states that the soil characteristics are of key importance for MAR. The soil should be permeable, ensure an infiltration rate above 25.4 mm/hr and the pond should be able to empty within 24-72 hours. Contamination and to what extent plays a large role in determining the pond suitability as well[55].

As shown in the figures, the soil of the Cape Flat aquifers consist mainly of sand [30].

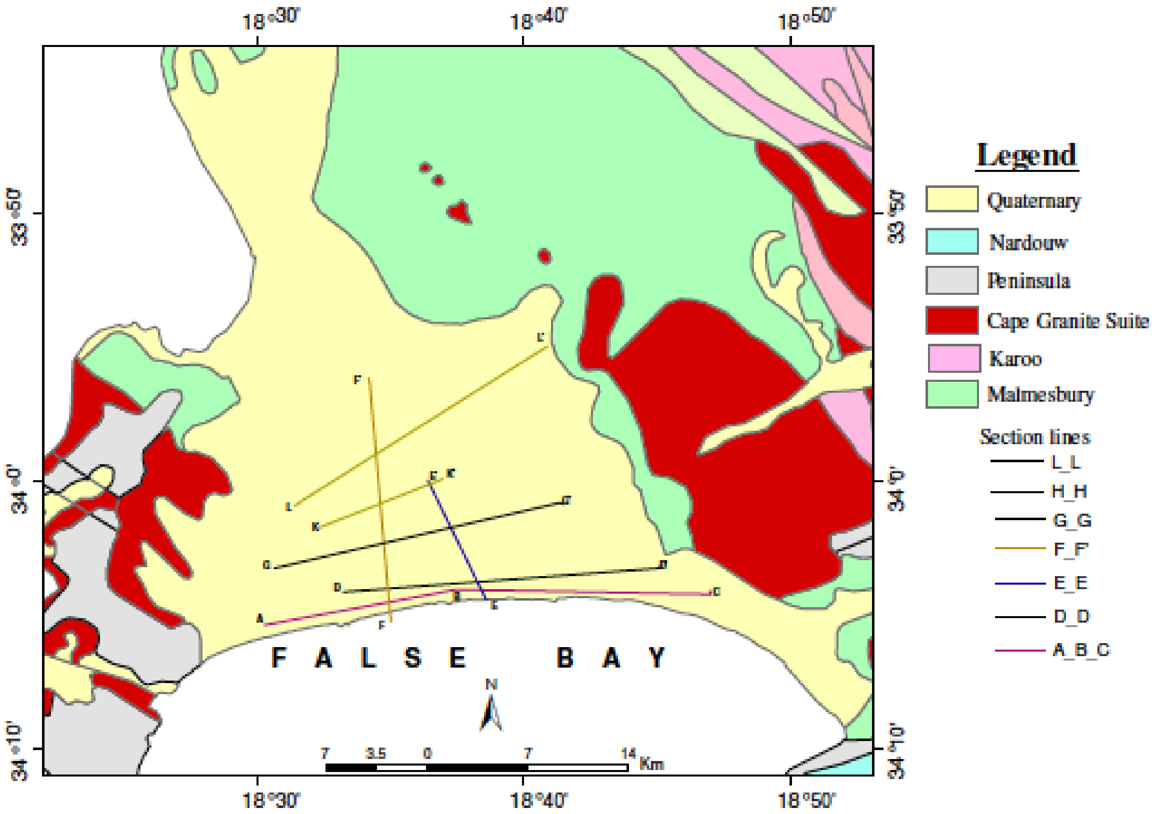

Figure 7.1: Geological map of the area around the Cape Flats [30]

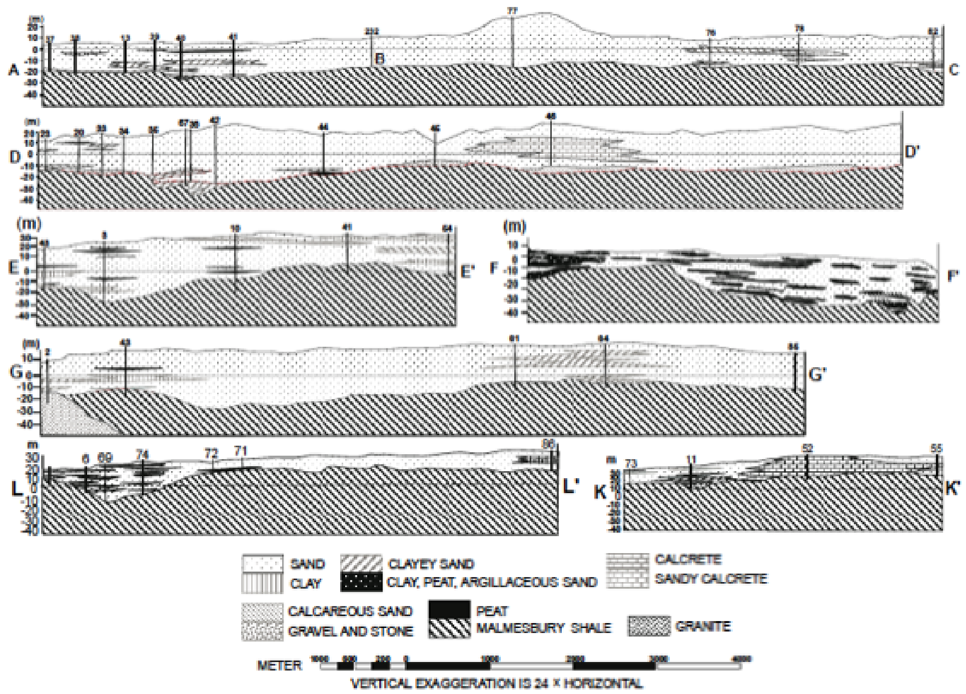

Figure 7.2: Geological cross-sections of the Cape Flats area [30]

Table 7.1: Basic infiltration rates, adapted from [79]

Texture class	Infiltration rates [mm/hr]
Sand	210.1
Loamy sand	61.2
Sandy loam	25.9
Loam	13.2
Silty loam	6.9
Sandy clay loam	4.3
Silty clay loam	2.3
Sandy clay	1.5
Silty clay	1.3
Clay	1.0

The structure, texture and corresponding porosity and permeability of this sand allows for sufficient infiltration rates, if no other layers such as peaty lenses are present [30]. Field studies should reveal that the subsurface of the site consist of this sand. Lithologies from the well points can prove the existing of the expected sand layer via a simple method described in the field manual (Appendix B). More samples can be taken via an aluminium core to generate a more precise soil profile. If these cores deviate from expectations, they must be taken to the laboratory for a detailed examination. Here, the soil structure, texture, porosity and permeability must be examined.

Soil Contamination

Once the soil characteristics are known, the question *'Is the soil contaminated and until what depth?'* needs to be assessed. Assessing soil contamination in a pond is a difficult and tedious task since pollutant concentrations vary largely with the dominant size fraction in a soil layer, its pH, the electrical surface charges of particles and the amount of oxygen in the soil. Important measures for assessing soil contamination and soil risk assessment are concentrations of heavy metals-, trace organics-, pharmaceutical concentrations, the electrical conductivity (EC) and the pH. The EC can give an indication about the salt concentrations in the soil and the pH indicates whether there is a risk of already present heavy metals leaching to the groundwater in case of infiltration. The importance of soil contamination also depends of the future end-use. Since the end-use of the infiltrated water is not defined groundwater contamination should be limited. Therefore, a soil with high initial concentration would be a bad starting point for infiltration pratice. In the PHA area for instance, groundwater is abstracted for irrigation purposes, heavy metal contamination of the groundwater would be of severe concern since this water further concentrates during irrigation practice as it is already the case with nutrient concentrations [37]. In the following section it is briefly discussed how to measure heavy metal pollution, EC and pH. Measurement of trace organics and pharmaceuticals is not discussed since these measurements are expensive and require sophisticated laboratory equipment.

The soil sampling should be as representative as possible. This however is very site specific and therefore the objective of sampling must be determined first. From which follows the density of sample points the sampling time, sampling procedures, subsequent treatment of samples and the analytical requirements [80]. Within this section the focus lies upon how to assess soil contamination. Assessment of soil contamination is necessary as part of a hazard and risk assessment when the potentially contaminated land is used for a specific purpose that might lead to human or environmental exposure to contamination. Sampling strategies should be developed specifically tailored to the site in question. For this purpose ISO 10381-5 (1995) and ISO 10381-4 (2004) can give guidance on how to assess soil contamination for a given urban site [80].

Soils with high pore space are more likely to let pollutants pass through thus taking a longer time for those soil to become contaminated but on the same posing a higher risk for groundwater contamination. Heavy metals (i.e. copper, zinc, lead) and trace organics can build up in the upper soil layer of infiltration basins. Leaching seems to be minimal and risk of contamination of underlying groundwater therefore low. Most of the contamination is bound in the fractions below < 2 mm. Other pollutants which are highly soluble such as pesticides and salts are more likely to leach from the soil and pose a potential risk for groundwater contamination. Overall fine soils seem to act as a good pollutant trap but can pose a future solid waste problem since pollutant levels can reach environmentally critical levels [81].

Sampling Heavy Metal Pollution

Total metals and dissolved metals can be measured by bringing them into solution, normally with an acid. The obtained solution can then be analysed in an AES or AAS device with prior filtration. When taking samples in the field it is crucial to sample in periods without rainfall. Taken samples should be stored in plastic bags and in a cool and dark place until analysis in the laboratory. Sample preparation involves removing any large stones, plant components and or artefacts and crushing into a fine fraction, e.g. below 2 mm. For a more detailed description of soil sampling and analysis methods (heavy metals, AOX and PAHs) for soil contamination one can refer to [82].

Sampling Soil pH and Soil EC

Measurements that can be done relatively easy and without expensive laboratory equipment are the measurement of the soil pH and the soil EC which can give a first indication if the soil is polluted by salts (EC), if leaching of heavy metals is likely to occur or if biological activity is to be expected [83].

Measurements should be taken at different locations in the pond. It is crucial that the sampling depth is consistent. Due to the spatial variation of EC and pH in the field, taking a couple individual samples distributed over the field measurement area gives more information than repeated sub-sampling in fewer locations. To measure the EC and the pH a soil sample is mixed with an equal part of distilled water in a beaker to bring ions into solution. The EC and the pH are then measured with a conductivity meter and a pH probe respectively. The EC should be measured before the pH since salts are diffusing from commercial pocket pH meters which can lead to wrong EC readings. Before measuring both meters must be calibrated. Conductivity was shown to be dependent on soil texture but they are related in a consistent manner. A more accurate but more time intensive method is the saturated paste method which can be used if the described quick field method indicates problems [83]. For a detailed description and discussion of the described measuring procedure see [83].

7.2.4. Infiltration

The key component determining the suitability of the site is the ability of water flow through the soil [70]. Infiltration is the process where surface water enters the subsurface (the vadose zone). Percolation describes the downward movement of water through the subsurface after infiltration [84]. Water that infiltrates can percolate the water table and enter the aquifer, evaporate, be stored in the vadose zone or flow through downgradient discharge areas. The term 'recharge' describes the flux of water across the groundwater table into the phreatic zone [70].

Infiltration Rate

The infiltration rate describes the velocity at which water enters the soil and is usually expressed in mm/hr or m/day. This amount varies over time, due to the amount of available water, the moisture content and clogging due to sediment particles [84]. Hydraulic conductivity describes the ease with which water flows through the subsurface.

Infiltration Capacity

The infiltration capacity is defined as the maximum rate at which the infiltration will occur, when the rate is not limited by the water supply. The capacity for a given soil is expressed per unit area under given conditions [85]. The rate of infiltration will be higher when the soil is dry, due the greater capillary action. The recharge rate on the other hand will be lower when the soil is dry since the infiltrating water will first complement the soil-moisture deficiency. Once the field moisture capacity is achieved, the infiltrated water is available for groundwater recharge [84]. 'Field or field moisture capacity' is the amount of moisture or water in the soil after excess water has drained away and the rate of downward movement has decreased [84].

Measuring Infiltration

In order to answer the question *What is the infiltration capacity of the pond's soil?*, it is needed to measure the infiltration at the pond. Although the subsoil may have sufficient hydraulic conductivity rates and is mainly based on soil characteristics, the topsoil can vary a lot due to e.g. sedimentation, long-term clogging due to siltation and the buildup of biomass. Therefore, infiltration testing on the site will reveal the local conditions of the topsoil. There are several methods for infiltration testing [70]:

- Single-ring and double-ring infiltrometer.

- Pilot (basin) infiltration test.
- Borehole permeameter.
- Velocity permeameter.
- Double-tube method.
- Air-entry permeameter.
- Core testing.

Infiltrometers are usually used to measure the rate of water infiltration into soil or other porous media, whereas permeameters are used to measure the hydraulic connectivity at different depth. The measured infiltration rates are affected by the permeability and capillarity of the soil and the initial soil moisture content. Complications that both, the infiltrometer and permeameter test, may face are lateral flow divergence and air entrapment. Flow divergence in the lateral direction due to vertical infiltration is caused by capillarity in the soil and variance in hydraulic conductivity. Divergence effects may increase when the infiltration rate decreases and the permeability (as a function of depth) decreases [86]. A method that provides a partial solution to overcome the effects of divergence is the double ring infiltrometer.

Double Ring Infiltrometer

The double ring infiltrometer measures the rate of steady-state vertical infiltration which equals the saturated hydraulic conductivity. Due to the lateral divergence that might still occur, this test overestimates infiltration rates, but less than single ring infiltrometer tests. To correct for this overestimation, one can increase the test area or correct for divergence in the calculations [70]. Nevertheless, constant-rate double-ring tests are adequate to test sandy soils and are cheap and relatively easy in its use and therefore suitable for the Cape Town context [87]. Therefore, this method is recommended for the site analysis as long as sufficient correction factors for the design are used [88].

Infiltration calculations

There are different empirical and physical based methods to describe one dimensional infiltration such as the Lewis, the Horton the Green-Ampt, and the Philip equation. From previously mentioned methods, the Green and Ampt is the only physical based one. The advantages of this formula are that it can be related to the physical properties of the soil [89, 90]. The infiltration measurements obtained from the field can be used for as direct estimation of the infiltration rate as an input for e.g. the water balance, rainfall-runoff relations and yield estimations. The hydro-geological parameters such as capillary suction, saturated hydraulic conductivity and initial soil moisture deficit can also be used to estimate the infiltration rate via the Green-Ampt formula. An estimation of the saturated hydraulic conductivity can be made based on the soil characteristics and the. The capillary suction can directly be obtained from the field, like the (initial) soil moisture. Soil moisture measurements at the pond can be done by profile probe [91].

The Green-Ampt formula links instantaneous infiltration rate to cumulative infiltration [70].

$$F(t) = K_s t + \psi_f \Delta\theta ln[1 + \frac{F(t)}{\psi_f \Delta\theta}] \tag{7.1}$$

$f(t)$	Instantaneous infiltration rate at time 't'[mm/h]
$F(t)$	Cumulative infiltration at time 't' [mm]
K_s	Saturated vertical hydraulic conductivity [mm/h]
ψ_f	Soil-water potential (suction head) at the wetting front [mm]
$\Delta\theta$	Change in soil moisture across the wetting front [-]

The infiltration rates also serve as input for the hydraulic analysis.

7.2.5. Influence of TSS and Hydraulic Parameters on the Infiltration Rate

TSS pose significant problems for the operation of infiltration systems since they can quickly clog a pond which is a common reason for infiltration ponds to fail. Therefore, pre-treatment, i.e. pre-sedimentation (see chapter 11) of the non-biodegradable fraction (sand and silt) and biodegradable solids, must be applied to ensure operability of the infiltration pond over the designed lifetime. Biodegradable solids can clog the pond as well but in contrast to inorganic sediment they can degrade over time. However, there is the risk of clogging due to biomass growth. This growth can be limited when the pond is dry most of time. A promising tool, developed by INOWAS to estimate Reduction of infiltration rate (clogging), is explained in Appendix G. This tool is not further included in the assessment methods of the Physical assessment since it needs further refinement, however it might prove itself useful in the future.

Influence of Hydraulic Loading Rate and Wetting/Drying Cycles

Assessment of the hydraulic loading rate and the wetting and drying phases can give an indication of how fast an infiltration pond will clog and how much maintenance is required to maintain infiltration rates. On one hand the hydraulic retention time (time the water remains in the pond) must be long enough to allow for adequate treatment but on the other hand short enough that the pond can dry out after a rain event. This is required to let the soil restore its aerobic conditions at the surface layer which facilitates natural degradation of the clogging layer [92].

Hydraulic Loading Rate The Hydraulic Loading Rate (HLR) is the volume of water that is planned/possible to be infiltrated. The HLR is dependent on the hydraulic capacity which is a site specific parameter itself dependent on soil texture and bulk density which is dependent on the availability of water and the hydraulic conductivity (see chapter 11). The HLR (m/a) is the water column that is infiltrated above 1 m^2 in 1 year. Multiplying the HLR with the surface area of the pond and dividing by the number of days one can expect rainfall, will give the amount that is infiltrated per square meter per day. This number is the required infiltration rate per day.

Hydraulic Loading Cycle The Hydraulic Loading Cycle (HLC) is the relation between wetting phase and drying phase with the first number being the unit of wetting time. For instance an HLC of 1:2 would indicate that the dry phase is double as long as the infiltration time.

With an operation of seven days wetting- and seven days drying-phase the infiltration rate for fine textured silt soils is significantly reduced. A cycle of three days wetting- and seven days drying-phase enabled to achieve infiltration rates close to initial conditions and prevent further clogging. Algae growth leads to fast clogging of the soil and reduces infiltration rates significantly. If the hydraulic retention time is maintained short to prevent ponding, algae growth was found to be negligible. In finer textured soils such as clayey soils there was significant ponding and algae growth which lead to fast clogging of the soil column [93].

Ideally, for the operation of an infiltration pond the dry phase should exceed the wetting phase to restore aerobic conditions and to remove the clogging layer. Since, drying and wetting cycles in stormwater infiltration ponds occur naturally it might be required to bypass water to control the wet and dry phases. This however, would increase the flood risk for areas further downstream of the pond. Reducing the clogging rate caused by the wetting and drying cycles will only work for biodegradable solids which can degrade naturally. For sediments such as sand and silt pre-sedimentation will be required (see chapter 11).

7.3. Hydraulic Analysis

Understanding the hydraulics of the stormwater is a vital part of retrofitting the existing stormwater ponds into infiltration ponds. The dynamics and quantity of runoff that emanates from the urban sub-catchment will govern much of the decisions made during the design phase, and is important to be able to assess the potential risks. The hydraulic analysis is necessary to estimate flow peaks, runoff volumes and time distribution of runoff. With this information, the necessary detention, infiltration and flood-control functions of the pond can be obtained.

This section outlines the general approach taken to obtain the final framework of the hydraulic analysis. The purpose of this chapter is to explain the reasoning behind the chosen parameters and methods that are presented in the chapter 8.

The overall methodological approach for the hydraulic analysis steps are guided by the following questions:

- What is the maximum surface runoff volume the pond should be able to drain given its dimensions?
- What is the current and potential annual yield, infiltrated water, of the stormwater pond?

The sub-questions that arise to answer the first question are the following:

- What are the rainfall characteristics of the area?
- What are the characteristics of the upstream urban sub-catchment?
- What are the dimensions of the pond?
- What is the estimated resulting flow rate and runoff volume that will enter the pond?

This chapter is therefore categorised into five parts, according to the questions mentioned above; climate and rainfall, catchment characteristics, pond characteristics, drainage analysis and annual yield estimation.

7.3.1. Climate and Rainfall

The climate and rainfall characteristics are key factors to assessing and designing stormwater systems. As stated in the SUDS Manual, a depth of rainfall is required in order to make assessments on the likely rate and volume of runoff from a developed site or catchment [55]. Rainfall is variable in both space and time, which makes estimating urban runoff rate and volume challenging.

Nonetheless, an estimation of the rainfall characteristics of the sub-catchment is a necessary input for sizing an infiltration pond. As argued by Okedi, “rainfall data is a key input in hydrological modelling” [11].

Rainfall data is obtained from weather stations, which are in itself point measurements and thereby not representative of a larger area, but using the data from various stations and interpolating between these will more accurately represent the spatial distribution of rainfall.

A ‘design storm’ is a characteristic weather event that corresponds to a given probability level (or return period), derived from statistical analysis [55]. The quantitative properties of a design storm for a certain location include the value of the maximum or peak rainfall intensity, the duration of the storm, the cumulative rainfall depth and its spatial distribution of the intensity [94]. As mentioned before, rainfall characteristics are by nature extremely complex, and the diversity of land-uses within a catchment results in nonlinear runoff response. Considering this, a single design storm as input to a hydrological system doesn’t realistically represent rainfall characteristics and will not adequately portray a wide range of possibilities [94]. A more accurate representation of rainfall can be obtained from high spatial and temporal resolution historic data which shows the internal structures that may exist within historic rainfall events. However, the directly inferred design storm from IDF is common practice and also used in the The South African SuDS Guidelines [20]. The main reasons to represent rainfall in such a way are; scarcity of adequate data for more advanced options, lower computational cost compared and this method is widely employed for engineering urban drainage applications [94].

7.3.2. Catchment Characteristics

The existing ponds all receive and manage runoff from different drainage areas with different catchment characteristics. In order to understand the rainfall-runoff relationship for a certain pond, the land-use, topography and stormwater reticulation of the upstream catchment must be understood.

Different land-uses lead to different runoff amounts, depending on the level of imperviousness of the surface. GIS is a functional tool to visualise the various land-uses of the catchment and calculate the degree of imperviousness of the catchment. Since the stormwater ponds are situated in an urban environment, the stormwater reticulation system is necessary for the drainage analysis. The stormwater drainage design in Cape Town consists of a minor and a major systems [95]. The minor system consists mainly of an underground pipe network that is designed for storms with a 2 to 5 year return period. The major system includes watercourses, roads and ponds and is designed to attenuate the runoff from extreme, infrequent storm events. The various layers that are necessary to estimate runoff and can be loaded into GIS are: land-use (including soil type), topography and the minor and major stormwater reticulation system.

7.3.3. Pond Characteristics

Assessing the size of an existing detention pond that is to be transformed into an infiltration is conceptually simple. The basin should have adequate infiltration capacity and storage volume such that the inflow runoff volume either evaporates, infiltrates, overflows or is temporarily stored. Knowing the exact volume of the pond is thus crucial to include in the drainage analysis. The existing ponds vary widely in size and dimensions, and are often shaped irregularly. Estimating the size with common tools such as a measuring wheel will often not sufficiently capture the exact shape and therefore lead to wrong estimates of the volume. Thus performing an extensive survey to obtain a model of the pond is recommended as part of the hydraulic analysis. The method to obtain more accurate dimensions is explained in section 8.3.

7.3.4. Drainage Analysis

Although the pond should be tested with worst case high intensity and long-duration storms with statistical analyses, continuous storm water simulation should be done in order to optimise the pond during the design phase [55]. The pond performance depends on the antecedent soil moisture conditions of the pond, which depends again on the time distribution of rainfall events. For more detailed analyses computer models must be used to more accurately represent the hydrological cycle. Several modelling tools such as SWMM-Based programs exist that integrate climatic factors that are important for the wetting and drying cycles of the ponds.

Due to the fact that infiltration ponds have thus far not been constructed in Cape Town, the South African guidelines and criteria that exist focus on flood attenuation of stormwater ponds rather than criteria such as the infiltration capacity of ponds. Certain volume-based stormwater runoff quality and quantity management standards have been developed elsewhere. The 'Management of Urban Stormwater Impacts Policy, 2009' states that "all stormwater management systems shall be planned and designed in accordance with best practice criteria and guidelines laid down by Council, to support Water Sensitive Urban Design principles" and "This Policy is applicable to any land use, development or activity proposals within the metropolitan area of Cape Town draining to any watercourse, wetland or coastal area" [96]. The definitions and guiding principles behind the interim criteria provided in the Policy are from the following documents, and often used in the context of Cape Town:

- The South African Guidelines for Sustainable Urban Drainage Systems, 2013 [20].
- Georgia Stormwater Management Manual, Volume 1 and 2, 2016 [97]
- Minimum Standards for Roads and Stormwater Design, Version 2, 2014 [95]

Table 7.2: Interim criteria for achieving SUDS objectives [96]

Criteria	Definition Georgia Stormwater Manual	Definition SA Guidelines SUDS [20]	Policy [96]
Water Quality Volume (WQ_v)	Retain or treat the runoff from 85% of the storms that occur in an average year	Volume of water from small storm events where the focus is on treating for water quality	1:0.5 year, 24 hours
Channel Protection Volume (CP_v)	Provide extended detention of the 1-year, 24 hour storm event released over a period of 24 hours to reduce bankfull flows	The Channel Protection Volume refers to the volume and rate of flow required for management to reduce the potential for degradation in natural channels	24 hour extended detention of the 1-year RI, 24h storm event
Overbank Flood Protection (Q_p25)	Provide peak discharge control of the 25-year, 24 hour storm event	The reduction of peak storm flow to the pre-development scenario typically for stormevents with a RI of between 2 and 10 years depending on the type of development	Up to 10-year return period peak flow reduced to pre-development level
Extreme Flood Protection (Q_f)	Evaluate the effects of the 100-year, 24 hour storm on the stormwater management system, adjacent property, and downstream facilities and property	Prevent damage to property, and risks to life for storm events with a RI of greater than 10 years	Evaluate the effects of the 100-year, 24 hour storm on the stormwater management system, adjacent property, and downstream facilities and property

7.3.5. Annual Yield Estimation

This section will discuss ways to determine the current annual yield of the pond via measurements, Annual Yield Measurement, and it will discuss tools to determine the current annual yield of a stormwater pond and expected potential annual yield of a infiltration pond by simulation and calculation, Annual Yield Calculation. The annual yield, in m^3, is defined as the amount of water that is infiltrated via the infiltration pond in a year. In this context the annual yield is the amount of water which is infiltrated into the soil. The annual yield % is the ratio of infiltrated water (annual yield) to incoming water.

Annual Yield Measurement

The Annual Yield can be calculated via the following water balance [11].

$$\Delta S = i + q_0 - e - f - q_1 \tag{7.2}$$

Where:

ΔS	change in water storage in the pond
i	precipitation falling directly into the pond
q_0	inflow to the pond from runoff captured from catchment
e	evaporation
f	infiltration of water into the soil
q_1	pond runoff or overflow

The infiltration can be determined by the following formula, equation 7.3, assuming the pond stays dry and therefore the water storage (ΔS) does not change and evaporation is neglected for simplification. If the inflow and outflow (pond runoff or overflow) are measured for a full year the current annual yield of the pond can be determined.

$$f = i + q_0 - q_1 \tag{7.3}$$

There are many ways to determine inflow and outflow rates. The challenge is to find a method which can measure the discharge with a sufficient interval time. Open channel flow should be measured continuously at 5 minute intervals in order to capture the hydrological variability [98]. Furthermore the measurement method needs to be reliable, cheap and hidden to work in the local South African context.

A smart low-cost remote-monitoring flow sensor is therefore proposed. The sensor is specially developed for developing countries and can measure the water flow [99]. The sensor contains low-cost off-the-shelf sonar devices. These devices are used to gauge river/water height as a proxy for flow rates. The logged data is transmitted to a centralised server in order to facilitate real time data analytics [99]. The sensors measures distance every 6 minutes. With the water level known the flow rate can be calculated with the appropriate equation for the specific condition, e.g. open channel flow, partially or fully filled pipe flow. The sensor has already been applied to calculate the flow rate using an Bernoulli based equation for discharge over a rectangular crump weir [99]. When the flow rate at in the inflow and outflow point are measured for a full year the annual yield can be obtained. Only evaporation is neglected, which has a negative impact on the yield.

The flow sensor has been demonstrated for open channel flow, using a crump weir [99]. To determine the discharge and subsequently the yield via the low-cost remote-monitoring flow sensor for small tubes, that occasionally fully fill with water other configurations and equations are needed. For fully filled pipe the Venturi principle and related equations can be used [100]. For partially filled pipes the Manning equation can be applied [101].

Annual Yield Calculation

This section will discuss three tools to give an estimate of the annual yield of the stormwater pond and to determine the expected potential annual yield, should the stormwater pond be retrofitted into a infiltration basin (changed outlet height and changed top soil). In this context the annual yield is the amount of water which is infiltrated into the soil, equal to the incoming water into the pond minus the out flowing water of the pond. The annual yield % is the ratio of infiltrated water to incoming water. These three tools are:

- Minimal Impact Design Standards (MIDS) Calculator.
- Personal Computer Storm Water Management Model, PCSWMM
- Green Infrastructure Flexible Model, GIFMod

Annual Yield Calculation: MIDS calculator

The Minimal Impact Design Standards Best Management Practice (BMP) was developed by the Minnesota Pollution Control Agency to aid regulators and designers in designing and sizing of drainage schemes. The MIDS BMP calculator can be used to estimate the annual stormwater runoff volume reductions for various BMPs (drainage components). The MIDS calculator is essentially a Microsoft Excel sheet with a graphical user interface [102]. The calculator can be used to calculate multiple BMPs, even in series, but for the assessment of annual yield the calculator will be used to calculate for one individual BMP. Namely, the infiltration basin. Therefore the calculation excel sheet has been modified to solely calculate for one infiltration basin, this to simplify the inputs. Furthermore the inputs have been converted to allow for metric calculations. The original excel file can be accessed via [102], the modified excel file can be found in appendix E. The MIDS calculator requires input parameters about, among other, the watershed area and pond dimensions. The MIDS calculator will calculate, among others, the annual stormwater runoff volume reduction (annual yield) achieved by the BMP, in this case due to infiltration, refer to appendix E.

The calculator sheet determines the annual yield by multiplying the total annual inflow with the percentage annual reduction of the BMP, the pond. The percentage annual reduction for the BMP is calculated from so called 'removal tables'. The removal tables are the product of the 'performance curves'. The MIDS calculator determines the annual percentage reduction via the relation to certain pond characteristics. This relation is made possible by a conversion. The conversion is facilitated by performance curves. The performance curves namely relate the annual percent reduction (infiltrated percentage of water) to the ponds volume, the ponds infiltration rate, the watershed area of the pond and the percentage impermeable surface of the watershed area. Figure 7.3 shows a performance curve made for the MIDS calculator with weather data from Minneapolis. More about the development of the performance curve, refer to Appendix F.

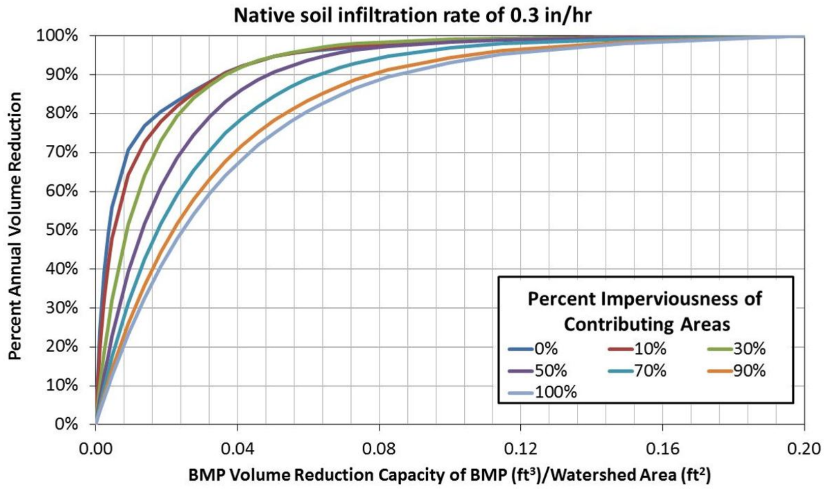

Figure 7.3: Generated performance curve for soils with infiltration Rate of 0.3 in/hr.

New Performance Curves based on Cape Towns precipitation data sets have to be generated first in order to apply the MIDS calculator for assessing potential yields of ponds in Cape Town. Precipitation variability should be considered, especially for the Cape Flats region. If the precipitation varies too much the Performance Curves derived from precipitation data from a certain catchment are not representative for others. In Cape Town the Mean Annual Precipitation varies from 350 - 2500 mm, for the catchments of the Cape flats the Mean Annual Precipitation varies from 500 - 1000 mm [11]. When the Performance Curves are generated and subsequently the removal tables. The excel sheet allows for quick calculation of potential yield.

Annual Yield Calculation: PCSWMM

SWMM is a hydraulic and hydrologic modelling system. It was originally developed for the Environmental Protection Agency. SWMM is a comprehensive model for analysis of quantity and quality problems related with urban runoff. PC-SWMM is a proprietary shells that provides the basic computations of EPA SWMM with a graphic user interface, additional tools, and a few additional computational capabilities [103].

PCSWMM was already used to reliably model the Diep River subcatchment's stormwater ponds to investigate the economic viability of stormwater harvesting from these existing stormwater ponds. Every stormwater pond was modelled to account for infiltration applying the Green-Ampt infiltration model [104]. Okedi [11] went one step further and selected PCSWMM based on, among others, the possibility to adequately define extended detention of water in a pond and the opportunity to infiltrate into the underlying aquifer. The model was used to model 61 stormwater ponds in the Zeekoe Catchment to determine the viability of stormwater harvesting using aquifer storage. This was done by determining the potential of stormwater transfer to the groundwater primarily through the existing stormwater ponds. The basic approach was to modify the stormwater ponds to allow for an additional infiltration function. PCSWMM contains low impact development (LID) controls, such as porous pavements, vegetative swales or bio-retention cells. Elements from bio-retention cells were chosen for this since PCSWMM does not have ordinary infiltration cells. PCSWMM was run to estimate the recharge volumes. The modelled mean annual values for infiltration and other values such as evaporation, evapotranspiration, surface runoff is depicted in Figure 7.4.

It is demonstrated that stormwater ponds and catchments can be modelled with PCSWMM to see the amount of infiltration of stormwater into the groundwater [104, 11]. Although this is done on catchment scale it could also be done for individual ponds if the precise watershed area of the pond is known or the when the inflow into the pond is known from measurements. Although it is possible to compute yields and expected potential yield for individual ponds with PCSWMM it still mainly developed for catchment-scale applications making use added LID futures. Meaning that PCSWMM is not developed specifically for specific LID practices. The

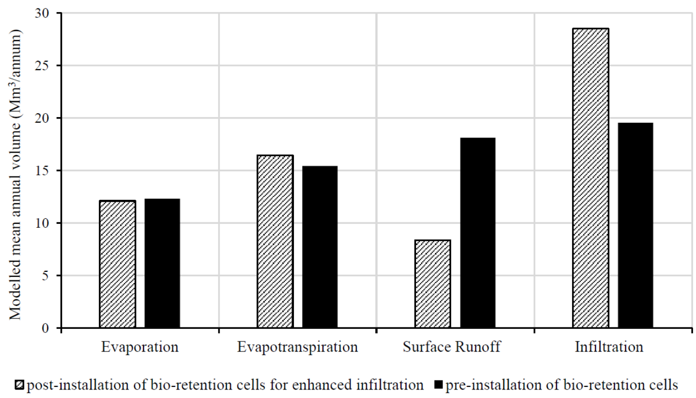

Figure 7.4: Comparison of existing stormwater ponds and post-modification to bio-retention to allow for MAR [11].

LID futures in PCSWMM lack the details needed to consider detailed processes occurring within one or more LID practises or details needed to considers site specific design aspects [105].

Annual Yield Calculation: GIFMod

GIFMod is a flexible process-based GI modelling framework. GIFMod can simulate hydrological and water quality performance of a wide range of GI elements with user defined structures and level of complexity [105]. GIFMod is already applied for GI such as a bioretention system, a permeable pavement system, wet pond and a infiltration basin. GIFMod allows for user flexibility and expandability in modelling, besides quality parameters, the hydraulic aspects of GI performance. The flexibility of the hydraulic components allows for flow considerations in different elements often encountered in stormwater GI practises which includes ponds, runoff, saturated and unsaturated media, storage layers or structures and pipes [105]. The flexibility and expandability of GIFMod allow users to model their unique GI projects such as stormwater detention ponds or retrofitted stormwater ponds into infiltration ponds. For more information on GIFMod, especially on its water quality capabilities, see Appendix K.

GIFMod can be used to model a stormwater pond. Clay substrate lining and low outflow height. After running the simulation one can obtain, among others, the infiltration rate and recharge rate. Integrating the first over time gives the amount of infiltration. With the amount of inflow an estimate of the yield of the pond can be made. GIFMod can also be applied to model an infiltration pond eg. sandy top soil and high outflow height. A stormwater and infiltration pond were modelled, see Appendix L, to demonstrate the flexibility of modelling specific GI's and the possibility to simulate infiltration and groundwater recharge, see Figure 7.5.

GIFMod requires direct GI inflow data and evaporation data or it can also simulate a catchment for this it requires precipitation and evaporation data. The direct GI inflow data can be obtained from field measurements, see subsection 8.3.5. GIFMod can also be used in combination with existing watershed such SWMM. The output hydrographs of SWMM can be used as input to GIFMod [105].

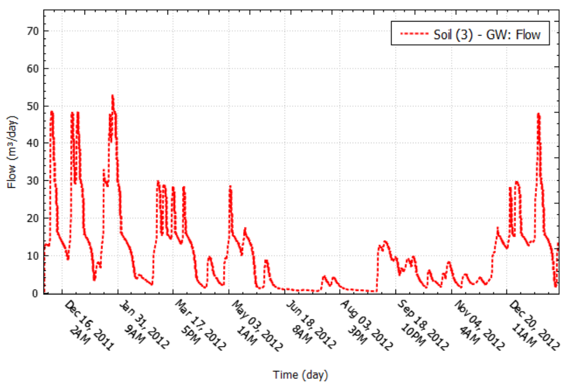

Figure 7.5: Modelled groundwater recharge rate for stormwater pond with clay lining and outlet height at 5 cm, by authors

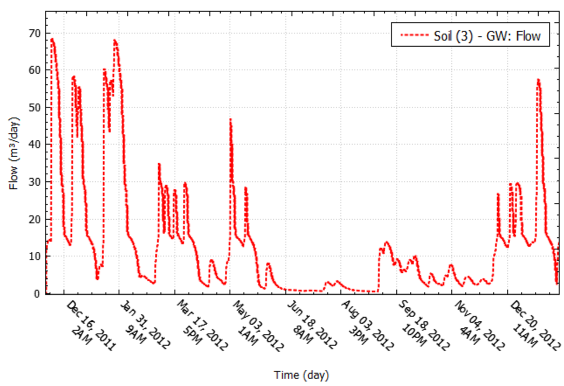

Figure 7.6: Modelled groundwater recharge rate for retrofitted pond with sand substrate and outlet height at 60 cm, by authors

7.4. Water Quality

In the current stormwater system in Cape Town, urban runoff ends up in open water systems which will eventually enter in the sea. Infiltrating the runoff into the ground will naturally treat the water and thereby reducing the load on aquatic systems. This contributes to a more water resilient city. For safe stormwater management it is crucial to know the main stormwater pollutants and their pathways during infiltration. In order to assess the impacts of stormwater infiltration on groundwater quality it is necessary to monitor the quality of the groundwater. This will also answer the question introduced earlier: 'Is the groundwater contaminated?'. The second question, 'is the influent water contaminated', is also answered by this methodology. Assessing these two questions will give insight in the treatment capacity of the soil.

Monitoring the quality of both influent and groundwater provides insight in the performance of the pond. It is also the main recommendation given by the case study of AWSS and therefore implemented in this framework. Although the soil functions as a natural treatment system, saturation of the soil can lead to leaching of pollutants to the groundwater. Processes occurring in the subsoil can re-contaminate the groundwater. Clogging also influences the performance of the pond, pre-treatment to minimise this problem is essential and further discussed in subsection 11.5.1. Monitoring the influent needs to include a solution for the fluctuation of the quality throughout the seasons and especially before and after rain events.

The foundation and background of the physical assessment of the framework presented in section 8.4 are explained in this section. It begins with introducing the common pollutants in urban stormwater. Per pollutant the influence on groundwater is discussed, which determines. From this it follows if it should be taken into account in the physical assessment of the framework. The approach to what extent the pollutants should be removed is explained afterwards. Different methods exist for sampling and measuring groundwater and in- and outflow water. Before a decision can be made which method is the most suitable, certain factors should be paid special attention to in Cape Town, which are explained in the last part of this section. This also influence which parameters can be measured and is further clarified in subsection 8.4.5.

7.4.1. Pollutants in Stormwater

Categories of pollutants in urban stormwater commonly reported and potentially harmful to receiving water bodies are [106, 107, 32]:

- Solids
- Oxygen-demanding substances
- Nutrients (mainly nitrogen and phosphorus)
- Pathogens
- Trace organics (mainly hydrocarbons)
- Metals (mainly lead, zinc and copper)

These pollutants come from a great number of different sources such as traffic, soil erosion, cleaning activities and illegal disposal [55].

7.4.2. Influence of Pollutants on Groundwater

From each of the pollutants introduced above, their necessity of monitoring is discussed now. Knowing the effect on the groundwater is key for deciding this. More detailed descriptions on the pathways of these pollutants and the treatment mechanisms of the soil is of importance for the design phase, discussed in Phase III (subsection 11.5.1).

Solids

The amount of solids in the stormwater is an important parameter that directly influences the success of infiltration, since high loads of suspended solids can clog the infiltration pond [108]. The clogging rate is difficult to determine and there is no accurate prediction model in literature yet, since it is depending on many factors and highly variable with change in environmental conditions. INOWAS [109] developed a tool to estimate clogging rates by comparing field measurements to results of other existing studies. The INOWAS Tool seems to be a promising approach for collaboration in the field of stormwater infiltration. However, it is not possible to find the references of the studies that are considered in the tool. This is problematic since the clogging rate is not only dependent on the parameters considered by INOWAS but also the solids concentration which is not reported. This specific INOWAS tool is therefore not advised to be used in the framework at hand, but nevertheless the tool is explained in Appendix G since it might prove itself useful in the future once updated. Clogging is however expected to be a major influence and pre-treatment is required. Design measures to reduce the rate of clogging are given in chapter 11. A difference is made between macro solids (litter) and micro solids (Total Suspended Solids (TSS) and Total Dissolved Solids (TDS)).

The most frequent reported issue by local residents and City of Cape Towns officials regarding stormwater ponds is litter[110]. An estimation for the total amount of litter ending up in the drainage system of Cape Town is 3544 ton per year [111]. This problem can not be solved by natural treatment solely. In phase III design options are discussed which can filter out the litter. Although litter is visible by the eye, quantification is a challenge. The approach used in this framework is a combination between two methods used by Rohrer and Armitage [110] and Kitsap County [68] and given in subsection 8.4.1.

Another challenge is TSS in the stormwater, which can have many sources. The concentration is generally heavily influenced by the discharge of sediments. The material can vary from colloids to bigger (in)organic particles. Since its surface can be charged, it can carry dissolved substances such as nutrients and heavy metals. The effect on the groundwater is minimal, since most infiltration systems are very effective in removing TSS. Filtration acts as the main mechanisms for removal, but clogging is a major problem associated with the TSS load flowing into a pond [92, 108]. Estimating the effects of TSS on clogging is discussed in subsection 7.2.5.

TDS does not clog the system, but is a measure for all dissolved solids and often the electrical conductivity (EC) is used to track this parameter. Although EC does only measure the salts, the method is common since it is an easy procedure and most dissolved compounds in water are charged [112].

Oxygen-demanding Substances

The amount of oxygen-demanding substances in the runoff influences the Dissolved oxygen (DO) concentration. Different studies on DO reveal different results: some mentioned increased levels of DO in groundwater by urban runoff [113, 114], while others reported decreasing levels [115] which suggests that it is very case specific. It is though to mainly depend on the microbiology in the soil, which varies with different parameters such as temperature [114]. The effect of DO on groundwater is important, because it can e.g. determine the valance state of metals Rose and Long. It is advised to measure this parameter, but the sampling method hinders this option further clarified in subsection 8.4.5.

Nutrients

The two main nutrients of interest are nitrogen and phosphorus. Phosphate can be a significant problem for the aquatic environment since along with nitrogen it promotes eutrophication already in low concentrations (1 mg/L) [117]. This mainly happens in places where water stands still for a longer time period. It will depend on the hydraulic design and purpose of the pond if water will be retained for a longer period of time.

Tracking the two nutrients can provide information on the pollution source; e.g. agricultural runoff and wastewater can cause elevated levels. Tracking is also important because the soil and vegetation can only adsorb until exhaustion, after which elevated levels of nutrients can leach into the groundwater. Total nitrogen (TN) and total phosphorus (TP) are therefore considered to be important to add in the framework.

Pathogens

Many pathogens will die naturally or are removed by filtration before reaching the groundwater. This is however very depending on the treatment capacity of the soil. Especially viruses are known to possibly migrate through very permeable soil or when the loading rate is high EPA. How to minimise this risk if discussed in the design phase (subsection 11.5.1).

A potential public health risk related to pathogens in urban runoff is possible, when citizens are directly exposed to the water. Therefore, measuring this parameter is important when the pond is used for recreational purposes [107]. Since this is not in the scope of this assessment, it is not taken into consideration. Sampling and soil handling must be done carefully though, to reduce human exposure.

Trace Organics

Organic compounds of which the risk on ecological and human health is fairly unknown, but of which is expected that they are released to aquatic environments are called trace organics [118]. These compounds are often not measured or standardised. Examples from an urban environment are petroleum hydrocarbons, mainly coming from traffic. It includes oil, grease, benzene, ethyl benzene, xylene and polynuclear aromatic hydrocarbons. These are already toxic at low concentrations [107]. They are especially dangerous when entering the drinking water system, but infiltration systems are known for the capacity of removing trace organics effectively [106, 119]. Leaching to the groundwater should be avoided as much as possible and tracking this compound is therefor included in the framework.

Metals

Heavy metals in urban runoff is often the pollutant of major concern, end of pipe concentrations frequently exceed many quality criteria standards Strassler, Pritts, and Strellec. Practically any metal type can be detected in the runoff, but the once most often reported for having a negative effect on aquatic systems are zinc, lead and copper [120, 107, 121]. The metals can enter the groundwater system and form a threat to environmental health and be of concern for the end use of the groundwater. An important parameter for heavy metals is pH, since a lower pH can increase the solubility [119]. Monitoring of the soil pH is therefore advised (see Table 7.2.3). Analysing the heavy metals content of both the runoff and groundwater is crucial for designing a safe infiltration system. Comparing the concentrations between runoff and groundwater provides insight in the metals dissolving by infiltration and is essential for the redesign. The pathway and removal mechanisms of the metals is further explained in phase III (subsection 11.5.1).

Salinity

Another parameter important to measure is salinity. This is not one of the pollutants of concern in urban runoff as introduced above (subsection 7.4.1), but does influence the groundwater quality. Surrounded by two oceans, saltwater intrusion might be a risk for Cape Town. The effect depends on hydro-geological parameters [122] and on over-exploitation of groundwater [123]. Little information is known about this phenomena in CT and measuring the salinity in the groundwater is an indicator for this problem and taken into account in the physical assessment of the framework. In general, the risk of over-exploitation will be replenishing the groundwater by infiltratio. Retrofitting stormwater ponds to infiltration ponds will therefore reduce the risk of saltwater intrusion.

7.4.3. Standards for Pollutants

No solid standards for quality are provided in this framework. The advantage of infiltrating the water is that the quality will always improve to some extent and runoff to open aquatic systems is avoided. The natural treatment by soil will reduce the impact of polluted water on the environment. This framework is not focusing on the end-use of the infiltrated groundwater. Once this is decided it might be needed to update the standards or it should be decided to treat the water to required levels after extracting.

It is however important to regularly track the quality of certain pollutants. If certain pollutants are present in worrying concentration, it might be wise to track down the source. Preventing pollution at the source before mixing with runoff is often the most efficient solution [55]. Testing the quality of the inflow, outflow and groundwater will be an input for the design phase. It can not only indicate to what extent the current stormwater pond treats the water, but it also essential for monitoring the performance of the pond after retrofitting.

7.4.4. Sampling and Measuring Pollutants

Before quality test on inflow, outflow and groundwater can be done, samples should be taken from the pond. This is often done with automatic samplers [124], which gives continuous results showing the relations between discharge and quality. This continuously measuring is of importance, because concentrations of pollutants in the urban runoff will vary largely and quickly with discharge of stormwater and rainfall events. A relatively small rainfall event after a long dry period can contain high concentrations of pollutants, the so called 'first flush' [55]. The concentration in the groundwater will be more steady, since the water is treated while infiltrating and due to dispersion of the incoming water less variation is expected. Taking samples of the groundwater will therefore have a different procedure than for the in- and outflow. In Cape Town it is not feasible to install these automatic samplers since the risk of vandalism and/or theft is too large. A low cost solution should be included in the framework, to make sure sampling is done regularly. This solution is introduced in subsection 8.4.2.

7.5. Risk Assessment

It is vital to know about the risk constraints related to the use of infiltration before considering implementation. Therefore, these risks should be identified and evaluated before any site can be considered a potential location for infiltration [55]. This also implies for infiltration retrofit. This section reports on the approach taken to develop a risk assessment framework. The aim of the framework is to answer the following questions related to risks and issues posed by infiltration:

- Is there a risk of groundwater flooding in or near the pond?
- Is there a risk of subsidence or other forms of soil instability due to infiltrating water?
- Are there risks associated with infiltrating water in proximity to existing structures?

The framework will assist in answering these questions via a flow diagram and corresponding assessment methods or advice for further investigation of the risks. This was done by a literature review to find the common risks related to infiltration. Formulation of sub-questions from these risks and linking these sub questions to answer the main risk related questions. Lastly the flow diagram will offer guidance trough the questions and assessment methods. This section starts with introducing the associated risks of infiltration, grouping these risks in categories followed by the motivation of the flow diagram and finally methods are introduced to determine if it is safe to infiltrate on the specific site. The final flow diagram and methodologies to assess certain risks are featured in the results section of this phase.

7.5.1. Risk Related to Infiltration

The following risk related to infiltrating water into the ground have been identified from literature [55, 125, 126, 127, 128, 129]. A change in the water table will result in a change of the pore pressure and therefore of the effective soil stress. Change in effective soil stress implies a change in the volume of the soil skeleton. The risk of local rise and subsequent drop of the water table related to infiltration have been considered. Risks related to structural change of the groundwater level have not been considered. The following sections will discuss them in more detail.

- Risk of slope instability
- Risk of solidification
- Risk of leakages to foundations, sewers, tunnels, basements and other underground structures
- Risk to structural stability
- Risk of groundwater flooding
- Risk of subsidence by: erosion, dissolution, wetting collapse or fill compaction.
- Risk of heave due to swelling clay

Slope Instability

Slope instability should be assessed for infiltration systems on or near sloping sites as steeper slopes will increase the runoff velocity [55, 127]. Additional attention to slope instability should be given for slopes usually greater than 3% to 5%. Slopes above 15% are considered too steep and infiltration is not recommended [55, 127].

The following should be considered when infiltrating near or on slopes. The likely velocities in basins, due to the steep gradients, can affect scour (erosion). Additional risks arise when water is infiltrated behind slopes or retaining walls. The water can issue from the face of the wall or increase the pressure on the wall or slope causing it to fail [55]. The additional risk of water seeping out of the slope at lower levels, also known as water reappearing as spring lines, can occur. The spring lines can lead to flooding and instability. Layered strata containing impermeable soils or rocks present the biggest risk of spring lines developing [55]. Therefore infiltration basins should be located at a sufficient distance from slopes and retaining walls [55].

Whether infiltration will cause a problem for steeply sloping sites, depends on the following components. Firstly, the geology below the site. Secondly, the ratio of the contributing watershed area to the surface area of the pond. The impact of infiltration on sloping sites or near them has to be assessed by a geotechnical engineer or engineering geologist [55].

Solifluction

Solifluction is known as the gradual movement or slow creep of saturated soils down slopes. Solifluction results from freeze-thaw action in fine-textured soils. The freeze-thaw action causes the slow mass wasting or slow creep of saturated soils in cold, non-glacial environments, where the vegetation is lack or sparse [130]. While the risk of solifluction as a result from infiltration is mentioned in literature it is considered not to be likely for the Cape Town context, or more precisely for the Cape Flats context. The reason is the climate of Cape Town, a Mediterranean climate with dry, warm summers and wet winters [15] plus the presence of vegetation and otherwise man made objects prevent solifluction. Therefore assessment of this risk will not be a part of the further framework and flow diagram.

Leakages Into Underground Structures

It is recommended to assess the risk of groundwater leakage, inundation or flooding into underground structures that can arise from infiltration [55, 128, 131]. This risk is divided into leakages due to direct inflow of infiltrated water, inflow because of groundwater mound or because of water table rise.

The risk of water leaking into a local foul or combined sewer will depend on the area of the pond compared to the drainage area, depth of soil between the sewer and base of the infiltration cell and horizontal separation [55]. Groundwater mounding occurs during interaction between the infiltrated water and the native groundwater, leading to the local rise of the water table adjacent to an infiltration system [70, 69]. Besides slowing down the systems infiltration and causing reduction in the treatment, excessive mounding also affects underground structures such as basements, sewers, pipelines and cemeteries [69]. A requirement before design of a infiltration pond can be a mounding analysis to demonstrate that infiltration systems will not cause surface ponding or flooding, the flooding of basements and other underground structures [70].

A rising water table resulting from increased infiltration rates can cause progressive flooding and damage to underground spaces or structures. In addition, the rising water table will lead to leakages of water into sub surface facilities and structures [128, 131]. Despite the severe consequences this risk framework and corresponding flow diagram will not set out to assess this specific risk. Because the overall rise in water table will result from multiple increased infiltration rates due to multiple infiltration ponds [128, 131], this requires an integral assessment of multiple infiltration ponds while this framework sets out to investigate the feasibility of individual stormwater ponds.

The risk assessment of stormwater ponds closer than 5 m to the foundation of buildings or structures should be approved by a geotechnical engineer or ground engineering adviser [55].

Structural Instability

Structural instability can be caused by the rise of the groundwater table. Flotation or hydrostatic uplift and structural design risk to storage's, underground structures or impermeable liners can occur due to high groundwater levels [55, 128, 131]. Other affects of a rising water-table are damages to underground engineering structures as a result from reduced bearing capacity, chemical attack on concrete foundations or other underground structures [128].

This risk is divided into groundwater level rising because of groundwater mound or because of overall water level rise. Like the assessment of leakages into ground structures the risk framework and corresponding flow diagram will not set out to assess risk related to the overall rise of the water level. The reason for this is discussed in the previous paragraph of Leakages into underground structures.

Similar to the risk to structures posed by leakages the risk assessment of structural instability should also be carried out by a geotechnical engineer or ground engineering advisor when infiltration is within 5 meters to the foundations of buildings or structures [55].

Groundwater Flooding

Groundwater flooding is the emergence of groundwater at the surface [132, 133, 134]. Groundwater flooding can also mean the rising of groundwater level into underground structures including basements and other subsurface infrastructure [132], this is discussed in the previous paragraphs of leakage and construction instability risks. Groundwater flooding related to infiltration for steep sites increasing the risks of spring lines developing and emerging lower down the slope [55] is discussed in the slope stability paragraphs.

Groundwater flooding is caused by water table level rises that are induced by extreme rainfall events. Especially concerning unconfined aquifers that do not have impermeable materials above them [134, 133]. The flooding occurs when prior conditions of already high groundwater levels plus a high unsaturated zone moisture content is followed by a exceptional rainfall event [133, 134]. This risk framework will not focus on a natural occurring groundwater flooding, but the risk of local substantial water infiltration and groundwater recharge leading to water levels near the pond reaching the topographic surface.

Subsidence

Subsidence refers to a surface point sinking gradually or suddenly to a lower level and occurs when the soil beneath it is unstable and sinks downward [135, 136]. While some claim subsidence includes structures settling into the ground [135] others state that settlement, caused by the weight of buildings, is not the same as subsidence [136]. Furthermore, many cases of subsidence can be caused by mining or lowering of the water table [135, 136]. This section on subsidence will focus on sinking of landforms to a lower level as a result of movement of earth materials due to infiltration. There are many different causes leading to subsidence these are discussed in the upcoming sections.

Subsidence by Washing out of Fines

The infiltration of water into the poorly consolidated soils can lead to the internal erosion of the soil skeleton and causing instability. Infiltrated water washing out the soil can lead to instability and therefore causes subsidence [55, 136]. Areas of attention are those that contain loosely compacted soils having marginal stability, such as infilled solution features. The infiltrating water can cause loss of material due to the washing out of fines, resulting in the collapse of the soil [55].

Subsidence by Dissolution

Dissolution of carbonate rocks, like limestone, is another common type of subsidence [136, 55, 126]. Precipitation contains a small amount of carbon dioxide from the atmosphere forming carbonic acid with the water. Infiltrated water can cause the chalk to slowly dissolve over time.

Subsidence by Wetting Collapse

Certain soil types may develop a collapsible fabric. These soils are typically formed with an open, metastable structure that are susceptible to collapse upon wetting [137]. It is widely acknowledged that microstructure plays an essential role in the collapse behaviour [137]. Also, soils with complex micro-structures cause saturation-induced compaction as a design factor [138]. Loessial soils are typically formed with a complex loose honeycomb-type meta-stable structure and are prone to wetting collapse, furthermore arid sands are also susceptible to wetting collapse [139, 137, 140]. The susceptible Loess soils, are unsaturated and have water sensitive cementations at the particle contacts or high matric suction. Addition of water reduces the matric suction or destroys the cementations [137, 140].

Subsidence by Fill Compaction

Settlement of backfill is likely to cause surface level drop, infiltrating water can cause compaction of fill material present in the soil. This can occur on sites with infilled solution features, e.g. old landfill sites, infilled open cast sites, old shafts or adits into mine workings. It is therefor advised to avoid infiltration on or near these sites if it can not be demonstrated that the fill material is sufficiently well compacted [55].

Heave

The heave of ground is the opposite of subsidence and is the upward movement of the ground [55]. Infiltration can cause heave as it is usually associated with the expansion of clay soils. The absorption of large volumes of water causes the swelling clays to increase substantially in size compared to the dry state of the clay [136]. When the soil cannot expand downwards or side wards as it generally does the soil will expand upwards, the overall soil swelling or upward movement is not that extreme but can cause damage to buildings and structures [136].

7.5.2. Sub-questions for the Flow Chart

The following sub-questions have been derived from the common risks related to infiltrating water. Answers to these questions will indicate if there are risks related to the infiltration. The question are grouped together with the main questions.

Is there a risk of groundwater flooding in or near the pond?

- Question: Can infiltration lead to local water table rises up to the surface?

Is there a risk of subsidence due to infiltrating water?

- Are there loosely compacted fill material present in the soil?
- Does the soil contain loess or other soils with open, meta-stable structures?
- Does the soil contain carbonate rocks, such as limestone or chalk?

Is there a risk of other forms of soil instability due to infiltration of water?

- Does the soil contain types of swelling clay?
- Is the infiltration basin situated on or near a steep slope?

Are there risks associated with infiltrating water in proximity to existing structures?

- Can infiltration cause the local water table to reach underground structures or foundations?

7.5.3. Motivation of Flow Chart

It was chosen to group the soil instability risks together as this forms one block within the flow scheme. This block can be skipped when one can show that the underlying soil is predominately incompatible sand. Section 7.2.1 already describes that the Cape Flats is a sand covered coastal plain and that the predominant material is sand. Moreover, that via extensive studies and open GIS data, areas containing other materials than sand, such as clay, vleis and limestone deposits, can be excluded. Field assessment is still necessary to verify the site specific ground types. Should there be too much other material besides sand one has to perform the assessment of soil stability. It is recommended that subsidence and heave issues have to be assessed by a geo engineer/specialist [55].

Risk of adjacent slope instability follows as the next block. Slopes under 5% are considered flat surfaces and slopes over 15% are considered very steep and unsuitable for infiltration [127]. Therefore when a pond is on a slope measuring 5% to 15% there should be a slope instability assessment performed by a professional geo engineer/specialist [55].

After the slope assessment it was chosen to put the Mounding analysis up next. The Mounding analysis is performed with the Hantush equation and therefore used as a mere indicator for risks associated to building and to groundwater flooding due to infiltration. This because the Hantush equation incorporates simplifying assumptions, these are: all flow is considered horizontal, the aquifer is homogeneous and isotropic, a constant infiltration rate and the change in the saturated aquifer thickness is trivial relative to the original saturated thickness [141]. Because of this, at places where vertical anisotropy is present, the height of the groundwater mounding is underestimated as the vertical anisotropy is not accounted for by the equation [142]. Similarly the equation leads to overestimation of groundwater mound when storage in the unsaturated zone or delayed yield from the unsaturated zone occurs [142]. It is recommended to use a finite-difference numerical flow model eg. MODFLOW to account for vertical hydraulic anisotropy and vertical flow [141].

8 Results

From the methodology it follows which parameters are essential to obtain in order to assess if a stormwater pond has potential to be retrofitted into an infiltration pond. This chapter describes the procedure on how to determine these crucial parameters and proposes an order in which the field assessment should be done. This is based on the arguments as introduced in the methodology and is modified by executing a case study. It is adapted and tailored for the context of CT. This part of the framework will either lead to input for the design phase or eliminate a pond if it is not feasible for infiltration.

This chapter is again divided in the four parts 'hydro-geology', 'hydraulic analysis', 'water quality' and 'risk assessment'. For each of these 4 groups a flow chart is presented which shows the order of the actions and guides the assessor through the different necessary steps. Before these detailed flowcharts, the framework starts with an overall order in which the 4 parts should be assessed.

The four flow charts consist of 3 columns. The main steps are the 'actions', the steps an assessor has to go through in order to achieve all the required information about a pond. To perform such an action, 'inputs' are needed which can be e.g. data obtained from an external source or from a measurement in the field. When an action or input requires an explanation on how to perform or obtain a certain parameter, it is marked with either blue or green box. The blue boxes are for parameters obtained by desktop studies. The green box are for parameters that should be obtained by an actual field study. All these parameters are explained below each corresponding flow chart, but a detailed description of the field work denoted by the green boxes is given in Appendix B. This appendix serves as a self-contained manual that is used during fieldwork. If a detailed and generalised manual is used for assessing the different ponds, a smooth and complete field study is more probable and comparing the results is more reliable. The 'output' of the flow charts is the third column and mentions the conclusion obtained by the input and actions. Sometimes the output can lead to input for the design phase, as presented in purple blocks in the flow charts. It can also eliminate a pond, which is included in the chart.

8.1. Overall Framework

The overall flow chart as depicted in Figure 8.1 consists of the 4 main groups. The hydro-geology is placed first, since it described the measurements needed as inputs in following parts. It also include steps that can eliminate a pond, which makes it favourable to do these first.The water quality (mainly field and lab work) and the hydraulic analysis (mainly desktop study) can be performed at the same time. The risk assessment is the last step needed before a design can be made.

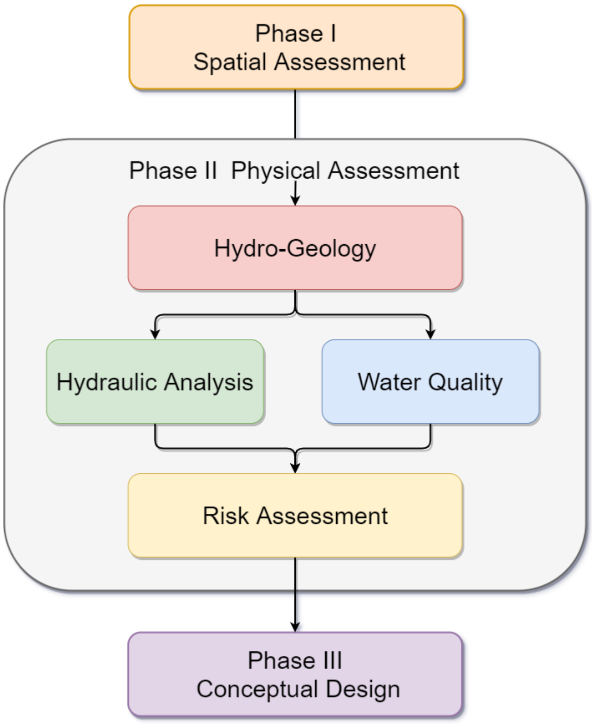

Figure 8.1: General Flow Chart of the framework including the 4 groups of which phase II consist of.

8.2. Hydro-geology

This flow chart (Figure 8.2) contains the steps that must be followed in order to obtain the parameters needed to determine the suitability for retrofitting a pond in terms of its hydro-geological character. The following question can be answered after completing the steps described in the flow chart:

- What is the maximum groundwater level beneath the pond
- Is the soil contaminated and until what depth?
- What is the infiltration capacity of the soil beneath the pond?

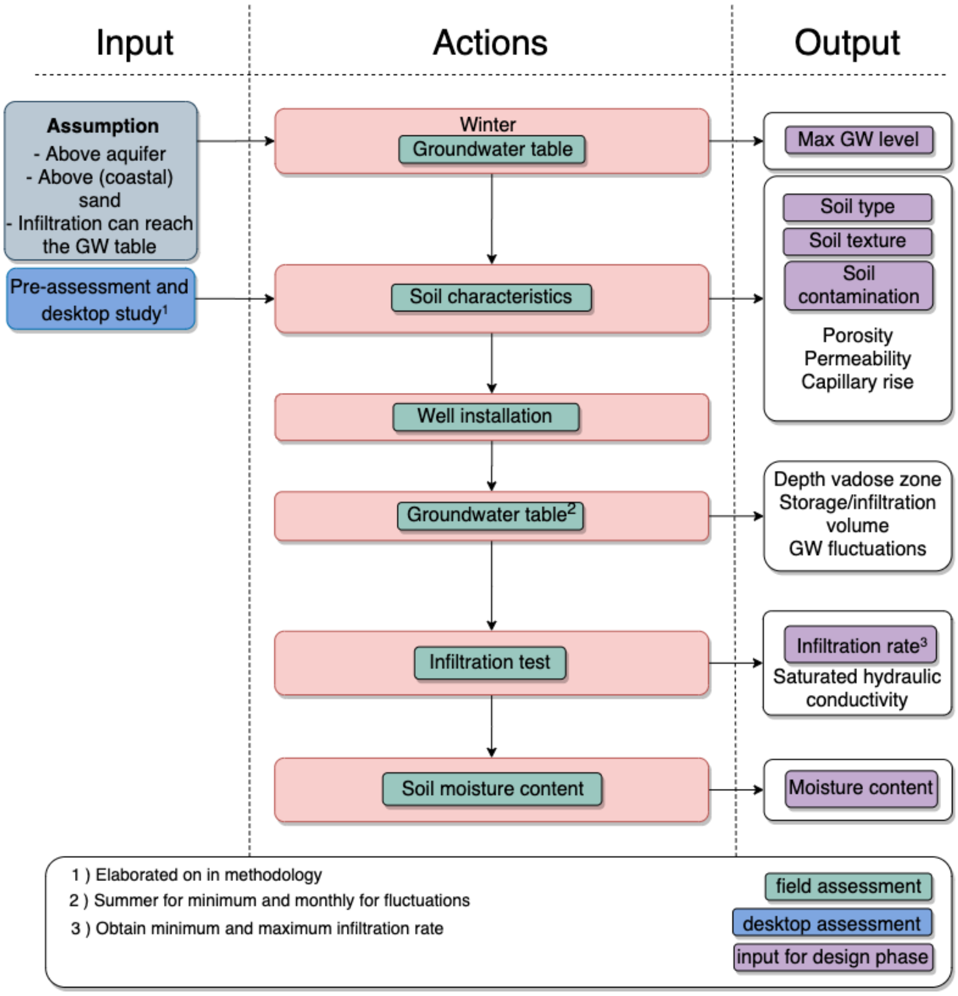

Figure 8.2: The flow chart to assess the hydro-geology characteristics of the pond.

After completing the steps as described in the flow chart, it can be determined if the pond is suitable for retrofitting based on its hydro-geological character. The hydro-geological parameters that need to be adjusted for a suitable design will also be apparent.

8.2.1. Groundwater Table

Before starting the field assessment, the desktop study must show that the pond is above the aquifer, above sandy soil and that infiltration can reach the groundwater level in order to recharge it. The first stringent threshold value that the pond must meet is a distance of at least 1 meter between the seasonally high groundwater table and the pond surface [55]. To asses the question *what is the maximum groundwater level beneath the pond?*, the distance between the maximum groundwater level and the lowest part of the pond need to be obtained. Therefore, a measurement must be taken at the end of the winter [40].

8.2.2. Soil Characteristics

Two boreholes must be made in this phase, one at the inlet of the pond and one at the ponds outlet. Soil profiles obtained in this way must be investigated whether they contain the sand layer as indicated by the desktop study or not. The field assessment can be done by the method described in the filed manual It is expected that the topsoil will reveal different characteristics than the subsoil, therefore it is important to precisely indicate where the topsoil changes into the subsoil. If the structure and texture of the subsoil is determined, the corresponding porosity, permeability and hydraulic conductivity can be obtained. The capillary rise of the specific soil can also be obtained from the soil profiles as well. In the event that the profiles show very different behaviour than expected, they must be taken to the laboratory for extensive analysis. This can be done simultaneously with the soil contamination tests. In that case it is also advisable to take multiple soil profiles for a more comprehensive understanding of the site specific soil conditions.

Soil Contamination

The two soil profiles must be taken to the laboratory for contamination analysis. In the laboratory, they are examined if they are polluted by salts (EC), if leaching of heavy metals occurred or if biological activity is present. The analysis will determine the degree and depth of contaminated soil at the pond.

Groundwater Fluctuations

To monitor the groundwater levels and quality, two wells need to be installed in the boreholes at the ponds inlet and outlet. Here, the groundwater fluctuations and groundwater quality can be measured.

8.2.3. Infiltration Test

The topsoil of the pond can vary a lot due to sedimentation, long-term clogging due to siltation and the buildup of biomass. To obtain the infiltration range, multiple double-infiltration tests must be performed both at the surface and the subsurface (30 cm below the surface). The soil moisture content before and after the infiltration test need to be measured as well, from this, the soil moisture deficiency can be obtained.

With the parameter obtained in the field, the infiltration capacity can be obtained. The procedure to obtain these values are described in the Field Manual.

8.3. Hydraulic Analysis

The hydraulic analysis flow chart is depicted in Figure 8.3. The steps are ordered such that the pond is firstly screened on their hydraulic suitability, and only if the pond suffices, further calculations are done to obtain the necessary parameters for drainage analysis and risk assessment.

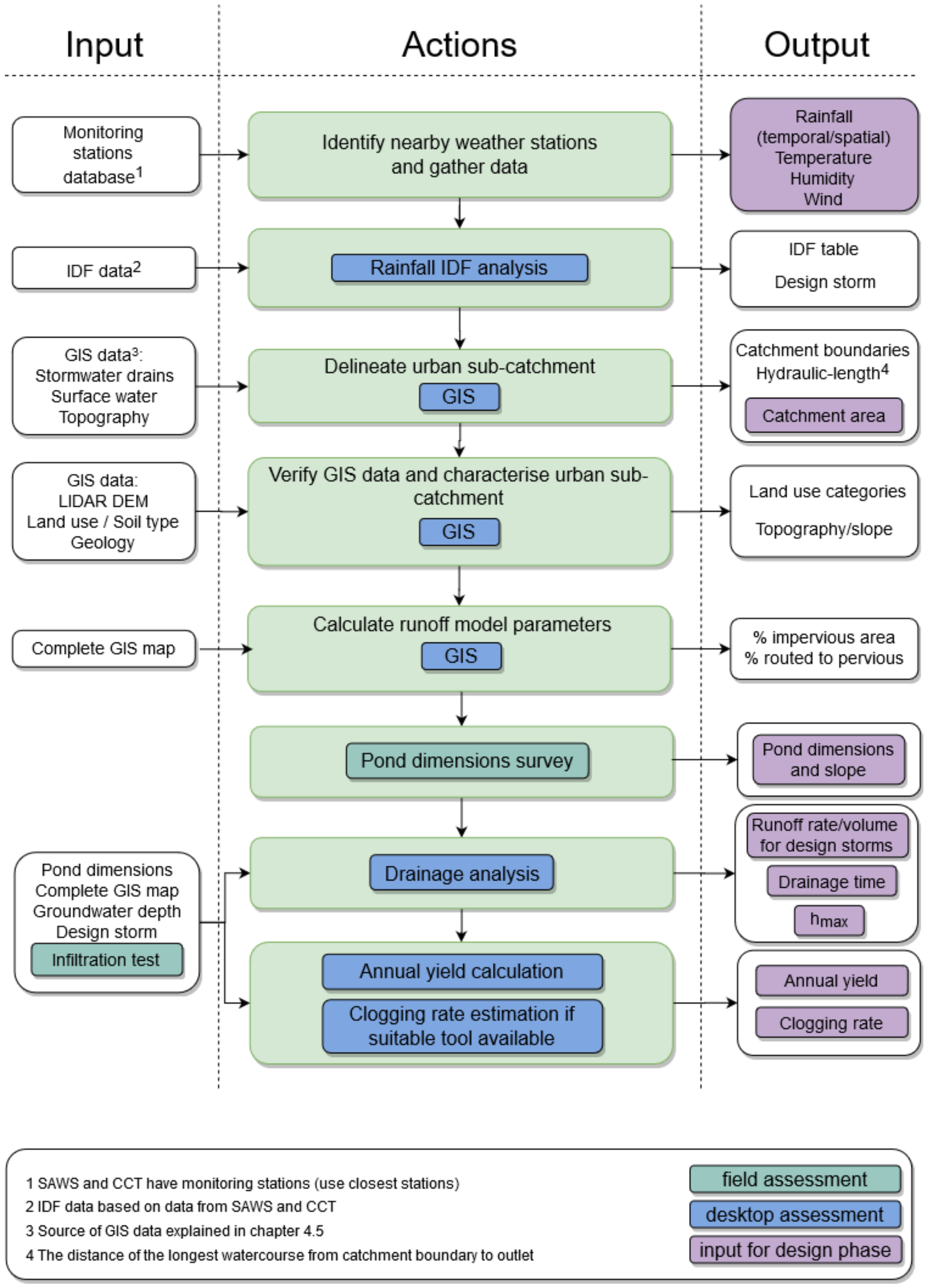

Figure 8.3: The flow chart of Hydraulic Analysis

8.3.1. Rainfall Intensity-Duration-Frequency (IDF) Analysis

IDF is a mathematical formula that relates the rainfall intensity with its duration and frequency of occurrence [143]. The formula is derived from the underlying probability distribution function of maximum intensities, and thus differs regionally. It is widely used in flood forecasting and by drainage engineers to assess the likely rate and volume of runoff from a catchment area. Koutsoyiannis, Kozonis, and Manetas describes the general method of constructing an IDF curve. This method uses regional rainfall statistics and the accuracy of the data depends on the length of the rainfall series and the density of meteorological stations. The South African Weather Service (SAWS) has archived daily rainfall values since 1836 and hourly data of wind direction, wind speed, temperature, humidity, pressure and sunshine is available from 1950 on wards. The IDF method including an uncertainty analysis has been applied in the Ghaap Plateau in South Africa [144]. A more detailed explanation of the calculation steps can be found in Appendix D.

8.3.2. GIS

ArcGIS or QGIS can be used to perform the hydraulic analysis steps labelled with 'GIS'. Delineating an urban catchment is slightly more complex than for a natural landscape, because the stormwater reticulation network does not always follow the topography and the various land uses can also influence the hydrological flow paths. Fortunately there are tools such as ArcHydro (free download), that can be used to specify flow accumulation based on DEM topography data and drainage infrastructure [145].

The sub-catchment can be characterised by land-use and soil type. The GIS land use data can be obtained as explained in section 3.5. The available land use categories are rural, urban, agricultural, informal settlements, and soil type. Based on area percentage, the ratio of pervious and impervious can be obtained. The default Personal Computer Storm Water Management Model (PCSWMM) values of depression storage (volume of water that must be reached before it results in runoff) assigned to land use categories maximise the amount of runoff and are thus on the conservative side. A sensitivity analysis has shown that the depression storage does not have a large impact on the sizing of stormwater treatment practices, thus setting the depression storage to zero for impervious areas is advisable [146].

8.3.3. Pond Dimensions Survey

In order to calculate the storage volume of the pond, the dimensions should be determined. Comparable research conducted at UCT have used Light Detection and Ranging (LiDAR) to determine topographical data [11, 110, 115]. LiDAR is an optical remote-sensing method that uses laser light to densely sample ranges as distances to earth, which produces highly accurate x, y, z measurements. Cape Town's LiDAR data has an accuracy of 0.5 metres [11]. This is thought to be insufficient to determine a ponds dimensions properly. Instead, the use of a Total Station is recommended, since this method will provide pond dimensions at the required accuracy for hydraulic calculations. A total station uses a movable telescope to measure angles in the horizontal and vertical plane in combination with a distance meter to map out pond dimensions. It is assumed that the field researcher is familiar with the capabilities of the Total Station and has the knowledge to operate one. Otherwise the manual provided by Leica ® - 'Surveying made easy' is recommended [147]. Pond dimensions and pond slopes can be obtained using the total station. Leica Captivate ® is a software that creates 3D renderings to calculate pond volume.

8.3.4. Drainage Analysis

The drainage analysis must be performed to predict the expected runoff flows and responses along drainage systems based on a design storm.

The runoff coefficient is a measure of the ratio of rainfall that is converted to runoff. The characteristics of the urban catchment determines the amount of water that will runoff into the pond. Different land uses include buildings, roads, parking lots, brick, asphalt, vegetation, water bodies and bare soil.

There are several hydrologic methods to estimate the runoff characteristics from an urban catchment. These methods vary in analytical complexity, and should be chosen on the basis of catchment size applicability, the purpose of study, desired accuracy of the result and data availability.

The drainage analysis can be performed with a single design storm event or by continuous simulation.

The most common method to calculate peak runoff is the (modified) rational method. This straightforward method gives a direct approximation of the peak flow rate from rainfall intensity (design storm) and can be used for initial sizing of the inlets. Note that this method is not sufficient for storage design [148]. These calculations can be done in a simple spreadsheet. Stafford, Che, and Mays provides a thorough explanation of peak flow calculations with the (modified) rational used for optimisation model for the design of infiltration basins.

Another useful tool that can easily be implemented at the planning stage when there is very little information available is a potential flow model developed by Guo.

On the basis of the hydrological model selection done by Okedi (2019), PCSWMM is the recommended stormwater runoff modelling program for infiltration ponds in the context of Cape Town. The advantages of PCSWMM over the 7 other models assessed in the literature review are listed below [11].

- Model the urban catchment in detail with Google Earth visualisation
- Often used in South Africa (annual training workshops and extensive support)
- High temporal resolution of modelling hydrological processes such as rainfall and infiltration (rainfall in minutes and data is sourced from Radio Detection and Ranging (RADAR) imagery)
- Real-time-control assessment
- Surface to groundwater transfer simulation

Minnesota Pollution Control Agency classified 50 stormwater models and provides concise information on the complexity and applicability [103].

8.3.5. Annual Yield Measurement

The annual yield, m^3 per year, is defined as the amount of water that is infiltrated via the infiltration pond in a year time. The annual yield % is the ratio of infiltrated water (annual yield) to incoming water. The Yield can be calculated via a simplified water balance if evaporation is neglected. The amount of infiltrated water is equal to the amount of direct precipitation falling directly into the pond and inflow into the pond minus the outflow from the pond, see equation 7.3.

If the, precipitation, inflow and outflow are measured for a full year the current annual yield of the pond can be determined. When one divides the annual infiltration, f, with the annual inflow, q_1, the annual yield % is obtained.

A smart low-cost remote monitoring flow sensor has to be installed at the inlet and outlet channel or tube to determine the flow rates. There are several possible set up configurations to install the smart low-cost remote monitoring flow sensor and corresponding equations to determine the flow speed and flow rate.

- For open channel flows or big tubes, provided they do not fully fill under certain precipitation events, refer to Appendix I.
- For fully and partially filled pipe flows, refer to Appendix J.

8.3.6. Annual Yield Calculation

The annual yield can be calculated with the following three tools:

The first tool provided is an excel sheet called MIDS calculator. The calculator can be used to determine, among others, stormwater runoff volume and it estimates the annual stormwater runoff volume reductions for various BMPs (drainage components). It was developed by the Minnesota Pollution Control Agency, based on P8 simulations [151, 152]. The calculator is essentially a Microsoft Excel sheet with a graphical user interface [102]. The original excel file can be accessed via [102], the modified excel file to calculate potential yields for infiltration ponds can be found in Appendix E.

The second tool provided is PCSWMM. It is the PC version of EPAs Storm Water Management Model. SWMM is a dynamic precipitation runoff simulation model, it can be used for single events or long-term simulation of water quantities from primarily urban areas [153]. It was developed by the United States Environmental Protection Agency. PCSWMM is not public domain but can be obtained via pcswmm.com.

The third tool provided is GIFMod. It is a flexible framework created to model multi-dimensional hydrological and water quality processes within stormwater green infrastructure components [105]. GIFmod is open source and freely available via www.gifmod.com. It contains the distribution package of GIFMod including examples and a detailed manual [154].

Important to realise that stormwater flows are very hard to model accurately. This has two reasons, firstly, rainfall characteristics are highly variable and might even be affected by climate change. Secondly, the physical layout of the catchment and drainage component into a pond is both complex and continuously altered [20]. Hence, if possible, it is still recommended to monitor the inflow and outflow of water into and out of the pond, for at least one year. To determine, using a simple mass balance calculation, what the annual yield of the storm water pond is. This is explained in more detail in section 8.3.5. The limitation of the measuring method is that it only determines the current yield of the stormwater pond, it will not determine or indicate what the potential yield can be when the outlet of the pond is changed, or even the soil within the pond. Nonetheless influent measurement data can be used as more precise input for the models, which in turn can calculate an expected yield after retrofitting. Should for any reason, may it safety, costs or technical issues, it be not possible to install measurement devices one can still provide an indication of the current and expected yield of the pond using the discussed models. An overview of the limitations and possibilities of the various yield determining tools/methods is provided in Table 8.1.

Table 8.1: Comparison of discussed tools to obtain annual yield

Tool	Current Yield	Anticipated Yield	Infiltration Calculation	Inflow input for simulation
Measuring Device and Mass Balance	Yes	No	Measuring Device and Simple Mass Balance	Not applicable
Annual Yield MIDS calculator	No	Yes	Performance curves	Annual Directly Measured inflow
PC SWMM	Yes	Yes	Horton, Green-Ampt or Curve Number	Directly Measured Inflow, Catchment and Hourly Precipitation data
GIFmod	Yes	Yes	Richards Equation	Directly Measured Inflow, Catchment and Hourly to Daily Precipitation data

8.4. Water Quality

When physically assessing a pond for the water quality, the flow chart presented in Figure 8.4 is used. This flowchart does not require any input and consists out of field assessment actions and outputs. Below the figure, each step is shortly explained. More extensive descriptions of the field assessment actions is given in the field manual (Appendix B). The first step is assessing the litter problem. Once this is done, samples from the groundwater and the in- and outflow should be taken for which the chart splits in two paths. A well is already installed in the pond (for hydro-geology measurements), which allows groundwater samples to be taken easily. Collecting the in- and outflow needs a capture system before this can be done. Both samples can be taken at the same time and eventually analysed in the lab, which provides knowledge about the qualities of the complete water system.

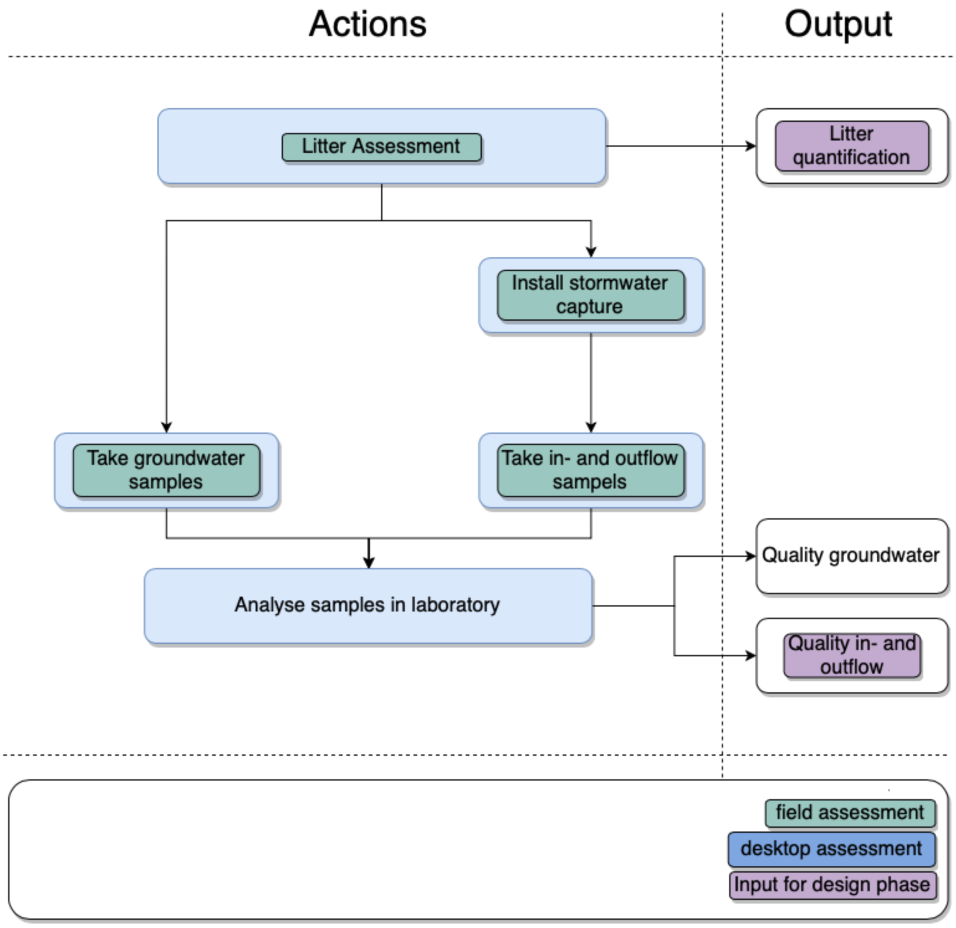

Figure 8.4: The flow chart of Water Quality

8.4.1. Litter Assessment

To get an insight in the problem size of pollution by litter, an assessment in the field is necessary which helps to find the best solution in the design phase. Very precise quantification is very difficult, but also not essential. The field manual (Appendix B) includes a table for assessing this problem.

8.4.2. Install Stormwater Capture

A low cost basic solution for taking samples of the in- and outflow tested in Cape Town is presented in Figure 8.5 [155]. It is referred to as a 'stormwater capture' from now on. The water will enter the tube once the level is high enough and fill the bottles one by one. It is recommended to use at least 4 bottles, so that a larger gradient of concentrations is obtained in the different bottles. Although this gradient is not very accurate, since leakage in other bottles might occur, it can give an idea of the fluctuations in quality. It is mainly important to know the maximum concentrations and how these are related to rainfall. It is advised to prepare this equipment before going into the field. The design will need some trial and error before the best installation is made. The next description is proven to be useful, but the exact method will largely depend on the local situation (e.g. discharge) in the pond:

Attach four 330 mL plastic bottles with an interval of 20 cm to a PVC pipe with a diameter of around 5 cm. The last bottle is used as a stopper and connected to the pipe via a 'L' joint. The other three are connected with a 'T' joint fitting. How to install this equipment in the inlet and outlet pipe is given the fieldwork manual (Appendix B).'

Figure 8.5: Sampling the in and out flow of stormwater by a 'stormwater capture' [155]

8.4.3. Take In- and Outflow Samples

Preferably the bottles of the stormwater capture are switched with empty ones after every substantial rainfall event. The samples should be brought to a lab where the quality tests are carried out. This step is also included in the field manual (Appendix B).

8.4.4. Take Groundwater Samples

Using the permanent well instead of drilling every time a sample must be taken is much more efficient and will prevent the samples from containing high levels of TSS. How this well should be installed is explained in Appendix B.2.6.

To understand the changes in groundwater quality relating to rainfall events, it is advised to take a sample at the same time as when the bottles of the stormwater capture are collected. The stagnation of water in a borehole may adjust the chemical constituents in the water and may not be representative of the average groundwater quality of the area. Considering a single groundwater well will not be able to monitor whether the borehole is being replenished under natural flow, an active method of monitoring is advised. A process known as purging is where the still-standing water in the borehole is emptied until the measured parameters are constant, and only then the sample is taken [156]. The chosen sampling technique is a point source bailer. How to exactly take these samples is explained in the field manual (Appendix B). The samples should be brought to a lab as well where the tests can be carried out at the same time as the in- and outflow tests.

8.4.5. Analyse Samples in the Laboratory

After collection the samples are analysed in the lab. The presence of the introduced pollutants in subsection 7.4.2 should preferably all be examined. However, some parameters are not useful to measure since the state and/or concentration of the pollutants will change between sampling and analysing. The stormwater capture collects the in- and outflow, with this method the samples are not directly analysed after a rainfall event. Bacteria present can reproduce in the meantime, not only changing the pathogens concentration but also the DO. The accuracy of TSS is also low, since sedimentation will already happen in the inflow pipe and the concentration of suspended particles will not be distributed evenly throughout the pipe.

The remaining parameters that should be measured and their corresponding methods are given in Table 8.2. Different methods exist to analyse these different parameters, recommended examples are given in the table. The measurement of nitrate and nitrite is only of importance when ammonia is present. The samples for both heavy metals and hydrocarbons should be send to a specialised lab where these compounds can be analysed, for which many methods exist [157, 158, 159, 160, 161, 162], which mainly depends on the available equipment.

Table 8.2: The water quality parameters that should be measured in the lab with their corresponding method
[1] Only when Ammonia levels are significant

Parameters	Method
EC	EC Meter
pH	pH meter
Salinty	Salinity meter
Ammonia	Hach®kit
Nitrate[1]	Hach®kit
Nitrite[1]	Hach®kit
Orthophosphate	Hach®kit
Heavy metals	Specialised lab equipment (e.g. spectroscopy)
Hydrocarbons	Specialised lab equipment (e.g. chromatography)

8.5. Risk Assessment

The flow diagram of the risk assessment is depicted in Figure 8.6. This flow diagram contains the steps that have to be followed in order to assess the risks related to infiltrating water via an infiltration pond. When certain risks are too big the flow diagram will advice not to apply infiltration. Certain risks also have to be assessed by a certified ground specialist or geo engineer, this has been indicated with an asterisk. In the following subsections each different step is shortly explained. The following main questions should be answered after completing all the steps described in the flow diagram.

- Is there a risk of groundwater flooding in or near the pond?
- Is there a risk of subsidence or other forms of soil instability due to infiltrating water?
- Are there risks associated with infiltrating water in proximity to existing structures?

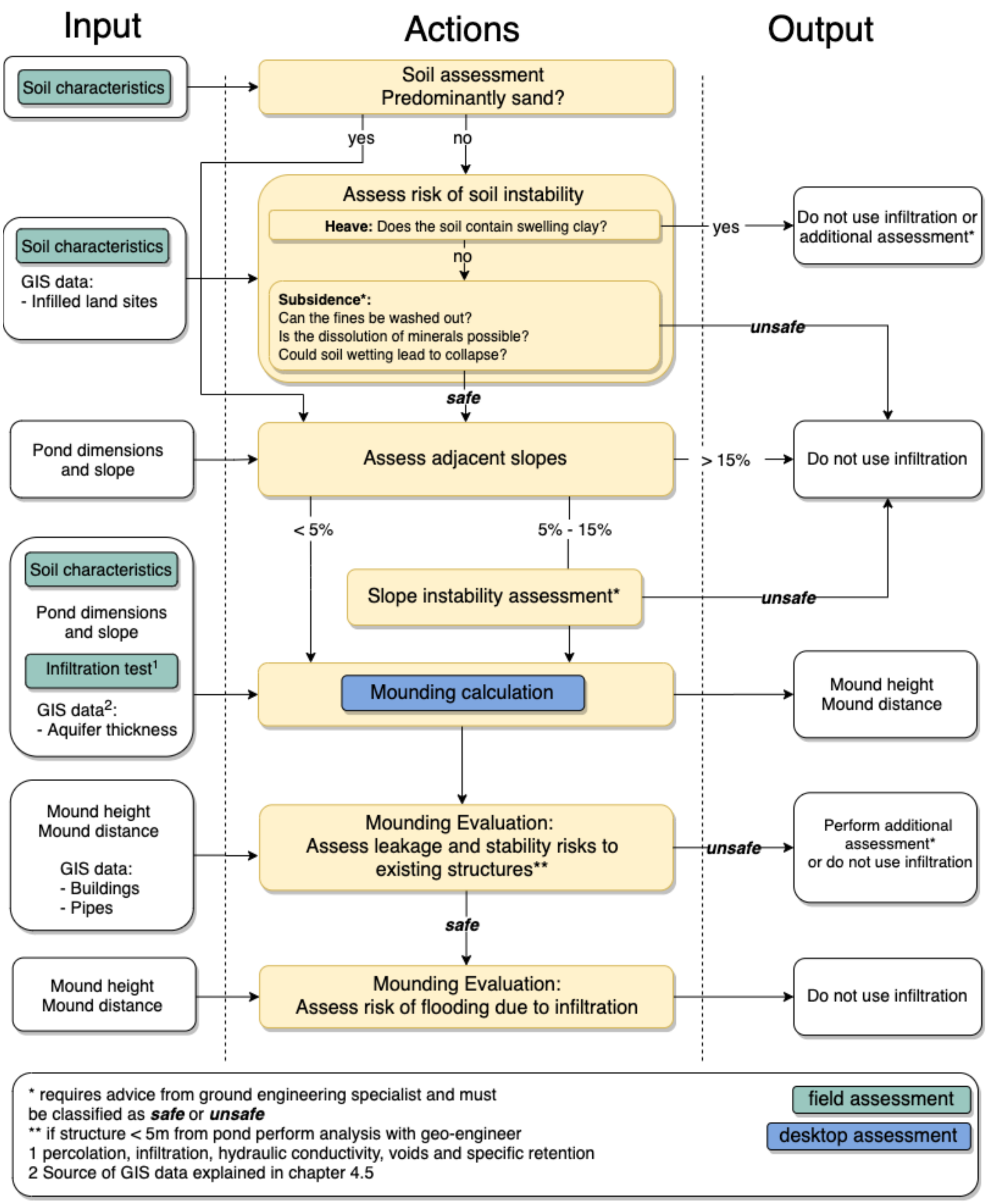

Figure 8.6: The flow chart of Risk Analysis

8.5.1. Soil Assessment

The first assessment of the flow diagram is related to the characteristics of the soil underneath the pond. These soil characteristics are obtained by examining the soil profiles from boreholes, this is explained in subsection 8.2.2 and the field manual, Appendix B and from GIS. When the soil samples show predominantly sand which is sufficiently compacted it is safe to infiltrate water with respect to soil instability issues. When other soil types or loose fill materials are present and when one questions the degree of compaction of the sand it is advised to assess the soil instability.

8.5.2. Risk of soil Instability Assessment

Infiltration of water can lead to the heave of the soil or the subsidence of the soil. For this assessment the characteristics of the soil underneath the pond is required and GIS data (or other sources) indicating the location of infilled land sites. Obtaining the soil characteristic is explained in subsection 8.2.2 and the field manual (Appendix B).

For the risk of heave one should identify the presence of swelling clay. When present it is not advised to infiltrate or further investigation on the heave risk is needed, this should be performed by an ground engineering specialist. The specialist has to determine if the achieved heave is classified as safe or unsafe.

For the risk of subsidence as a result of infiltrating water one should identify if the following conditions apply, these are formulated in the following questions.

- Are there loosely compacted fill material present in the soil?
- Does the soil contain loess or other soils with open structures?
- Does the soil contain carbonate rocks, like limestone or chalk?

When one or more of the soil types or conditions apply it is advised to assess the risk of subsidence with a ground engineering specialist. The specialist has to determine if the achieved subsidence is classified as safe or unsafe.

8.5.3. Adjacent Slope Assessment

This assessment is to check if the pond is located on a slope and subsequently if the steepness of this slope can lead to slope instability issues. The degree of steepness of the adjacent slopes of the pond have to be determined. LiDAR data can be used to determine the degree of the adjacent slopes, subsection 8.3.3 describes this in more detail. Is a pond located on a flat surface or a surface with a slope under 5 degrees infiltration of water has low potential to cause slope instability. When a pond is located on a slope of 5 to 15 degrees or near such as slope it is advised to consult a geo engineering specialist to conduct a slope instability assessment. Ponds located on slopes over 15 degrees are classified as unsuitable for infiltration.

8.5.4. Mounding Calculation

Mounding is the local rise or a perched water table toward and in cases above the land surface beneath or adjacent to an infiltration site [70]. To evaluate if mounding can affect underground structures or cause local flooding, mounding at land surface, it is necessary to calculate the mounding potential.

Calculating the mounding is solving the Hantush analytical equation for 'growth and decay of groundwater mounds in response to uniform percolation' underneath an infiltration cells. Appendix H contains and describes the Hantush equation and inputs. The equation contains an integral that cannot be solved explicitly and has to be solved using iterative numerical methods.

Online mounding calculators and mounding calculator spreadsheets can help solve the Hantush equation. One calculator is provided by Inowas and can be accessed via inowas.com [141]. The online mounding calculator accepts user supplied values and solves the Hantush analytical equation automatically. Furthermore the calculator has a user friendly interface, see Figure H.1. Appendix H describes the input values for the calculator and how to obtain them.

The output of the calculation will be the mounding shape. This is the mounding height at certain distance in the, x and y directions perpendicular to the square infiltration basin (Figure 8.7).

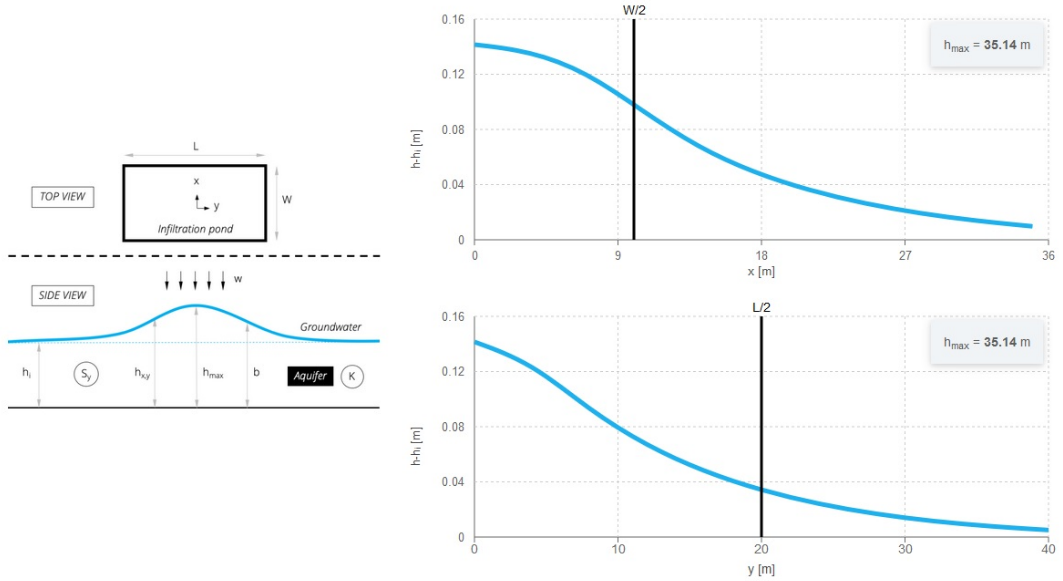

Figure 8.7: Output online mounding calculation: height of mounding over x and y-axis

8.5.5. Mounding Evaluation

Following the calculation of the mounding potential is the evaluation of this potential mounding on the surroundings. The evaluation is required to indicate potential risks of surface ponding or local flooding, the flooding of underground structures and the interference with underground structures eg. sewage systems. This translates to the following two assessments:

- Does the groundwater mound calculations show the possibility of the local water table to reach underground structures or foundations?
- Does the groundwater mound calculations show the possibility of the local water table to rise up to and above the surface?

The following inputs are necessary to assess if the groundwater mound can reach underground structures and foundations . The groundwater mound heights and the location of underground structures. GIS data can be used to identity the locations of these underground structures. When groundwater mound can reach adjacent underground structures, it is advised to not infiltrate or perform an additional risk assessment with a licensed geo technical engineer.

To assess if the groundwater mound can reach the surface and therefore cause local flooding is a matter of determining if the maximum mounding height exceeds the initial water depth. This will directly follow from the Mounding calculation. In case the mounding calculations shows a perched water table it is not advised to convert the stormwater pond into a infiltration pond.

9

Discussion and Conclusion

Numerous manuals and design methodologies have been developed for the engineering and construction of infiltration ponds. There are a limited amount of manuals that are aimed specifically at retrofitting existing stormwater attenuation sites into infiltration ponds, and there are none developed particularly for the context of CT. Based on an extensive review of literature, the assimilation of local knowledge and data from field investigations, this chapter proposed a site assessment framework that guides through the process of acquiring the crucial physical parameters which determine the functionality of an infiltration pond. The chapter is lead by several guiding questions expressed from the perspective of one who wishes to retrofit a stormwater pond into an infiltration pond. It is thereby accommodating for this particular audience and helpful to piece together the many parameters and methods which are otherwise difficult to take in. There are several points of discussion for each of the four chapters addressed below.

Hydro-geology
Understanding the ponds site specific hydro-geology is of key importance to determine its infiltration capacity. The hydro-geological flow chart gives guidance in determining the following matters: the assessment of the maximum groundwater level beneath the pond, determining the top and subsoil of the pond, the amount and depth of the soil contamination and finally the infiltration capacity of the soil beneath the pond. Since the hydro-geological flowchart is specifically developed for the CFA, hydro-geological related assumptions have been made before the physical investigation phase takes place. The equipment and methods as described in this chapter as well as the field manual have been adjusted accordingly and are therefore not guaranteed to be suitable for a different context. The procedure for extensive soil contamination assessment is complex. Cape Town has no standards for soil contamination in relation to infiltration, therefore the tests and methods as described in this chapter are based on a research of international literature. Aforementioned methods might change when regulations about soil contamination are set.

Hydraulics
The flow chart for the hydraulic analysis is reliant on various data sets, and the reliability of the final drainage analysis is largely dependent on the quality of the original data. A problem faced by those researching stormwater harvesting in CT, is the incompleteness/incorrectness of data with regard to the stormwater reticulation system, as well as unreported pipes and incorrect dimensions or elevations. The inaccuracy of this data can cause repercussions in estimating the total runoff into the pond. This estimation is further compromised by the difficulty in accurately defining the catchment and rainfall characteristics. The limited resolution of rainfall data along with high spatial and temporal variability makes obtaining representative data a challenge. Furthermore, the expected hydraulic loading cycles are highly influential but difficult to model due to its dependency on various complex processes that occur upstream of the pond. In turn, the hydraulic loading cycles influences the clogging rate, which is thereby an even more complicated process to model. The given framework offers a systematic method, and thus, if this is followed correctly, allows for objective comparison between pond, regardless of the quality of the data.

Water Quality
Evaluating the water quality is key for retrofitting the stormwater ponds, runoff can be highly polluted in ur-

ban areas. Getting insight in the amount of pollution is important for understanding the system as a whole and is therefore recommended to monitor in the proposed framework. In the Capetonian context, the main limitation in monitoring practice is the method by which it is done. For accurate data, more advanced sampling techniques should be implemented but this is not regarded possible in CT due to high criminality. Safety and the use of expensive equipment cannot be guaranteed. The stormwater capture seems to be a promising solution to this problem since it is a very robust and simple technique to collect samples. However, this method comes with the cost of sacrificing accuracy with respect to data obtained for pollution rate relative to rainfall volume. However, the stormwater capture is proven to work and can provide an understanding of the scale of pollution. Currently, the stormwater system discharges the polluted runoff to open water bodies. By infiltrating, treatment of the water will occur naturally which has a positive effect on the ecosystem as a whole. Therefore, retrofitting stormwater ponds to infiltration basins will likely have a beneficial effect regarding water quality. This positively contributes to CTs wish of becoming a water sensitive city.

Risk Analysis
It is vital to know the risk constraints related to the use of infiltration before considering implementation. Therefore, these risks have to be identified and evaluated before any site can be considered a potential location for infiltration. In Phase II the risks for the CFA context were identified to be: soil instability, subsidence, groundwater flooding, and risk to existing structures. The risk assessment facilitates gaining insights with regard to mentioned risks. It does not incorporate advanced methods and tools to quantify and fully assess the risks. Therefore, it is not suitable to quantify the extend of a risk. However, the risk assessment does aid in indicating potential risks based on indicators. Consequently, the flow diagram is built up in such a way that it guides the reader through the evaluation process, using basic tools and observations, identifying risks and determining if the risk is likely to happen. If this was the case the flow chart will advice a full risk assessment undertaken by an experienced geo-technical engineer similar to other manuals. The proposed flow chart enables a laymen to perform a first risk assessment, identifying ponds with no indication of likely risks while simultaneously identifying ponds that need to be analysed more thoroughly by a specialist.

Outputs of Phase II
Phase II provided the methods for the physical assessment of the detention ponds. The next step is the redesign phase, meaning modelling/calculating changes and their influences to the physical system. The method and reasoning of what parameters can be influenced and must be considered for a good redesign is explained in detail in chapter 11. Table 9.1 shows the outputs of the physical assessment and the desktop studies which are used to model the initial state of the physical system and to redesign it. Some of the Outputs are design parameters of which some can directly by changed and others are fixed due to constraints. Other outputs are performance indicators which are used to evaluate the performance of the original state and later the redesign. The classification of design parameters and indicators is explained in detail in section 11.6.

Table 9.1: Outputs of Phase II that are used in Phase III

Outputs of Phase II	**Design Parameter**	**Performance indicator**
Hydro-geological assessment		
Soil type	✓	
Soil texture	✓	
Soil contamination	✓	
Infiltration rate		✓
Saturated hydraulic conductivity	✓	
Hydraulic assessment		
Weather data	✓	
Runoff data	✓	
Pond dimensions	✓	
Drainage time		✓
h max	✓	
Annual yield		✓
Clogging rate	✓	
Water quality assessment		
Litter quantification	✓	
In/out- flow water quality	✓	

III

Conceptual Design

10
Introduction

The output of phase I has provided the information on whether a pond is in a suitable area using GIS-MCDA. This has been used in phase II as input to select which ponds are to be physically assessed. Phase II confirms if a pond is suitable for infiltration or excludes a pond if it is not. However, many ponds have a potential to become suitable, but need redesign measures to achieve this. This phase introduces the method for redesign. The function of the ponds is changed from detention to infiltration ponds. Therefore redesign of the certain features of the detention ponds need to be changed to fit to the new function of the pond. In order to assess the physical state of the system and of the redesign five design indicators are introduced together with the factors that influence them. These proposed design indicators are: infiltration rate, yield, flood attenuation, drainage time and water treatment efficiency. This is further elaborated in the Methodology chapter 11. Consequently, a dependency diagram of the design indicators is constructed. Since the dependency diagram is not an easy to use tool due to the many influencing factors, a step-wise flowchart is provided. This serves as a simplified guidance through the retrofitting process and to verify if retrofitting is indeed possible for a specific pond. Afterwards, the Green Infrastructure Flexible Model [105] (GIFMOD) is introduced. GIFMOD can be used to to model the results of interventions on the design indicators. The step-wise flowchart is strongly recommended to be used as an iterative tool to assure a intervention for one design indicator does not negatively influence another design indicator. After this phase, it should be clear if redesign is feasible, and if so, what measures can be executed to redesign.

11 Methodology

In the process of defining the redesign phase five performance indicators were defined: infiltration rate, yield, flood attenuation potential, emptying time and water treatment efficiency. For those indicators, criteria were defined based on literature. Table 11.1 shows the design indicators and criteria. The methodology of the redesign chapter will firstly address the five design performance indicators and the design parameters which influence them. The performance indicators are obtained from the WUSD manual [55] and the client's interest. An indicator is understood to be a specific, observable and measurable characteristic that can be used to assess changes due to interventions. These design indicators are to be improved by redesign if this is required. For the redesign the purple outputs in the flow schemes of chapter 8 are used. Retrofitting should first of all not deteriorate the flood attenuation capacity since this is the reason why they were initially constructed. Therefore, the criterion defined for flood attenuation is not worsening the current physical state of the stormwater system. Secondly, phase 2 mentions a minimal required infiltration rate (25.4 mm/hour [55]). This value is set as the criterion for the infiltration time. There are multiple physical factors that influence the infiltration rate. The infiltration rate is thus a useful indicator to relate different design options. The same holds for yield and emptying time. For the yield no criterion was defined since without an economical framework it is not quantifiable what can be considered as a good yield. For the emptying time a half emptying time of 24 hours was set as criterion [163]. For the water treatment efficiency it is difficult to determine a criterion, since it would have to based on environmental regulations. In the course of building this framework no standards for groundwater infiltration where encountered. However, it is assumed that water treatment by infiltration will be highly beneficial for the aquatic environment. It has been encountered in numerous design frameworks for infiltration pond and more generally urban drainage design [55, 67, 68, 71] and therefore water treatment, especially in the context of a water sensitive city design, should be considered in the redesign besides hydraulic benefits. The criterion for the water treatment efficiency is therefore defined to be as high as possible.

The five design indicators and the factors influencing them are presented in the following five sections. The analysis of those factors was used to construct a dependency diagram to visualise the influences of the factors on the design. The multi-influencing diagram aims to provide a more comprehensive understanding of the complex interactions between the factors and their influence on the design indicators, and thereby facilitate the conceptual redesign process. At the end of each section, for each performance indicator design recommendations are given for their improvement.

Table 11.1: Performance indicators and their according criteria

Performance indicator	Design criterion
Infiltration rate	25.4 mm/hour [55]
Flood attenuation capacity	Not worsening the current flood attenuation capacity of the stormwater system
Emptying time	Half emptying time of 24 hours [163]
Yield	No criterion defined
Water treatment efficiency	As good as possible, no quantitative criterion defined

11.1. Infiltration Rate

The infiltration rate is the velocity at which water enters the soil, normally expressed in millimetre per hour. A prerequisite for infiltration is ponded water on a soil. The rate of infiltration is limited by the soil and the rate at which water is applied to the surface. Factors controlling the infiltration rate are the vegetative cover, the soil moisture content, the soil structure and texture, the porosity and soil permeability, organic matter content, the soil bulk density and compaction, the pond slope and the degree of clogging.

Vegetative Cover: The presence of vegetation in (semi)-arid areas increases the infiltration capacity of soils, both through the enhancement of the soil structure by the root system and by biotic processes facilitated by the presence of vegetation [164]. An additional benefit of vegetative cover may be the reduction of clogging [165]. To select appropriate vegetation the Australian plant selection for WSUD can be used as a guideline [166]. It is however recommended to use native plants, since within the Western Cape exotic species are a major contributor to the water shortage [8].

Soil Moisture Content: The soil moisture is a factor that cannot directly be designed for. It is however influenced by vegetation, the soil's texture, organic matter, soil bulk density and compaction [167, 164].

Soil Structure and Texture: The amount of sand, silt and clay present in the soil determines the soil texture. The minimum infiltration rates of a soil are determined by the soil texture [167]. This parameter can be redesigned for by adding or removing the soil with soil of different composition. Soil structure refers to the grouping of soil particles (sand, silt, clay, organic matter and fertilisers) into aggregates. Soil structure also refers to the arrangement of these aggregates separated by pores and cracks [167]. This parameter can be redesigned for by adding organic matter, plowing and adding vegetation.

Porosity and Permeability: The permeability of a soil is related to the porosity, but also to the shapes of the pores in the soil and their level of connectedness. This depends on both the soil texture and structure. Permeability is negatively influenced by the soil moisture content [167]. It cannot be directly be redesigned for, indirectly the soil texture and structure can be changed to change the porosity and permeability.

Organic Matter: Organic matter refers to organic material that has been decomposed. Addition of OM increases the water holding capacity of a soil, thereby increasing the soil moisture content. OM improves the soil structure by binding the soil particles together into aggregates. Additionally, it influences the soil bulk density positively [168].Soil bulk density is explained next. Organic matter content of the soil is a parameter that can be changed.

Soil Bulk Density and Compaction: The Soil Bulk Density , also known as dry BD, is the weight of dry soil divided by the total soil volume. Compaction causes BD to increase. An increase of BD decreases permeability and constrains root development [169]. This parameter can be redesigned for indirectly by plowing or mixing the soil with OM.

Slope A flat bottom provides an infiltration basin with a uniform inundation depth [28]. This provides a more homogeneous clogging rate of the surface soil, which in turn eases both the estimation of the infiltration rate using a model which will be elaborated on later and maintenance practises of the infiltration basin [28].

Clogging: "Clogging of the infiltration surface and resulting reductions in infiltration rates are the bane of all artificial recharge systems." [170]. Clogging reduces infiltration rate, diminishes the soils capacity to treat infiltrating water and requires regular maintenance of the infiltration pond. Clogging can thus be seen as a major factor influencing the success of a infiltration pond. Biological, physical and chemical processes can cause clogging. These processes and the resultant clogging are in turn influenced by the influent water quality, basin soil texture, ponding depth, hydraulic loading rate and cycle and vegetation [165]. This is discussed more extensively in subsection 7.2.5.

11.1.1. Design for Infiltration Rate

The factors that can be changed are represented by redesign options that can improve the infiltration rate:

- Plant adequate vegetation in the pond
- Improve the soil texture by either excavating or mixing the soil with more sandy, sandy loamy soil or gravel

- Improve the soil structure by adding OM, plowing or excavating the soil and replacing it with new soil
- Use a fore bay for sedimentation to reduce clogging rate
- Decrease clogging by removing the top soil. This top soil can be replaced with suitable soil for infiltration if deemed necessary

11.2. Flood Attenuation

The original purpose of the pond, flood attenuation, should not be compromised by a redesign. Flood attenuation is achieved by temporally storing water, after which the water is released back into the urban drainage system again. The temporal storage is thus dependent on the volume of the pond. Aside from changing the pond dimensions, changing the infiltration rate can also increase the storage. The pores within the soil and consequently the aquifer provides additional storage. The flood attenuation is thus impacted by changing the volume of the pond (which depends on the bottom surface area, top surface area and the maximum water height) and the infiltration rate. For the redesign of a detention pond to an infiltration pond, the outflow is normally above the inflow to allow time for the incoming water to infiltrate. This lengthens the detention time, will reduce the volume to cope with during peak flow or when multiple rain events occur after one another. An emergency spill outflow is necessary for excessive inflow volumes.

11.3. Annual Yield

11.3.1. Annual and Percentage Annual Yield

In section 7.3.5 the annual yield, cubic meter per year, is defined as the amount of water that is infiltrated via the infiltration pond in one year. The annual yield % is the ratio of infiltrated water to incoming water. The yield can be calculated via a water balance, refer to equation 7.2.

The infiltration can be determined by the following formula, assuming the pond stays dry at the beginning and end of the mass balance calculation and therefore the water storage (ΔS) does not change and is equal to zero.

$$f = i + q_0 - e - q_1 \tag{11.1}$$

Where:

f infiltration of water into the soil
i precipitation falling directly into the pond
q_0 inflow to the pond from runoff captured from catchment
e evaporation
q_1 pond runoff or overflow

This equation tells that the infiltration, f, increases when there will be more runoff or inflow, q_0, into the pond and less evaporation ,e, and overflow, q_1. This is a oversimplification because the parameters affecting the infiltration given in the mass balance are first affected by, among others, the pond characteristics, the hydraulic conditions, soil conditions and precipitation. The next section will discuss how the Minnesota Pollution Control Agency has related the Annual Yield to the pond characteristics [151, 152].

11.3.2. Annual Yield Related to Pond Characteristics

For the MIDS calculator the Minnesota Pollution Control Agency has related certain characteristics of a pond to the percent annual volume reduction, annual yield percentage. This relation is made possible by a conversion. The conversion is facilitated by performance curves, which relates the annual percent reduction (infiltration) to the ponds volume, the ponds infiltration rate, the watershed area of the pond and the percentage impermeable surface of the watershed area. The percent annual volume reduction due to infiltration can be used to determine the annual yield. How the performance curves can be obtained is explained in more detail in subsection 7.3.5. The performance curves are depicted in Figure 7.3. The following factors that relate the the percentage annual yield can be deducted from the performance curves:

Increases percentage annual yield:

- High soil infiltration rate

- Low percentage imperviousness of the contributing area
- Bigger volume of the pond
- Smaller contributing area

Summarised the following factors affect the annual yield.

- Infiltration rate related to soil type
- Evaporation and transpiration
- Dimensions of Pond
- Precipitation
- Runoff coefficient
- Percent impervious area of contributing area
- Size of contributing area

11.3.3. Design interventions for Annual and Annual Percentage Yield

The following measures and actions can be taken in order to design for an increased annual percentage yield.

- Increase the surface area of the pond by excavation of surrounding area
- Increase the height/depth of the pond by raising the outflow
- Increase the height/depth of the pond by excavation of the bottom
- Increase the infiltration rate of the pond, by changing the pond soil
- Decrease the watershed area into the pond
- Decrease the percentage imperviousness area of the watershed area

The following can be done to increase the annual yield. Note the annual yield can be calculated by multiplying the annual inflow by the annual percentage yield. Thus, the more water is flowing in the pond the more water can be infiltrated. However, some measures to increase the inflow also affect the annual percentage yield negatively.

- Increase the runoff ratio of the Watershed area
- Increase the amount of imperviousness of the contributing area
- Increase the Watershed area of the pond

11.4. Emptying Time

The emptying time, is a design criterion set to achieve emptying of the pond within a certain time, this in order to handle the following rainfall event. Furthermore, it is to avoid nuance by long ponding water within the pond. The infiltration pond should drain its contents within a defined time. This will avoid corollaries such as mosquito breeding, odour nuisance or even safety hazards such as of drowning. Therefore, it is usually required that an infiltration pond should be fully drained within 24 hours to 48 hours depending on the context or decision-making policies [163]. The emptying time is dependent on the infiltration rate of the pond and the maximal ponding height in the pond. The emptying time can be calculated as follows [163]:

$$Emptying\ time = \frac{Max\ height\ of\ ponding\ water}{Infiltration\ rate}$$

11.4.1. Maximum Ponding Height

The maximum ponding height in the pond is the maximum expected water level above the bottom of the pond. This maximum expected water level in the pond can be influenced by either one of the following two aspects.Firstly, considering the storage volume of the pond is a fixed entity, the ratio between the rate of inflow and the infiltration rate of the pond will determine the theoretical ponding height within the pond. The two determining factors, the rate of inflow and the rate of infiltration, are in turn dependent on multiple factors. The rate of inflow depends on, amongst other factors, the catchment/rainfall characteristics and the infiltration rate is determined by the factors explained in section 11.1. Secondly, the height of the outflow pipe, emergency overflow or the pond edge if none present will also influence the ponding height.

11.4.2. Infiltration Rate Related to Drainage time

The time needed for the pond to drain depends on the height of the water level and the rate of which it enters the soil. The rate of which water enters the soil depends on multiple parameters and is separately discussed in section 11.1. Water that enters the pond has several outflow possibilities. It can infiltrate, flow to controlled outlets, evaporate or be pumped out

11.4.3. Design Interventions for Drainage time

Now that the physical aspects affecting the emptying time are known, one can choose to change these to meet the criteria. When the desired emptying time is not met one can first question whether the chosen time is feasible, or make the decision to alter the following aspects of the pond or surroundings.

Change the maximum height of ponding water intervention to the pond:

- Lower the outflow
- Lower the emergency overflow
- In case no outflow nor emergency overflow are present, install one on the appropriate height
- Increase the area of the pond
- Increase the infiltration rate of the pond, to minimise the maximum possible ponding height

Allow for quicker infiltration/drainage:

- Increase the infiltration rate
- Install a controlled outflow for additional drainage
- Install an emergency pump

Change the maximum height of ponding water by intervention to the surrounding:

- Draining a smaller area
- Changing the characteristics of the area to lower the peak runoff

11.5. Water Quality Design

In the following paragraphs the pathways of the main stormwater constituents (see subsection 7.4.1) are described, followed by a short list of important water quality design recommendations to ensure proper management of repurposed infiltration ponds. These recommendations should always be seen in the local context and can be different for each infiltration basin, therefore to design a safe system a thorough analysis is inevitable. Additionally, Cape Town is facing another major challenge regarding feasibility of redesign: The socio-economical context of social inequality and crime rates pose a safety risk to monitoring equipment, infrastructure and field researchers. This issue is out of scope for this report and should be evaluated in a individual social and economical framework. The processes that are described in this section are based on the findings for Soil Aquifer Treatment which is the controlled infiltration of wastewater in an earthen basin to reach the desired treatment efficiency. The same processes are relevant for stormwater infiltration [92]. For the water quality design it is essential to investigate and understand the geo-hydrological conditions (see chapter 7 of the basin since the SAT process is based on biological, chemical and physical interactions in the soil matrix [92].

11.5.1. Treatment Mechanisms and Design Recommendations

Solids

The removal efficiency for solids is high whereby filtration acts as the main mechanism for removal. This however makes them a significant problem for the operation of infiltration systems since they can quickly clog up a pond. Therefore, pre-treatment, in the form of pre-sedimentation of the non-biodegradable fraction (sand and silt) must be applied to ensure functioning of the infiltration basin over the designed lifetime (subsection 11.5.2) [92].

The pathways for biodegradable solids are filtration, absorption, adsorption, biological reduction and oxidation. In contrast to inorganic sediment biodegradable solids can degrade over time and pose less of a problem for the infiltration practice. Intermittent infiltration cycles are necessary to allow the soil to restore its aerobic conditions in order to maintain the infiltration capacity at the soil surface. The dry phase (reaeration phase) should therefore either match or exceed the wet phase [92].

Design recommendation:

- Forebay for pre-sedimentation
- The dry phase (reaeration phase) should match or exceed the wet phase to reduce the rate of clogging due to biomass, manage emptying time (see subsection 11.4.3)

Nutrients

Due to the many forms of nitrogen such as organic nitrogen, ammonia, nitrite and nitrate present in stormwater, the removal of nitrogen is based on dynamic processes and variety of chemical reactions [171]. Nitrogen that is contained in the organic particulate fraction is mainly filtered out during infiltration or sedimented in the pre-treatment. Ammonia is partially volatilised. Longer hydraulic retention times of the stormwater will lead to higher volatilisation and microbial consumption rates. Additionally to latter, ammonia can be adsorbed to clay minerals or taken up by plants, which however has a little contribution in infiltration ponds due to high hydraulic loading rates [92]. Nitrate can be taken up by vegetation or be converted to nitrogen gas by the denitrification process of denitrifying bacteria that reside in micro or macro anaerobic zones. Nitrification is a highly efficient process in infiltration basins as long as aerobic conditions can be maintained. However, denitrification is rarely effective [93]. The fraction that is not retained or reduced leaches through the soil profile which can pose a risk for groundwater contamination. Due to high nitrification rates compared to denitrification rates, nitrogen removal is incomplete and nitrate can be expected to leach to the groundwater where it might accumulate[172]. Since denitrification requires anoxic conditions, most design modifications aim for increasing the hydraulic retention time. This inevitably creates a trade-off between drainage/ infiltration goals and the desired water quality [171].

Low DO and alkaline conditions in lake sediments were shown to promote phosphate release from sediments [173]. Therefore, to ensure that mineralised phosphate is not re-released during storm events it is important that the hydraulic retention time is not too long to prevent anaerobic conditions in the soil. Moreover, phosphorus removal is dependent on the Phosphorus Retention Index of the applied soil [92]. In West Australia for instance due to the low PRI of most sands, soil amendment can be necessary to achieve higher phosphorus removal [174]. This might apply for the soils above the Cape Flats Aquifer, as well.

Design recommendation:

- Plant grass to provide a carbon source for microorganisms
- Limit hydraulic retention time by choosing a suitable outflow height (see also subsection 11.4.3)
- Use soil with suitable phosphorus retention index

Pathogens

In SAT the risk for groundwater contamination can be significant due to high hydraulic loading rates, coarse soil texture and high permeability of the applied soils. The main pathogens of concern are parasites, bacteria and viruses. SAT can achieve 2 to 3 log reductions of faecal coliforms (good and simple indicator for pathogen contamination)[92]. Possible removal mechanisms for pathogens in infiltration basins are adsorption, desiccation, radiation, filtration and decay. Pathogens can adsorb to charged clay minerals. Trapping by vegetation and exposure to sunlight is one way to reduce the concentration of pathogens travelling through the soil profile. Furthermore, effective pre-treatment will remove pathogens attached to litter surfaces and suspended particles. However, the silt fraction and smaller particles in the sediment load contain most of the contaminants. Most often it is not possible to remove the silt fraction completely by classical pre-sedimentation measures since they stay in suspension. The main removal mechanism for pathogens is filtration and adsorption processes. In loamy sand pathogens are retained within the first 80 centimetres of the soil [92]. Since the removal of viruses is partially dependent on the cation exchange processes and adsorption reactions the removal efficiency seems to be more effective in finer textured soils [92]. Changing the soil texture will therefore largely influence the treatment performance of an infiltration basin [92]. However, the designer must take into account that this change in soil texture cannot be done without affecting important hydraulic parameters such as hydraulic retention time and infiltration rate section 11.1. Furthermore, it will increase the risk of pond sealing since there is less pore space. Summarising, pathogens can be well removed provided that the soil layer thickness is sufficient and the soil is not to coarse. However, parasite eggs can survive for years in the soil. Consequently, sampling and soil handling must be done carefully to reduce human exposure. Viruses have longer travel times in most soils due to their smaller size compared to bacteria. [92].

Design recommendation:

- Use soil layer thickness of at least 1 m above groundwater table
- Fine textured soils function better than coarse soils for pathogen removal
- Charged minerals or organic matter in the soil can adsorb pathogens to the soil matrix and retain them
- Use grass to retain more pathogens
- Field measurements should be executed with care (health risk)

Trace Organics

Trace organics are normally well removed in infiltration practice as explained in subsection 7.4.2. Therefore, no design recommendations are discussed.

Metals

Heavy metal removal in soils happens by adsorption, precipitation, ion exchange, biochemical reactions, uptake by plants and microorganisms and complexation. Adsorption of most of the metals occurs on the surface of charged clay minerals, metal oxides or organic matter. Finer textured soils therefore offer more surface area for adsorption processes, thus increasing the removal efficiency. However, coarser soils can still be effective for metal removal if longer travel lengths to the groundwater can be achieved [92]. The solubility of most heavy metals increases with decreasing pH. In conclusion, low pH aggravates heavy metal leaching through the soil profile. Calcium carbonate offers a potential approach to tackle the problem. Calcium carbonate increases a soil's buffer capacity and thus indirectly reduces the solubility of heavy metals [175]. Furthermore, calcium carbonate and other carbonates function as a scavenger for heavy metals by carbonate precipitation [176, 177]. For above mentioned reasons, treatment by means of supersaturated carbonate solutions could be a possible approach to manage the issues associated with soils contaminated by heavy metals or linked to acidic soils.

- Use carbonates in soil matrix to increase soils buffer capacity and make it less prone to soil acidification
- Use fine particles and organic matter in the soil to bind heavy metals
- In emergency supersaturated carbonate solutions can scavenge heavy metals and prevent their leaching through the soil

Salinity

As discussed in chapter 7 the salinity of the water is monitored by measuring the electrical conductivity. However, it is not really possible to design for salinity removal in infiltration ponds. This problem should be addressed at the source of pollution instead and should be tackled by using multiple stormwater green infrastructures in the context of water sensitive cities. Wetlands for instance perform better in nutrients removal than infiltration ponds and can therefore contribute to a reduction of the salinity. Pre-treatment by means of bioswells and raingardens is another possibility.

11.5.2. The Role of Pre-treatment

Pre-treatment is crucial for maintaining the performance of an infiltration pond over its lifetime. In cases where one can expect high TSS load and runoff rate in combination with high intensity rainfall, pre-treatment of stormwater is highly advisable [178]. Without reducing the TSS load on the infiltration basin by means of pre-treatment it would clog very quickly. In addition to that, most of the contaminants are either adsorbed to suspended solids or incorporated in them (for instance biological particulate matter containing nutrients)[92]. The first flush occurring during rainfalls contains the majority of the pollutants [176]. Furthermore, litter in stormwater poses hazard to human health and the aquatic environment since they can bind many pathogens and contaminants on their surfaces [179]. Pre-treatment is an effective way to reduce litter load on the environment. Most common pre-treatment steps include litter and sediment traps. There is a variety of different systems which are potentially useful for stormwater treatment and suitable for urban litter removal. Chittripolu, Lau, and Ghani [180] thoroughly explains existing pre-treatment technologies.

11.5.3. The Role of Vegetation

As mentioned earlier surface vegetation is typically not part of SAT treatment and plays a minor role for nutrient removal and heavy metal uptake, due to the high hydraulic loading rates. Nevertheless, the vegetation provides some water quality treatment and the root network assists in preventing the basin floor from clogging by creating micro pores and keeping the topsoil permeable through rooting [181]. Additionally, plant roots can provide missing degradable carbon for denitrifying bacteria. Furthermore, vegetation enables trapping of pathogens and other contaminants at the surface of the pond which enables volatilisation (e.g. hydrocarbons) and exposure to sunlight (desiccation and elimination of pathogens). [92]. Whenever vegetation is applied, water-tolerant grasses are typically used [92].

11.5.4. Influence of Soil pH

The soil pH is an important parameter for the safety and functionality of an infiltration basin. Soil acidification occurs naturally when acidic rain or water containing ammonia or nitrate in general infiltrates dissolving minerals and salts in the soil and thus reducing the soil's buffer capacity over time (see also subsection 11.5.1) [182]. Normally, the optimum pH for most microorganisms found in soils ranges from 5 to 8 [83]. Therefore, to not interfere with biological processes taking place in the soil, the pH should not exceed this range [92]. Furthermore, maintaining a pH above 4 is advisable since for acidic soils the solubility of heavy metals and the risk of leaching to deeper, groundwater containing soil layers increases significantly [83, 183]. The soil pH should thus be monitored regularly to investigate if the infiltration system is still safe to use or measures must be taken such as chemical treatment,soil amendment or sealing of the pond.

11.6. Multi-influencing Flow Chart

In the previous sections all factors influencing the five design criteria (flood attenuation potential, infiltration rate, water treatment efficiency, emptying time and yield), are discussed. In Figure 11.1 these relationships are visualised. Green arrows in the figure represent an improvement whereas red arrows are used for a negative influence. The blue fields in Figure 11.1 represent performance indicators for which criteria were defined. The purple fields are the design parameters which can be either measured or directly changed, whereas the light green fields represent parameters that are indirectly altered by changing the design parameters.

From Figure 11.1 it becomes evident that the infiltration rate influences all other design indicators. An increase in infiltration rate improves the yield, the flood attenuation capacity and the emptying time of an infiltration pond. However, the water treatment performance is negatively affected. This is due to the fact that there is less time for particle soil interactions as well as reactive transport. The multi-influencing flow chart can be used during the redesign phase as an overview for the linkages between design parameters. Figure 11.1 can be used with the design decision flowchart (see Figure 12.1) as well as the GIFMOD (see section 12.2) to facilitate the redesign phase.

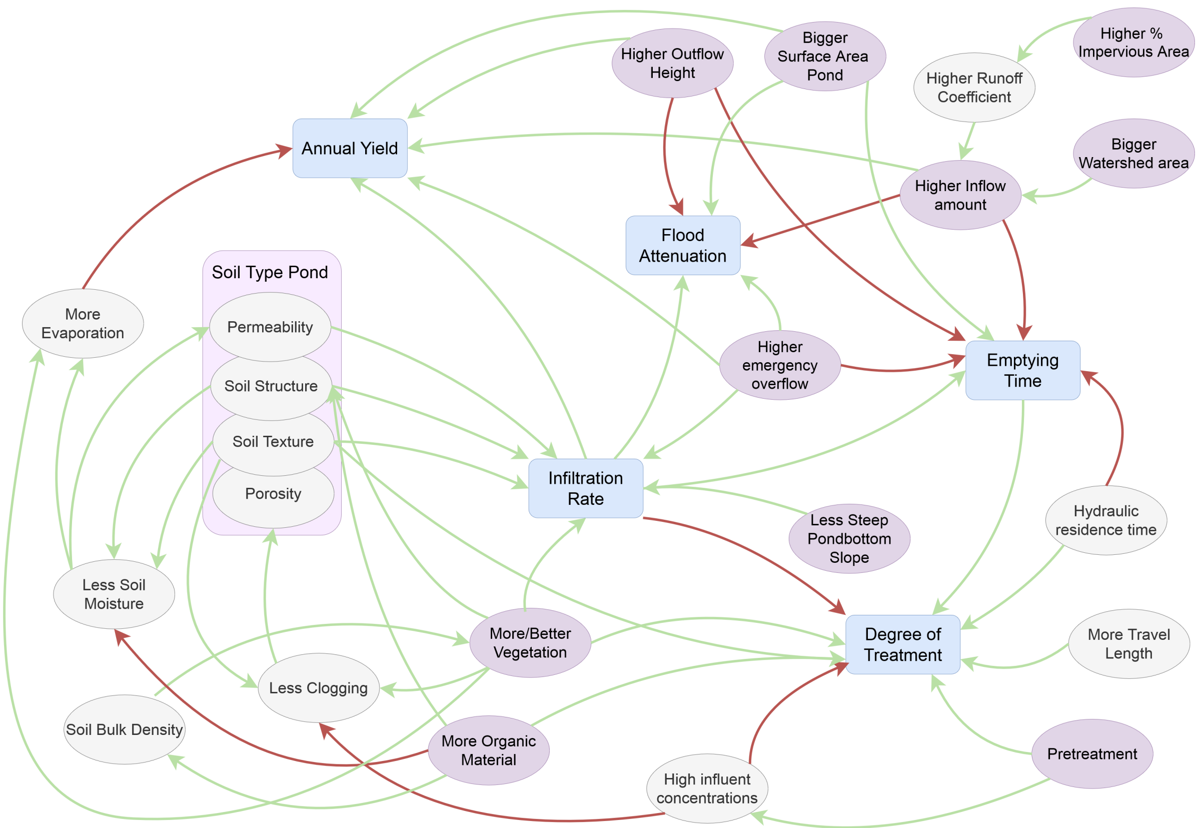

Figure 11.1: Multi-influencing Flow Chart, green arrows: positive influence, red arrows: negative influence, blue fields: performance indicators, green fields: not directly influencable parameters, purple fields: directly changeable/measurable parameters

12 Results

In this chapter two tools are presented which can be used to facilitate the redesign phase. Firstly, a design decision flow chart section 12.1 is presented which was developed based on the gained knowledge throughout the literature study for chapter 7 and chapter 11. Secondly, an open source model the Green Infrastructure Flexible Model (GIFMOD) [154] section 12.2 is introduced. This model can be used to model the initial state of the physical system and to analyse which design changes are beneficial for the infiltration practice and how to improve the water treatment efficiency.

12.1. Design Decision Flow chart

Redesigning an existing stormwater infrastructure into an infiltration basin can be challenging in multiple aspects. The redesigned infiltration pond must fulfil its original purpose (i.e. flood mitigation) and perform well for groundwater recharge, meaning that it infiltrates fast enough and cleans the water to an extend that is justifiable or complying to environmental regulations for groundwater recharge. Most of the changeable design parameters for a stormwater infiltration basin will affect multiple design criteria. Improving one performance category might therefore worsen the performance of the pond in a different aspect. In order to achieve a good redesign the Limiting Design Parameter should be known to design accordingly. The LDP (e.g. certain water quality parameter) is the parameter that cannot be compromised on, in other words the LDP is the parameter which has the highest priority [92]. The LDP is normally based on environmental regulations which themselves should be based on best current scientific knowledge. The flow chart (see Figure 12.1) is meant to assist the user of this framework during the redesigning process. The flow chart can be used together with the in section 12.2 explained computational model created by Massoudieh et al. [105].

Redesigning Cape Town's flood detention ponds must not jeopardise the flood mitigation measures of this already flood prone city (see section 11.2). Starting with the assumption that flood mitigation potential cannot be diminished (to not put adjacent areas at risk), leads to the consequence that pond dimensions cannot be decreased. Increasing the ponds volume might be a redesign option if space is available and excavation is economically feasible. This option is not considered in this framework, since it requires a financial analysis as well.

The first step in the redesign framework is therefore the redesign for soil contamination. The output of Phase II gives the designer the indication if the soil is contaminated and if improvements are necessary. After any change in the soil characteristics the infiltration rate (see section 11.1) has to be examined. This is facilitated with the GIFMOD [105] explained in section 12.2 of this framework. The field measurements acquired in Phase II serve as input for the GIFMOD. After simulating the pond by means of the model the designer will have an indication of the current pond performance in the five performance categories: flood attenuation, infiltration rate, water treatment efficiency, drainage time and yield. By redesigning within GIFMOD user interface the user will then be able to see how well the redesign performs compared to the assessed pond.

After designing for an acceptable infiltration time, the designer should proceed with the water treatment efficiency. This criteria is crucial within the context of water sensitive urban design and creating a resilient and sustainable liveable environment.

After optimising the water treatment efficiency treatment the designer can proceed with designing for an optimal drainage time (see section 11.4). Throughout the redesign process the performance indicators will change by implementing changes with regard to soil contamination, infiltration rate and level of treatment. When design parameters are changed to fulfil a criterion later in the process the user should go back in the flowchart and check if the previous performance indicators stills meet the criteria.

Lastly, the yield is optimised. This criterion should stand at the end of the redesign and only be optimised if the water treatment efficiency is not jeopardised below an unacceptable level. At the end of the redesign phase once the infiltration pond meets all the criteria the user can choose from the design recommendations given in chapter 11 to further improve the ponds performance, reduce maintenance or increase its lifetime. These recommendations are considered to be beneficial for the infiltration practice. Not all of the measures might be suitable for every pond. Therefore, the recommendations should be seen as guidance and not as a unrelenting dogma.

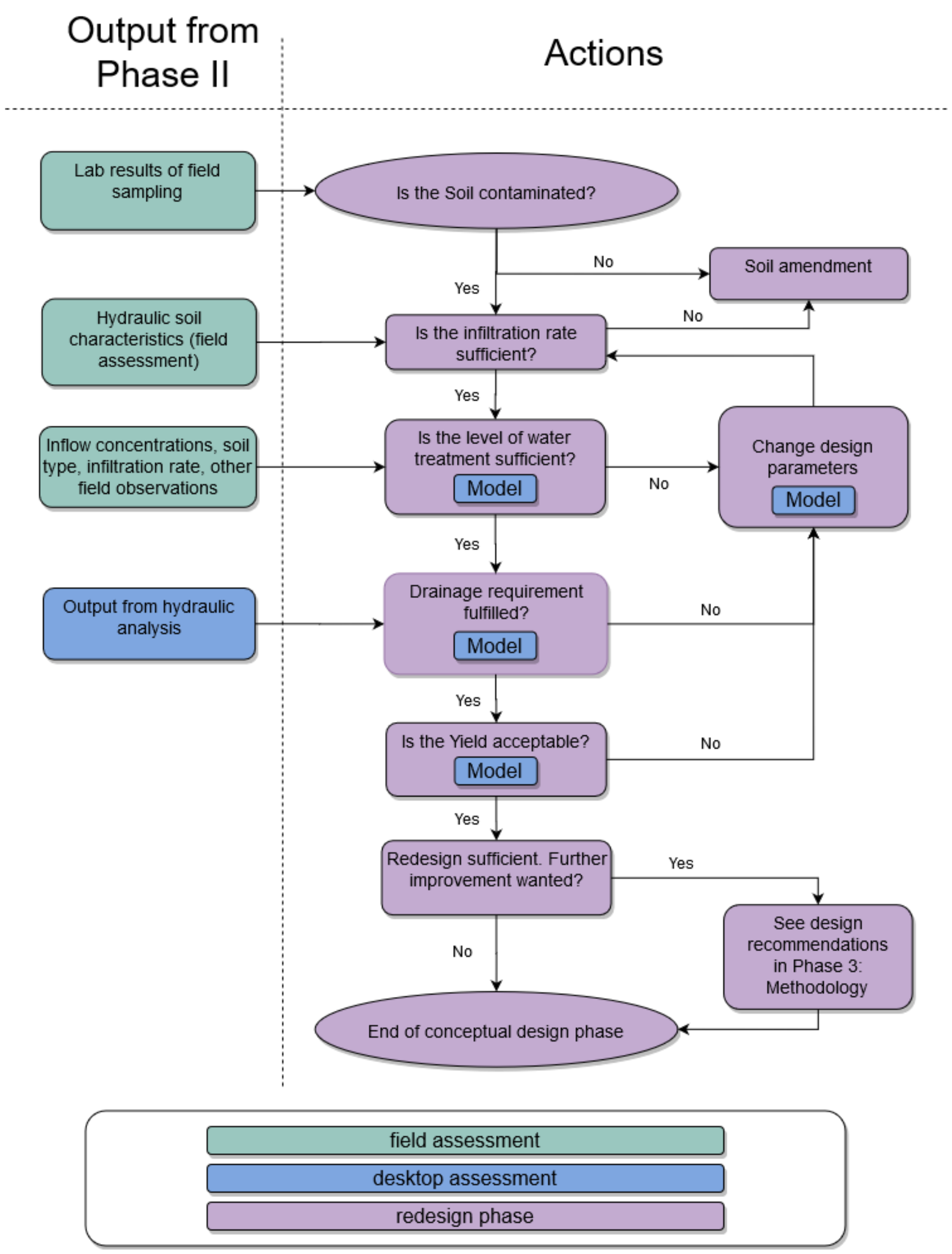

Figure 12.1: Design decision flow chart for the redesign phase

12.2. Green Infrastructure Flexible Model [105] for Redesign

For the redesign the currently existing flood detention pond must be modelled to establish a baseline for comparison of the redesigns. The Green Infrastructure Flexible Model developed by Massoudieh et al. [105] offers the possibility to model hydraulic and water treatment performance of Green Infrastructure (GI) . A variety of performance models exist already, however most of them are developed for catchment-scale applications or specific GI practices and have a limited scope [105]. The often used Stormwater Management Model version 5 (SWMM), for instance, can model infiltration rates and first-order decay of water quality constituents but does not allow for internal reactive transport processes which are happening during infiltration ([105]. According to Massoudieh et al. [105] the GIFMOD was developed to allow user flexibility in modelling three critical aspects of GI performance:

1. Hydraulics
2. Particles/colloid transport
3. Dissolved particle-bound reactive transport of contaminants

With this model the user is enabled to include flow considerations in different media and varying flow types (overland flow, saturated and unsaturated porous media flow, free-surface flow(pipes)). A particle/colloid transport module allows the introduction of multiple particles types present in different phases (mobile, reversibly or irreversibly deposited, bound to the air-water interface), as well as consideration of particles removal and even sorption-desorption with the soil matrix. The advantage of the GIFMOD is the incorporation of a large number of equations and user-defined complexity tailored to the application. The use of the model is facilitated by means of a graphical user interface which enables the user to discretise soil layers, define soil matrices and add spatial elements and functional components easily. For a more extensive description as well as a user guide to the software see Appendix K. The software can be downloaded at: www.gifmod.com. For an extensive elaboration on the model the authors of the framework at hand would like to refer to Massoudieh et al. [105] who also wrote a user manual [154].

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Discussion and Conclusion

The objective of this phase is to facilitate redesign decision making when a pond is potentially suitable but does not fulfil all criteria, yet. In order to do so design performance indicators and a more comprehensive understanding of the factors influencing infiltration practice is provided. The multi-influencing diagram (see section 11.6) visualises the most important factors that should be considered in a redesign. The design decision flow diagram (see section 12.1) was developed to provide a structure to the redesign process. Both diagrams can be used as support tools to build a model of an infiltration basin in the Green Infrastructure Flexible Model (GIFMOD) (see section 12.2). Furthermore, Phase III contributes to existing retrofitting literature and manuals by providing a structured retrofitting design framework and guidance for using a computational model for quantitative feedback during the retrofitting process.

A literature review as well as export knowledge was used to tailor Phase III to the Capetownian context which might limit its suitability for a different stormwater harvesting context. The multi-influencing flow chart does not include all influencing factors. However, it was not the intention to create an extensive overview nor was it feasible to represent all influencing factors in one diagram. Therefore, only the most important factors as stated in literature were included. The direction of influence for each factor is represented by one-directional arrows. The direction of influence in the diagram is based upon improving design, thus the one-directional influences. The sign of influence does not contain a quantitative indication but only represents a positive or negative influence with regard to an optimal design. Due to time constraints not all connections might be represented in the diagram. This could be checked and improved in further research/revision of the framework. The design-decision flow diagram is meant to provide guidance throughout the redesign process. The authors of the framework at hand do not claim the diagram to be perfect. Furthermore, it has not been tested for its capability of guiding the re-designer, yet. This can be verified in further research by actual modelling and redesigning a stormwater attenuation pond into an infiltration pond. Furthermore, in the future economical and societal decision making should be included which was not part of this framework. The GIFMOD seems to be a powerful tool since it is capable of modelling a number of equations that are not considered in other models. However, also the GIFMOD must be tested in the context of retrofitting existing stormwater green infrastructure. With regard to its limitations Phase III is an attempt to bring structure in a highly complex process for the Capetonian context. Along side with a socio-economical framework Phase III could prove itself valuable. Developing such a socio-economical framework would be a logical and complementing follow-up project to the one at hand.

14
Conclusion and Recommendations

The City of Cape Town strives to transform Cape Town into a water sensitive city that makes optimal use of stormwater and urban waterways. There seems to be a potential to use stormwater by infiltrating it into the CFA and store it underground for the demand in the dry summers. Therefore, recharge of the CFA by stormwater infiltration received increasing attention by researchers the last years. One identified way is to retrofit existing stormwater ponds into infiltration ponds. The research and work presented in this report was conducted with the objective to provide an overarching framework that can be applied to determine suitable detention ponds to allow managed aquifer recharge via infiltrating stormwater in CT's context and how to retrofit these detention ponds into infiltration ponds.

Numerous manuals and design methodologies have been developed for the engineering and construction of infiltration ponds. There are only a few manuals that are aimed specifically at retrofitting existing stormwater detention ponds into infiltration ponds, and there are none developed particularly for the context of Cape Town. In the course of this multidisciplinary project a new framework was developed tailored to the context of Cape Town, meaning that it is a retrofitting framework for existing stormwater infrastructure (i.e. detention ponds) to recharge the CFA. Therefore, it includes a method for quantification of the yield of aquifer recharge. The developed framework is a physical assessment framework and does not include social and economical aspects. These, however, are crucial for a meaningful feasibility assessment. Therefore a potential follow-up project could be the development of a socio-economical framework which should be linked to the physical assessment.

The framework constitutes of three phases. This choice was made in consultation with the client. It was requested by the client to write every phase in the IMRaD format (see chapter 1. The built up of the framework allows to use each phase consecutively or individually, depending on what is more suitable for the situation to be assessed. Phase I provides a method to help identify suitable areas for aquifer recharge by stormwater infiltration. The strength of the GIS-MCDA method is that a multitude of constraints and information can be combined in one suitability map. Even though that economical and social factors are omitted in the present framework, they can be included at a later stage in the GIS suitability map. Phase II analyses potential detention ponds lying in the suitable areas more in detail. This is done by field assessment and desktop studies. If this in detail analysis proves the pond to be suitable it can be redesigned in Phase III. As mentioned, every phase can be used individually. Assuming one has a pond of which it is known that it fulfils all main criteria, the user of this framework can directly use Phase III to structure and facilitate the redesign process.

Phase I has shown to be able to produce a suitability map. However, at the moment this map is not conclusive due to data limitations. Therefore, the input data for the GIS-MCDA analysis must be improved. This could be facilitated by means of a central data gathering platform in collaboration of universities and the municipalities.

Phase II proved to generate valuable insights of the detention ponds. A constraint for Phase II is the safety of researchers. This factor should receive special attention when executing Phase II. Therefore, a socio-economical framework should be developed to analyse which urban areas are safe for infrastructure, measuring equipment and researchers. In conclusion to above mentioned reasons phase I and II are suitable to generate valuable output. Furthermore, the strength of Phase II is that it can also be used to generate scientific data in a consistent way for Phase I to further improve the GIS suitability map.

The acquired insights from Phase II can be used in Phase III to model the initial state of the detention pond. Based on the initial condition the infiltration pond can then be modelled by changing the design parameters. The current main limitation of Phase III is that is has not been tested if it is suitable to actually facilitate the redesign process. However, testing is strongly advised to verify the functionality, possibly in a follow-up research/project. Another limitation is that there are no criteria defined for water treatment efficiency and for the yield.

Outlook During the course of this project it was not possible to answer questions such as how many ponds in Cape Town can be redesigned to infiltration ponds and what the potential aquifer recharge would be but the developed framework is a tool to investigate and finally answer these questions by collecting required data in an uniform and thus comparable way. A follow-up project should investigate if the framework at hand is suitable to assess the retrofitting potential of detention ponds. This test phase was executed in the course of this project due to time constraints. For a potential follow-up project it is advised to use this framework and test it with an extensive case study. This case study is also required to test the time demand of assessing one pond in detail and thus the feasibility of retrofitting ponds. Furthermore, a socio-economic framework can be included to see whether it is feasible to combine the two frameworks as envisioned.

General Recommendations:

- Build central data platform
- Test framework as a whole
- Develop socio-economical framework and combine the two frameworks (potential follow-up project)

Specific Recommendations:

Phase I:

- Collect better GIS data to improve the conclusiveness of the suitability map
- Add socio-economical factors

Phase II:

- Aside from the field-work the desktop assessment must be tested
- Risk assessment methodology should be tested in field

Phase III:

- Determine a way to estimate clogging rates
- Define missing performance criteria
- Use GIFMOD to test the redesign approach and if it is possible to accurately model hydraulic and water treatment performance of an infiltration pond

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Appendices

A

Suitability Mapping in GIS

This description is not exhaustive, knowledge of GIS is assumed. The steps are: Data transformation, screening, suitability mapping. The latter one will be explained in more detail, since that is the result of phase 1.

A.1. Data Transformation

Firstly, the data needs to be transformed such that it can be used for the GIS-MCDA.

1. If whole maps have been imported, all 'junk' layers are to be removed
2. Clip all layer to the Cape Town municipal border
3. Rasterise all vector layers, grid size should be
4. Categorise the layers to their thematic layer
5. Due to literature research, the rough location of the CFA is already known. Therefore the zoom is on this area. This excludes a part of the Cape Town municipal border area, which conveniently also leads to smaller file sizes and thus faster processing.

Now that the thematic layers are there, the next step is screening.

A.2. Screening

The steps to conduct the screening are listed below:

1. The pixel values of geological aptitude are changed, pixels predominantly within the aquifer border obtain a value 1. Pixels predominantly located outside the aquifer border a value of 0.
2. The pixel values of groundwater depth are changed, pixels with a groundwater depth of 1 metre or lower obtain a value 1. Pixels with a groundwater depth higher than 1 metre lower obtain a value 1.
3. Apply the 'AND' Boolean approach using raster calculations
4. The screening map is now done

A.3. Suitability Mapping

The last step is the suitability mapping. This consist out of the three sub-steps provided in chapter 3; WLC, standardisation and weighting. The first step to be able to apply WLC is to provide the same grid on top of all the thematic layers. The grid size is chosen arbitrarily based on data available. Consideration should however be given to the fact that a too small grid size increases files sizes, slows done processing and if your data is coarse the fine grid size will not increase your accuracy. The data you have is as good as the coarsest data you have for this approach. The standardisation is based upon retrieved literature. The attributes of each thematic layer are put on the same scale from 1 to 0. The attribute with 1 are regarded as the most suitable, whereas the attribute with 0 is regarded the least suitable.

Flood prone areas are standardised after the return period of the flood lines. The more frequent flooding is occurring, the less suitable the area is. The data obtained is one return period flood line so the following standardisation could not be performed. The standardisation function proposed is linear. A once in half a-year flood is given 0, once in 5-year flood 0.2, once in 10-year flood 0.4 and once in 50 or above 1.

Risk analysis the land uses have been classified as being opposed to most risk. Risk is defined as: the event of a infiltration basin induced flood, the likelihood of occurrence of the event, and the negative effect that the occurrence would have. The land use with the most economic value and the highest likelihood of losing this value is ranked least suitable and vice versa. Standardisation of risk analysis: urban 0, agriculture 0.25, rural 0.5, mountain 1 [63].

The first class consists of sandy soils as sand (S), loamy sand (LS), and sandy loam (SL) which represent "High" infiltration capacity, thus a value of 1.0 is assigned. Sandy clay loam (SCL) is assigned a value of 0.67; clay loam (CL) and loam (L) a value of 0.33; and "Unsuitable" soils, which consist of sandy clay (SC), clay (C), silty clay loam (SiCL), silty loam (SiL), and silty clay (SiC) are assigned a value of 0.0 [44].

The groundwater level needs to be at least at minus one metre for an area to not be excluded. At minus one metre the area is regarded as acceptable. However, due to the fact that the main soil type is sand, infiltration rates are high and the groundwater level can be locally elevated, mounding, which reduces the groundwater level to less than minus one metre. Therefore it obtains a low suitability, 0.1. From -50 metres and lower, the groundwater table will not increase the suitability for MAR [64]. A linear standardisation is applied between – 1 to -50 metres [64].

The weighting steps required in AHP are [61]:

1. Problem definition and information determination (setting criteria)
2. Problem hierarchy structure
3. Construct a set of pairwise comparison matrices for the criteria
4. Use the obtained weights for the criteria to determine the overall priority of the suitability for MAR using SWH of the area under investigation.

The first step has been conducted in section 3.3. Step 2 is provided below:

In the general hierarchical model of some problem might be one that descents from an overall objective (level 1), or focus. This hierarchical model will then follow down to the criteria (level 2), or even down further to sub-criteria, which can be seen as subdivisions of the criteria and finally down to the alternatives (level 3) from which the choice can be made [184], Figure A.1. In this case the focus is: choose the best place(s) for infiltration and the criteria related to this do not have any defined sub criteria. Furthermore, there are no distinctive alternatives to choose from, as they have to be determined by the WLC method. Hence, there is only a two level Hierarchy involved in this case, because only the weight of the various criteria have to be determined in respect to each other in terms of most affecting infiltration, the focus. Because of this only one pairwise comparison matrix needs to be constructed, with respect to the overall focus of infiltration. The explanation for this is given in the next section, the third step.

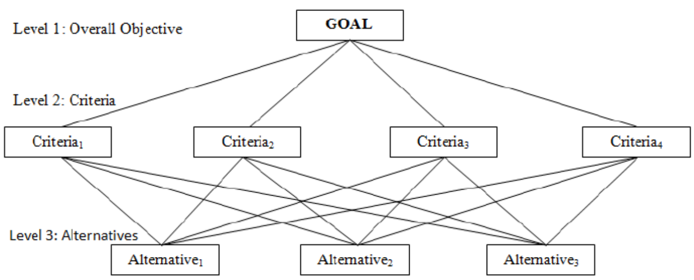


Figure A.1: General hierarchy structure of AHP, [185] For the third step, the AHP requires experts/panel to administer the pairwise comparison matrix by giving the preferences, on a scale from 1 to 9, among the criteria.

Table A.1: AHP scales with explanation, modified after [61]

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
2	Weak or slight	-
3	Moderate importance	Experience and judgement slightly favour one activity over another
4	Moderate plus	-
5	Strong importance	Experience and judgement strongly favour one activity over another
6	Strong plus	-
7	Very strong or demonstrated importance	An activity is favoured very strongly over another, its dominance demonstrated in practice
8	Very, very strong	-
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity i has one of the above non-zero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	-
1.1 - 1.9	If the activities are very close	May be difficult to assign the best value but when compared with other contrasting activities the size of the small numbers would not be too noticeable, yet they can still indicate the relative importance of the activities.

Table A.1 provides a brief explanation on the scale and its definitions. This is then consequently used in pairwise comparison matrices [61].

Pairwise comparisons are fundamental in the use of the AHP. The experts or user must establish priorities for their criteria by judging them in pairs for their relative importance. In this way the pairwise comparison matrix is generated. Table A.2 shows the overall matrix of pairwise comparisons of the selected criteria with respect to the overall focus of infiltration. The question is: 'how much more or less is element A affecting infiltration compared to element B'. In the matrix the first comparison is Land Use against Geology, as Geology is affecting successful infiltration more than Land Use the reciprocal value of 1/4 is entered in position (1,2) and the value of 4 is entered in position (2,1). When the matrix is filled in it is time to calculate the eigenvalues and eigenvectors. The eigenvectors will give the scale of priorities or weights. This scale is obtained by solving for the principal eigenvector of the matrix and then normalising the results. In case of the presented matrix in Table A.2 the eigenvectors are (Land Use, Geology, Top Soil, Flood Plain, Groundwater Depth) = (0.140, 0.528, 0.528, 0.264, 1) and normalised it is (5.71, 21.48, 21.48, 10.74, 40.60).

Table A.2: Pairwise comparison matrix regarding infiltration

Focus: Infiltration	Land Use	Geology	Top Soil	Flood Plain	Groundwater Depth
Land Use	1	1/4	1/4	1/2	1/6
Geology	4	1	1	2	1/2
Top Soil	4	1	1	2	1/2
Flood Plain	2	1/2	1/2	1	1/2
Groundwater Depth	6	2	2	4	1

Lastly the eigenvalue is needed to check the consistency of the assigned weights to the different criteria. To do so the 'Consistency Ratio' is used [184]. It is calculated using the following equation:

$$CR = \frac{CI}{RCI} \tag{A.1}$$

Where:

CR is Consistency Ratio
RCI is the Random Consistency Index
CI Consistency Index

The Consistency Index is determined as follows:

$$CI = (\lambda_{max} - n)/(n-1) \tag{A.2}$$

Where, Lambda.max is the principal eigenvalue computed by eigenvector technique and n is the number of criteria (factors). The Consistency Ratio should be less than 0.1, if it exceeds 0.1 it is advised to re-evaluated the weights [184]. The CI value of the proposed case is 0.002. The AHP method allows for additional criteria of different nature compared to the physical criteria of successful infiltration and MAR. This means that in future assessments economical criteria or social criteria can be added to determine the best location for infiltration. The AHP method can then allow for multiple hierarchies, for instance 3 levels. The Focus of successful infiltration being level 1. The different fields being the criteria, physical, economical and social, all at level 2. Level 3 will exist out of the sub-criteria of each criteria. For the physical-criteria the sub criteria would then be: Land Use, Geology, Top Soil, Flood Plain and Groundwater Depth. This expansion means that now 4 pair wise comparison matrices should be undertaken, one for level 2 and three for level 3.

The following tool has been used to perform the calculations: INOWAS, INnOvative web-based decision support system for WAter Sustainability under a changing climate by the Technical University of Dresden [186]. It services additionally as an open source database. Instead of filling in a pairwise comparison matrix it displays the various criteria with a moving slider, see figure A.2. This way all the criteria can be compared with each other by moving the slider to either the left or the right side. Choosing where to position the slider depends on which criteria is considered more important/influencing. As with the comparison matrix the scale also goes from 1 to 9, and fractures are being represented as a negative value, for instance 1/7 is -7. It automatically calculates the normalised eigenvectors, weight per criteria and the tool immediately provides feedback whether the Consistency ratio is sufficient or that the process of administering weights has to be redone.

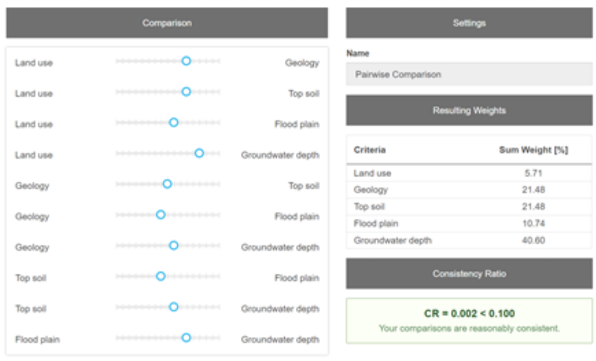


Figure A.2: INOWAS interface, Consistency factor and normalised weighted results

In a literature review a meta data analysis of AHP weights to criteria for MAR using spreading methods has been encountered [46]. The meta data analysis has been performed for the same criteria, the choice has been made to use the meta data weights instead of using local expert knowledge. This choice has been made because it was reported that experts tended to deviate in their assigned weights from one and another [46].

B

Field Manual

This field manual serves as a guide to go through the physical assessment discussed in Phase II of the Framework. The green boxes in the flow charts of the physical assessment are actions executed in the field. Each of them are extensively explained in this manual. Taken this manual to the field and following the exact steps, will contribute to a uniform data collection which increases the accuracy and allows for a proper comparison of data. The two sections ’infiltration calculation’ and ’installing a well’ are more detailed and in depth and not necessary for every field visit. This is why they are places in separate boxes.

B.1. Materials list

Field equipment:

- Hand auger for heterogeneous soils
- Soil core sampler
- Double-ring infiltrometer
- Soil moisture sensor or profile probe
- Measuring wheel
- 2 stormwater captures including 4 plastic bottles
- Point source bailer (of approximately 5 liters)
- DO meter (calibrated/or bring standard solutions to calibrate in the field)
- pH meter (calibrated/ or bring standard solutions to calibrate in the field)
- Measuring tape
- GPS
- Plastic bags to carry soil samples
- Water resistant marker
- Distilled water
- Glass beakers
- Metal cup
- Duct tape

B.2. Methods

B.2.1. Groundwater level

The maximum groundwater level can be assessed by drilling a hole until the groundwater table is reached.

The hand auger set for heterogeneous soils consist of a number of augers in a lightweight transport case. From these different types of augers is the Edelman auger suitable for the subsurface of the Cape Flat region. There are four different Edelman auger types as shown in the figure: clay type, combination type, sand types and course sand type.

The drilling section of the Edelman auger has two blades (1) that run into a point at the lower end (2). They are attached to the lower piece (4) with the use of a bracket (3). The auger point twists into the ground and takes the soil from the bottom of the auger hole.

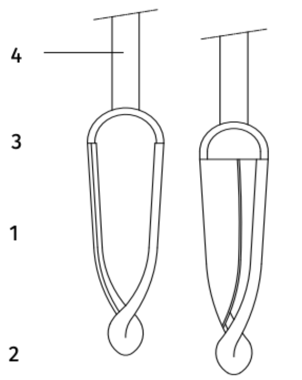


Figure B.1: Edelman auger combination type (left) and coarse sand type (right)

Preparing for use

1. To use the auger for the first time, loose the coupling sleeves from the extension rods and the upper part.
2. Screw the synthetic handle into the first part.
3. Select the specific auger.
4. Connect the auger parts: 1) Hold the coupling sleeve in the middle and slide it onto the upper part until it clicks on the nipple. The sleeve is locked when it cannot be rotated. 2) Join the upper and bottom part. 3) To lock the connection, unscrew the sleeve from the upper part, slide it across the connection and click it onto the nipple. 4) Check the lock, it will have a slight play.

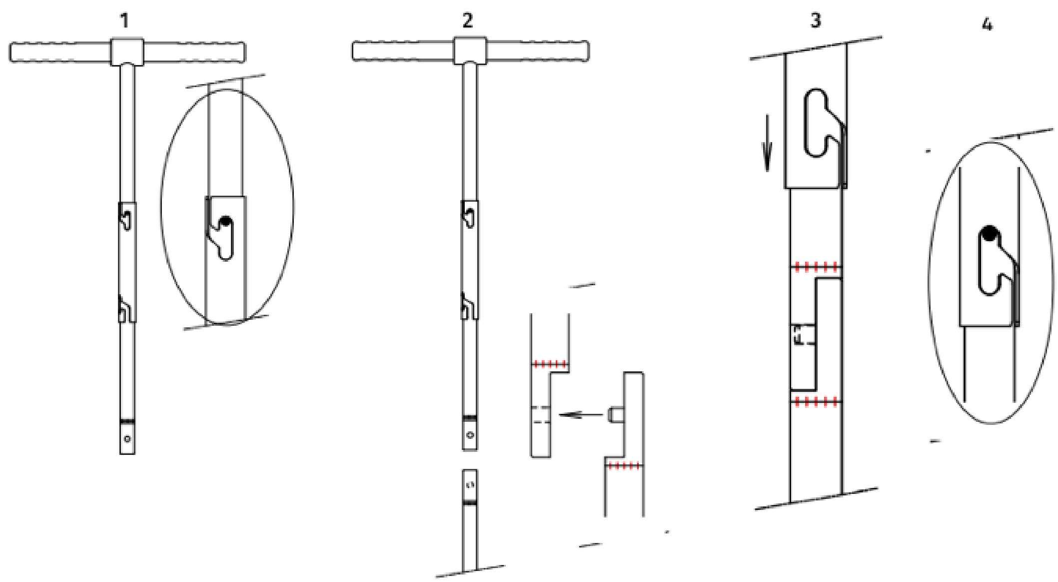


Figure B.2: Prepare the hand auger for use

Indicate the lowest part of the pond and place the auger in the soil. Turn the auger counterclockwise by using light pressure until the auger is filled with the soil. Empty the auger and keep drilling til the groundwater level

Figure B.3: Edelman drill bits for (from left to right): clay, combination, sand, coarse sand.

is reached. Take a measurement with a GPS of the location and elevation of the well. Note down the depth of the groundwater table and the depth at which the soil became wet, usually a few (tens of) centimeters above the the groundwater table. The maximum groundwater table obtained in this way.

B.2.2. Inlet and outlet wells

To determine the hydraulic gradient and to monitor the groundwater levels and quality, at least two more holes have to be made. These boreholes need to be drilled at the inlet and the outlet of the pond and these boreholes must become two wells. An electronic water level meter can be used to obtain groundwater levels. A probe is lowered into the well, when the probe comes into contact with water, the circuit is closed, which triggers a flash of light or noise. An alternative 'home-made' method can be used by making a 'plopper'. A metal cup is attached to the end of a long measuring tape and lowered into the well, a 'plop' sound indicates when the groundwater level has been reached. [187]. The borehole can be made by a hand auger described in the previous section. However, it is advisable to have a professional organisation install the wells.

B.2.3. Soil characteristics

Soil samples can be taken during hand auguring. To obtain a soil profile, the soil can be examined at different depths by applying the following method:

The soil must be taken to the laboratory for soil contamination assessment. If the soil shows an unusual composition it must also be examined in the laboratory.

B.2.4. Infiltration test

The double ring method is used to determine the infiltration capacity, the near-saturated hydraulic conductivity, the infiltration curve and the cumulative infiltration over a certain period.

A standard double ring infiltrometer consist of:

- Stainless steel ring of diameter 28/52 cm and height 25 cm.
- Stainless steel ring of diameter 30/55 cm and height 25 cm.
- Stainless steel ring of diameter 32/57 cm and height 25 cm.
- A driving plate.
- Impact-absorbing hammer.
- Measuring rods with floats.

Installation

- Put the inner ring with the cutting edge facing down on the ground. Remove small obstacles such as stones.

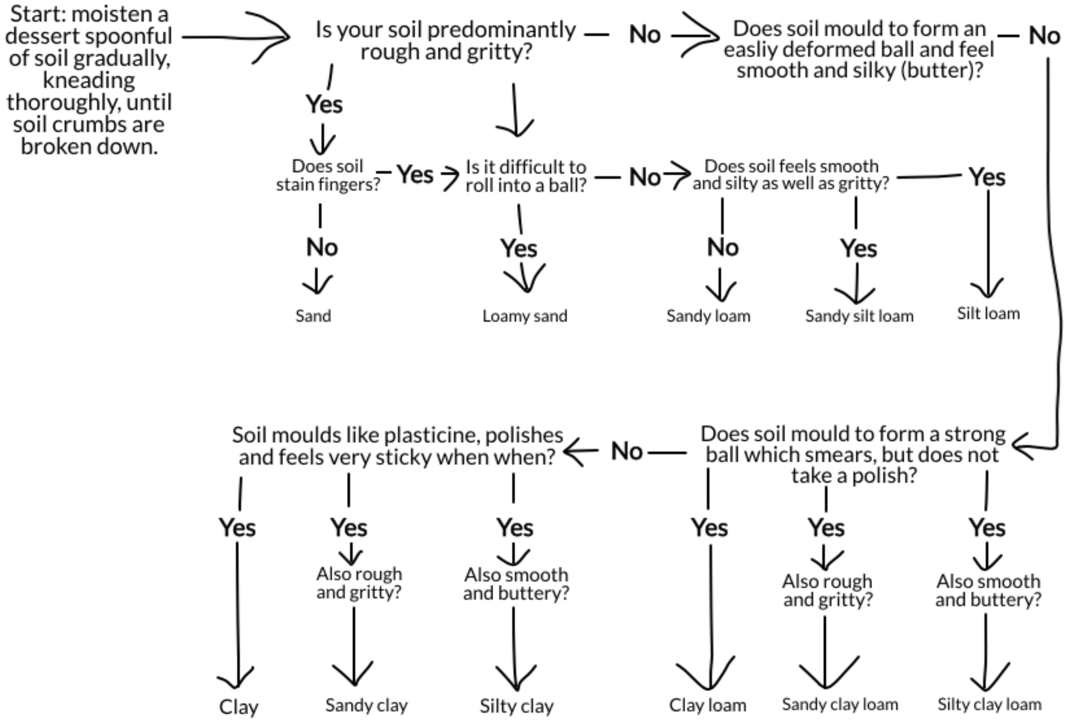


Figure B.4: Soil determination flow chart, adapted from projectblue.blob.core.windows.net

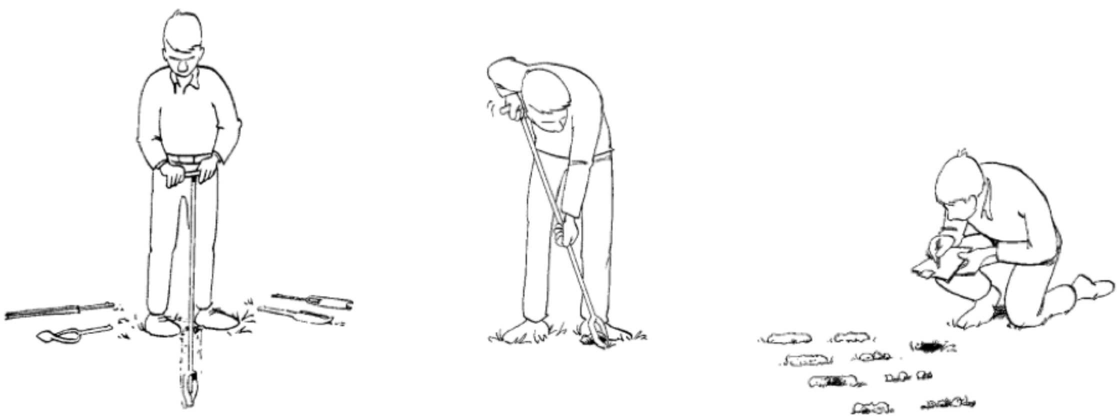


Figure B.5: From left tor right: augering, emptying and studying.

- Place the driving plate on top of the inner ring. The ring fits over, between or within the pins on the bottom of the driving plate.
- Use the impact absorbing hammer to insert the soil infiltration ring about 5 cm vertically into the soil.

- Place the outer ring with the cutting edge facing down around the inner ring.
- Put the driving plate on top of it. Keep the depth of placement as limited as possible. Insert the rings in any case to below a particular top layer.
- Use the impact absorbing hammer to insert the soil infiltration ring about 5 cm vertically into the soil. The shape of the driving plate will ensure a depth identical to that of the inner ring. If there is any loose soil between the ring and the surrounding soil, place the soil back.
- Place the measuring bridge with measuring rod and float on the inner ring.
- Remove, without disturbing the soil structure, vegetation that may hamper free movement of the water or affect the measurements.
- To protect the ground surface when pouring the water, use plastic foil, a jute cloth, sponge, gravel, sand or your hand to pour the water on the ground and will the outer ring with water.
- Fill the inner ring, to approximately 5 a 10 cm.
- Start the measurements immediately to determine the infiltration curve.

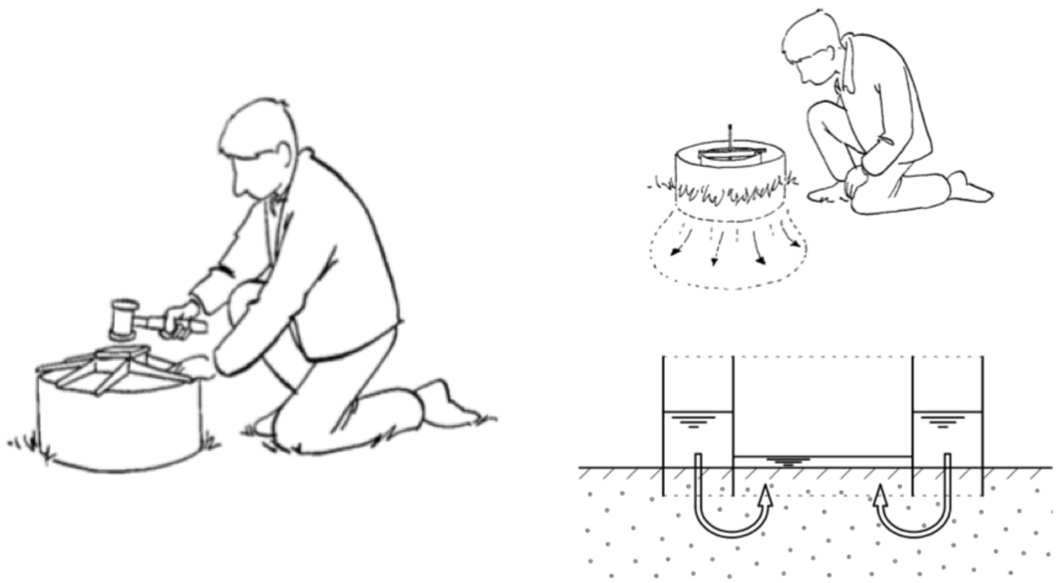


Figure B.6: From left tor right: augering, emptying and studying.

Measuring

- Start the measuring by noting the time and the water level in the inner ring (the reference level), as indicated in the measuring rod.
- Determine the drop in the water level of the inner ring during a certain interval and note the time and water level. Start with short intervals and conclude measuring with a longer interval.
- The infiltration rings should not dry during the measuring.
- The water in the inner and outer ring should stay at a similar level.

Consult for an extensive manual about the procedure.

Within a pond, it is proposed to obtain 10 measurements, 5 at the surface and 5 measurements below the surface (around 300 mm). Measure the soil moisture content at the beginning of the infitration test and at the of the infiltration test (in the inner ring).

B.2.5. Infiltration calculation

The time (column A) and the corresponding water level in the inner ring before filling (B1) and after filling (B2) are obtained from the field.

- Calculate the cumulative time in column C by using the data from column A. Start = 0
- Calculate the time interval in column D by using the data from column A.
- Determine the infiltration in column E by calculating the water level differences between intervals in column B.
- Calculate the infiltration capacity [mm/min] in column F by dividing for each interval the infiltration (column E) by the time step (column D). If needed, convert the infiltration capacity to e.g. [cm/hour].
- The tabulated data can be used to determine the infiltration curve. Plot the calculated infiltration capacity (column F or the converted values) on the y-axis of a graph and cumulative time (column C) on the x-axis.
- The near-saturated hydraulic conductivity equals more or less constant infiltration capacity.

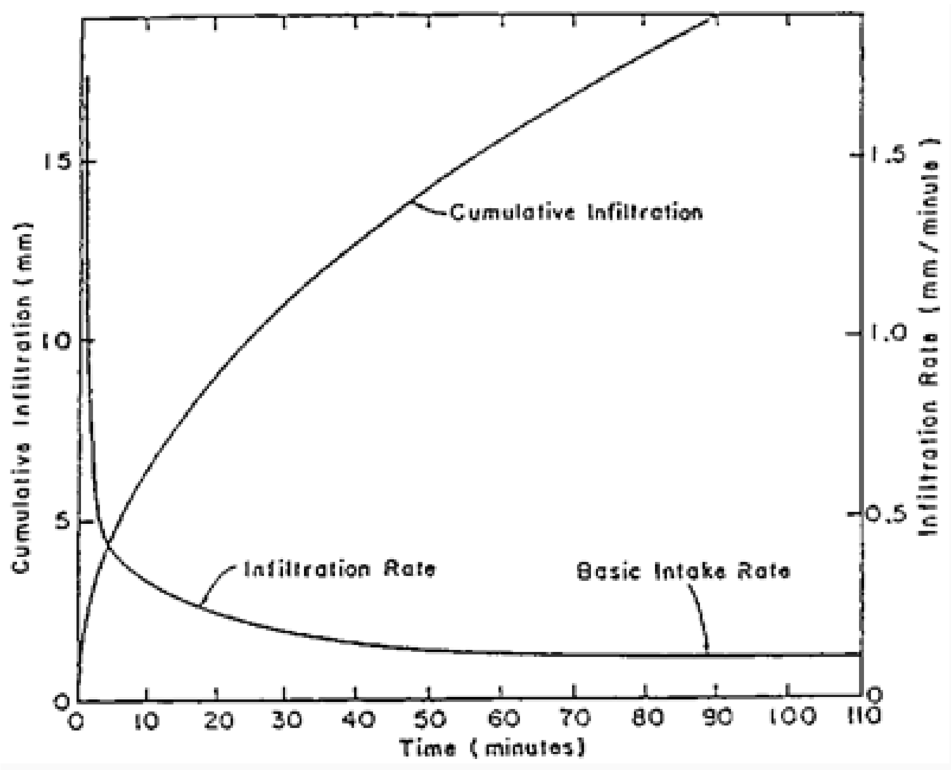


Figure B.7: Relation between infiltration rate and infiltration capacity

B.2.6. Installing a well

Installing a well requires drilling a borehole. There are several drilling methods and well designs, and the selection of the method and design is based on site characteristics and available expertise/equipment. The most important characteristics that influence the functionality of the well are; the anticipated duration and goal of monitoring, chosen sampling technique, (sub) surface conditions, safety hazards of the area and contaminants likely to be monitored [188]. Drilling methods vary from simple manual drilling techniques like hand auguring to more advanced automated techniques using borehole fluids.
The drilling diameter of the borehole should be at least 5 cm larger than the outer diameter of the PVC well casing. This standard should be followed in order to provide room for gravel around the well casing such that fine sand particles are not able to enter.During drilling a well-log should be created. The well-screen must be situated in the permeable layer and thus the exact lithology must be known in order to design the well-casing. Considering the exact depth of the aquifer is not known in this context, a standard drill depth of 15 meters is recommended.
Slots in the well casing should prevent soil particles from entering, which is mainly favourable for sampling groundwater . The slots must be smaller than the mean soil particle size, but in many cases this is not known exactly. Small slots can be made by hand using a hack-saw, or a pipe with factory-made slots (1 mm) is often small enough for a sandy subsurface.
Making a 1 m sump at the bottom end of the pipe is a requirement. A sump is a closed-end pipe without any holes. If small particles end up in the well through the slots, they are able to settle to the bottom of the pipe, which prevents blocking the slots [189].
The well casing should be installed such that it extends above ground, not much less than a meter or so. The well should be protected with a vented locking well cap (**??**). This will prevent unwanted abstraction and outside pollutants entering the well. The likely soil type at the stormwater ponds is sandy with a limited amount of clay. The depth that must be reached is around 15 meters.
Based on suitability for sandy soils, cost estimate, drill depth and drill duration, the most viable options for this case are hand auguring and rotary jetting. Hand auguring requires manual labour, but is much lower in cost and does not require additional water for the drilling process. Rotary jetting does not require as much manual labour, is quicker but requires a lot of water during drilling [189]. Therefore, hand auguring is advised for this particular situation. Note that drilling below the water table in sandy soils with a hand augur may case the soil to collapse. Considering the drilling process will extend beyond the water table, a temporary casing must be used in order to prevent this from happening.
An extensive technical training handbook is developed by the PRACTICA foundation, an organisation that works with low-cost technologies for water supply, irrigation and renewable energy in developing countries. A link to the detailed manual on hand auguring can be found in the reference list as [190].

B.2.7. Litter Assessment

Assess the inlets and outlets and fill the score in Table B.6. Be aware that several in and outlets can be present. For the litter assessment, a score is given to the amount of litter present. A description of the scores is found in Table B.2

Take pictures of the in and outlet.

Table B.2: Assessment of litter

Score	Criteria pond	Criteria in/outlet
1	No to little litter	No to little litter
2	Litter clearly visible	Litter visible but not blocking
3	Huge litter trap	In/outlet blocked

B.2.8. Install Stormwater Capture

This method will depend on the local situation. The PVC pipe can be connected with dowel rods and cable ties to the stormwater pipe. The stormwater capture in the inlet should stick out of the pipe, the stormwater capture in the outlet should stick in to the pipe to let the water be able to flow into the pvcpipes. A schematic picture is given in Figure 8.5. Always make sure the last bottle hangs lowest, so that gravity automatically fills the last bottle first. Secure the bottles to the pipe, so that the location towards each other does not change once the water will put pressure on the system.

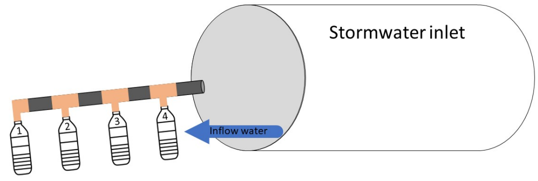


Figure B.8: Installation of stormwater capture at the inlet

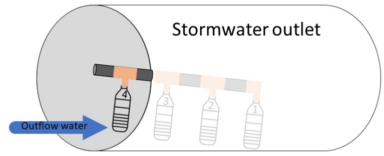


Figure B.9: Installation of the stormwater capture at the outlet

B.2.9. Take Groundwater Samples

The water in the well should replenish before an accurate sample can be taken. The pH and DO are tracked, to determine when a representative sample is reached.

- Hang the point source bailer in the well
- Move the bailer up and down a few times, to let water flow into the device
- Lift the bailer and empty it
- Repeat for at least 10 times
- Repeat once more and pour the next sample in a measurement beaker
- Measure the pH and DO
- Repeat the last two steps until the pH and DO become constant
- Once constant, pour the sample in a closed jar
- Bring to the lab, store cooled until analyses.

B.2.10. Take In- and Outflow Samples

Replace the bottles from the stormwater capture with fresh ones, make sure the numbers are in the right order so that bottle number 1 is the stopper (capturing the first flush) and bottle number 4 closest to the opening. Write the date on the harvested bottles. Bring them to the lab, where they should be stored in a fridge until analyses.

B.3. Field work sheet

Table B.3: Existing pond information

Existing pond information	(*after Rohrer 2014)
Pond ID:	
Pond type*:	
Verify pond type:	YES/NO it is a .... pond
Catchment	
Area (m^2)*	
Road name	
Suburb	
Property number	
Latitude	
Longitude	

Table B.4: Groundwater level

Groundwater level						
	Depth moisture winter (m)	**Depth moisture summer (m)**	**Depth gw winter (m)**	**Depth gw summer (m)**	**Coordinates**	**Notes**
If A < 500 m^2						
If A > 500 m^2						
If A > 750 m^2						
If A > 1000 m^2						
If A > 2000 m^2						
If A > 5000 m^2						
If A > 10000 m^2						

Table B.5: Soil profile

Soil profile		
Depth (m)	**Soil type**	**Notes**

Table B.6: Inlet, outlet and litter information, the higher the score the more severe is the condition

Inlet/Outlet		Notes
Number of inlets		
Inlet diameter	m	
Score litter at the inlet	1/2/3	
Erosion at the inlet	Y/N	
Height of the inlet from pond bottom	m	
Number of outlets Outlet diameter	m	
Score litter at the outlet	Y/N	
Erosion at the outlet	Y/N	
Height of the outlet from pond bottom	m	
Score litter total pond	1/2/3	

The time (column A) and the corresponding water level in the inner ring before filling (B1) and after filling (B2) are obtained from the field.

- Calculate the cumulative time in column D by using the data from column A. Start = 0
- Calculate the time interval in column E by using the data from column A.
- Determine the infiltration in column F by calculating the water level differences between intervals in columns B and C.
- Calculate the infiltration capacity [mm/min] in column G by dividing for each interval the infiltration (column F) by the time step (column E). If needed, convert the infiltration capacity to e.g. [cm/hour].
- The tabulated data can be used to determine the infiltration curve. Plot the calculated infiltration capacity (column G or the converted values) on the y-axis of a graph and cumulative time (column D) on the x-axis.
- The near-saturated hydraulic conductivity equals more or less constant infiltration capacity.

Table B.7: Infiltration test

Infiltration test							
A	B	C	D	E	F	G	
Time hr:min:sec	**Water level before filling (mm)**	**Water level after filling (mm)**	**Cumulative time (min)**	**Time interval (min)**	**Infiltration (mm)**	**Infiltration capacity (mm/min)**	**Notes**

C

Case Study

To test the practicality of the framework provided in phase II a case study on 29th of January 2020 is performed in a detention pond in Mitchells plain, from now on called 'school pond'. Figure C.1 and Figure C.2 show the exact location and the shape of the pond. The pond is located on a former vlei, which suggests that the pond would classified as unsuitable from phase I. However, for this case study other reasons where mainly important for the decision of location. This pond has namely specific interest within the Future Water Institute because it is located next to a primary school called 'the Leadership College'. One of the key elements in the overall project of Future Water is sharing knowledge about the water situation of the city. This pond can be used as an example of a water sensitive design, which can contribute to the education of the students on this topic. This might also increase the understanding of a water sensitive city for the whole community around the pond, which may help in successfully retrofitting this pond. An additional benefit of the school pond is that the performance of the pond can be monitored by the students, which can e.g. be made a part of the science curriculum. The last reason why this pond is chosen, is that data is already available about this pond. The results obtained in this case study can be compared, which can give an insight in variability and reliability of the data. Since more studies are going on in this pond, the fieldwork carried out will not only help to understand the practicality of the framework, but will also add value to the ongoing research within the Future Water Lab and useful for other researchers working on this topic.

This case study is used to fine tune the framework and make changes where deemed necessary. Due to limited time availability it is not possible to include all the tests presented. Some of the data is obtained by measuring continuously for a longer period of time and/or some measurements are seasonally dependent, which thus require at least a year to obtain. The field work is done on the 29^{th} of January 2020, which is in the middle of the summer. In the past few weeks there was barely rainfall. Therefore, the pond was dry.

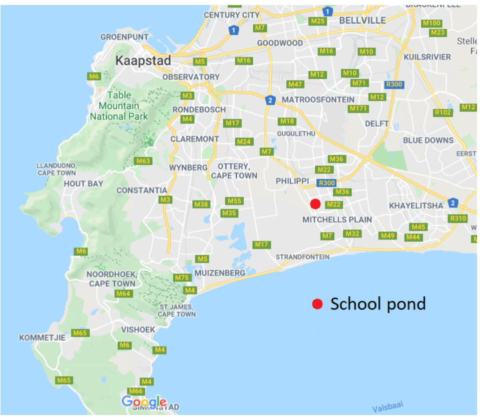


Figure C.1: The location of the school pond in Mitchells Plain, Cape Town

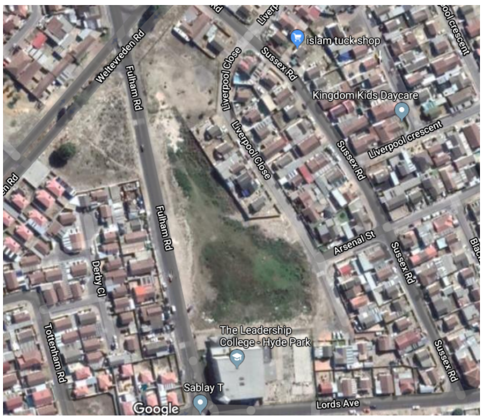


Figure C.2: A satellite image of the location and shape of the schoolpond

The goal of the case study is to improve the framework for the physical assessment of the pond. The case study focuses on the inputs in the flow charts that can only be obtained from field work and test their measurement and methods description. The flow charts, measurement sheet and materials list will be adjusted after the fieldwork. Each executed test is explained in a separate section, including the knowledge obtained from doing the experiment and how this is processed and improved in the framework. Ideally all the measurements mentioned in the 4 flow charts of Part II had to be tested, but due to the lack of appropriate equipment some test have not been conducted.

For the site hydro-geology flow chart (Figure 8.2) the groundwater table is measured (summer only) and the soil characteristics are determined. An infiltration test is executed with a single ring infiltrometer instead of a double ring infiltrometer, owing to the fact that the correct equipment was unavailable that day. The same goes for the soil moisture test, the equipment was not available at the university and out of stock in every garden centre. The results of the groundwater level and the soil characteristics are presented in the coming sections.

The hydraulic analysis (Figure 8.3) is mainly a desktop study and only a few paramaters obtained from the field are needed for a desktop study, such as infiltration rate and soil moisture.

The water quality assessment (Figure 8.4) needs several test before real conclusions can be made. The two steps in the flow chart that are tested (with certain limits) in the case study are quantifying litter and groundwater quality measurement. The details are described in the concerned sections below.

The risk assessment (Figure 8.6) doesn't require new input from the field and is therefore also the last step to go through in the framework. The inputs are already obtained in the previous steps and coming from desktop studies.

C.1. Groundwater Level

The first important measurement that is done in the field is measuring the groundwater level at the site. Although there is a data set available containing fairly recent values for the groundwater level in Cape Town (2015), the resolution is very low and the groundwater level is highly variable in space and time. Thus, the only way to obtain correct data on the groundwater level is to measure in both summer and winter time.

Using a hand augur a hole was drilled at the lowest point of the stormwater pond. The soil was already slightly moist at a depth of about 0.5 m.

Based on literature [30] it was expected that the distance between the lowest point of the stormwater pond and the highest groundwater level was at 2.9 m. However, the groundwater level was found to be at -0.6 m below the lowest point. The exact depth of the groundwater was found by letting the water seep into the drilled hole, inserting a simple stick into the borehole and reading of the height to which the stick was wetted.

The fieldwork manual prior to the case study did not contain specific equipment or methods to determine the depth of the groundwater. In the case the groundwater level was much deeper it would have been more challenging to determine the depth of the groundwater using the simple method described above.A more advanced method using an electric water level monitoring sensor is now included.

C.2. Soil Characteristics

Similar to the groundwater level, there is a GIS data-set available containing the spatial distribution of soil types in Cape Town. The precision of the data is limited, as the layer contains merely 4 types, and the description of these is generic. The soil type determines the physical characteristics of the subsurface including infiltration rate, porosity, permeability, capillary rise, subsidence and treatment capacity, and subsequently influence important risk and design considerations such as mounding and clogging rate.

The soil type is analysed at different depths in order to get a complete profile.

Figure C.3: Sandy soil at a depth of 50 cm

Based on literature it was assessed that this ponds consists of an upper layer of fine to medium sand. That calcrete was found at depth from 7-10 m and that coarser sand was located at a depth of 20 m. Also, it was known that the pond was previously a vlei. This pond would therefore be excluded from our deskstop study, since the soil characteristic of the vlei show non-favourable conditions for infiltration.

From the field assessment was obtained that the topsoil showed very different characteristics than the subsoil. A distinction is therefore been made between the topsoil and the subsoil. Furthermore, it has been emphasised that a comprehensive desktop study is of great importance for the assessment of the subsoil of the pond area since much is already known and might be excluded beforehand.

C.3. Soil Contamination

The soil samples were taken to the laboratory. However, the results of the analysis did not conform to expectations. The soil samples had little to no contamination at all. A possible explanation is that the samples were obtained from too deep in the ground. Therefore, a proposed depth of the soil sampling in order to assess contamination is included in the field manual.

C.4. Infiltration Test

Although there are standards infiltration rates for soil types, these are based on homogeneous soil samples tested in a controlled environment. Classifying the soil is usually not straightforward and the soil is spatially heterogeneous.

Due to the double ring infiltrometer being not obtainable, the infiltration test was done using a single ring infiltrometer. This method was not favourable as well as the site was not suitable for infiltration due to its clayey nature. The infiltration test are done within an radius of 3 meters, both at the surface and at a depth of 5 meters. However, the rates differed so much that a conclusion could not be drawn from these field measurements. It is expected that the double ring infiltrometer would measure more coherent infiltration rates.

C.5. Litter Assessment

The first step in the flow chart of Water Quality (Figure 8.4) is quantifying the litter. The sheet used during the case study was not effectively organised with regards to this parameter. The debris at the inlet and outlet was written in separate from the debris in general. A more uniform method is therefore necessary for updated framework.

Litter was clearly present, especially at the in and output (Figure C.6). The pond was not exactly a 'dumping area', since the litter was minimal over the majority of the area but especially present at the inlets and outlet. The inlets and outlets were not completely blocked thus water could clearly flow through easily. This distinguish is added to the framework.

C.6. Groundwater Quality

Installing a permanent observation well was not feasible within the time limits of the fieldwork. Therefore, the groundwater quality measurements are done with the water extracted from the borehole dug by the hand auger. Unfortunately this made it difficult to make strong conclusions about the results. The hole was very narrow and a syringe attached to a pole was used to scoop water out. The obtained sample contained a lot of sediment, which needed time to settle due to the fineness of the particles. If a permanent monitoring well is installed according to the explanation given in the manual, the gravel around the pipe and the well-screen will filter the water and the sump at the bottom of the pipe. Previous similar samples from a well in the Waterhub were transparent. It can be concluded that installing a well is favourable for these measurements, especially since the samples should be taken regularly.

Figure C.4: Groundwater sampling using augur and syringe

C.7. Analyse Samples in Lab

The groundwater samples were taken to the lab, in which they were stored in the fridge for around 36 hours. The liquid phase was clear (Figure C.5, that it was decided to not filter the water sample any further. The parameters tested on the water were pH, EC, orthophosphate, ammonia, and salinity. Firstly, it was tested if there was a difference between the results of the 3 different jars, which was not the case and therefor the average results are presented in Table C.1.

Figure C.5: The samples after sedimentation. The liquid phase was very clear, although the dirt on the jar and the condensation of the fridge doesn't imply this.

Table C.1: Results of the groundwater quality tests

Parameter	Value	Unit	Method
pH	7.28	-	pH meter
EC	1201	μS	EC meter
Salinity	0.7	ppt	Salinity meter
Ammonia	0.02	mg/L	Hach ® Salicylate kit
Phosphorus	0.08	mg/L	Hach Phosver ® kit

The pH shows expected results. The EC is higher than expected (compared to e.g. the groundwater EC in Atlantis [25]). This value is expected to lower when the sample is filtered before measuring, or when a well and point bailer are used to take samples. Salinity is also measured and although Mitchells plain is close to the sea (± 4 km), the concentration is low. Before the case study, salinity was not yet included in the framework. Salt water intrusion can be a problem for groundwater extraction and after the case study it is decided to include this. The nutrients ammonia and phosphorus were low, nitrate and nitrite are therefore not tested. Heavy metals and hydrocarbons are not tested due to time limitation and lack of equipment.

C.8. In- and Outflow Quality

Before the case study, the approach was to monitor the in- and outflow continuously with a low cost sensor. Inspecting the in- and outlet revealed that this was not a practical solution, since the pipes that are sometimes completely full with water. This would wet and ruin the sensor. It can be useful for ponds with wider inlets (e.g. a canal), but since most are with pipes, it is decided to implement another method. The stormwater capture is the new approach; it is also more theft proof and cheaper. Since no water was flowing through the pipes during the fieldwork, the stormwater capture could not be tested.

C.9. Inlet and Outlet structure

The detention pond functions to provide flow control through attenuation of stormwater runoff. The pond contains inlets and outlets sized such that the stormwater is released back into the stormwater system within 24-48 hours.

There are two inlet pipes and one outlet at the other end of the pond.

Figure C.6: Outlet structure with debris

Table C.2: Infiltration times measured in the field. *The water could not drain at all, therefore the test was stopped. **This test was taken in the dry stream towards the pond outlet.

Test [place]	Infiltration Time (IT) (s)	IT (s)	IT (s)
1 [surface]	16.66	21.35	23.49
1 [surface]	19.42	23.98	29.47
2 [surface]	09.16		
2 [surface]	24.12		
3 [surface]	*		
3 [surface]	*		
4 [surface]	58.70		
4 [surface]	12.12		
5 [surface]	07.51		
5 [surface]	13.60		
6 [-70 cm]**	09.48		
6 [-70 cm]**	12.11		
7 [-70 cm]**	178:.58		
7 [-70 cm]**	178:.58		

Table C.3: Soil types at different depths

Depth [m]	Ec [μS]	Ph []	Temp [degC]	Indicator
0.37	7.74	338	23.4	sandy loam
0.50	8.18	24.0	276	sandy loam
0.68	8.13	23.7	246	sandy clay loam
0.84	7.99	23.6	238	sandy clay loam

D

IDF Calculation

Firstly, precipitation data is to be obtained in at least daily rainfall, but preferably at a higher resolution of 10 to 15 minutes rainfall. The annual maxima are extracted using the generalised extreme value distribution (GEV). Although Cape Town has a strong seasonality in its rainfall pattern, no exclusion of the summer months is recommend [191]. The cumulative GEV distribution is given by the following formula:

$$F(x) = \exp\left\{-\left(1+\xi\left(\frac{x-\mu}{\sigma}\right)\right)^{-\frac{1}{\xi}}\right\}$$

Figure D.1: Cumulative GEV distribution [191]

$$f(x) = \begin{cases} \frac{1}{\sigma}\left[1+\xi\left(\frac{x-\mu}{\sigma}\right)\right]^{-\frac{1+\xi}{\xi}} \exp\left\{-\left[1+\xi\left(\frac{x-\mu}{\sigma}\right)\right]^{-\frac{1}{\xi}}\right\} & \xi \neq 0 \\ \frac{1}{\sigma}\exp\left(-\left(\frac{x-\mu}{\sigma}+\exp\left(-\frac{x-\mu}{\sigma}\right)\right)\right) & \xi = 0 \end{cases}$$

Figure D.2: Density function [191]

The parameters should be fitted to the GEV distribution using the Bayesian method [144]. Lastly, the return period are to be provided. The T year return is by the following formula:

$$F_X(z_T) = P(X \leq z_T) = 1 - 1/T \Rightarrow z_T = F^{-1}(1 - 1/T)$$

Figure D.3: Return period calculation, [191]

where zT is the return period or the level that is expected to be exceeded by the annual maximum of daily precipitations once every T years, on average. For a T, the quantiles can be determined by the provided formula:

$$z_T = \begin{cases} \mu + \frac{\sigma}{\xi}\left\{1 - \ln\left(1-\frac{1}{T}\right)^{\xi}\right\} & \xi \neq 0 \\ \mu - \sigma\ \ln\left[-\ln\left(1-\frac{1}{T}\right)\right] & \xi = 0 \end{cases}$$

Figure D.4: Return period quantiles [191]

The end product of the calculation is an IDF curve.

E

MIDS Calculator adapted Excel Sheet

E.1. Inputs and Outputs of the Sheet

The following, among others, will be determined with the MIDS calculator:

- Calculates the runoff coefficient
- Volume of pond
- Drawdown time (empyting time)
- Calculates the annual stormwater runoff volume
- Calculates annual stormwater runoff volume reduction (annual yield) achieved by a BMP, in this case due to infiltration.

The following input parameters are required:

- Land cover area, A,B,C and D soils, both Open and Managed Turf
- Fraction of annual runoff that produce runoff
- Impervious Covers
- Top surface area of pond
- Bottom surface area of pond
- Overflow depth
- Required drawdown (emptying) time

E.2. Input Results Sheet

Project Name:	
User Name / Company Name:	
Date:	
Project Description:	

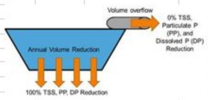
Legend
User input cells
Calculation cells
Constant values
Value obtained from another sheet

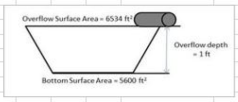
		Notes:	
Retention Requirment (cm):	2.794	Has to be set by authority	(Or design storm)
Annual Rainfall (cm):	77.7	Has to be determined	
Fraction of annual rainfall events that produce runoff:	0.9	Number from MIDS sheet	

Total Watershed Area					
Land Cover (hecters)	A soils	B Soils	C Soils	D Soils	Totals (acres)
Forest/Open Space (hecters) -- undisturbed, protected forest/open space or reforested land	16.1874	8.0937	6.0702	6.0702	36.4215
Managed Turf (hecters) -- disturbed, graded for yards or other turf to be mowed/managed	2.0234	2.0234	2.8328	2.0234	8.903
Impervious Cover (hecters)					40.4686
				Total:	85.7931

Runoff coefficients (or so for soil groeps)					
A	B	C	D		
0.02	0.03	0.04	0.05	For natural soils	1.113
0.15	0.2	0.22	0.25	For managed turf	1.837
Impervious:					
0.95				For imprevious	38.45

Infiltration Basin Characteristics	
Required treatment volume (RV) [m³]	11,307
Top surface area (A_0) [m²]	929
Bottom surface area (Am) [m²]	743
Overflow depth (Do) [m]	0.9144
Infiltration rate of underlying soils (I_R) [cm/hr]	3.81
Required drawdown time (T_D) [hrs]	24.00
Volume reduction capacity of BMP (V) [m³]	765
Volume of retention provided by BMP (BMPV) [m³]	765
Drawdown time of (hours)	24
Does it meet required drawdown time	No





Total impervious cover (hectars)	40.47
Total watershed area (hectars)	85.79
Site runoff coefficient, Rv	0.48
% Impervious	47%

Development volume retention requirement (cubic meter)	11,307
Volume removed by BMPs (cubic meter)	765
(cubic meter)	10,542
Percent volume removed	6.76%

Post-developoment annual volume (cubic meter)	289,566.77
Percent annual volume removed	30.03%
Annual volume removed by BMPs (cubic meter)	86962.89

Figure E.1: Input Result Sheet part 1

Infiltration Basin

Inputs from Other Sheets	BMP 1
Direct Watershed Impervious (%)	0.471699939
BMP Vol Capacity (cubic feet)	27,000
Total Weighted Drainage area (acres)	211.999367
Total Impervious Percentage (%) weighted by contributing area and volume	0.471699939
Infiltration Rate (inches per hour)	1.50

Calculations	BMP 1
Volume Reduction	30.03%
BMP Vol/Drainage Area (Max 0.2)	0.002923739
Volume Reduction Lower	23.53%
Volume Reduction Upper	31.12%
Infiltration Lower	0.9
Infiltration Upper	1.6

Volume Reduction

Soil Type Infiltration Rate	BMP 1
0	2.29%
0.2	15.27%
0.3	16.42%
0.6	20.21%
0.9	23.53%
1.6	31.12%

Infiltration Basin — **Metric Values**

Inputs from other sheets	BMP 1
Direct Watershed Impervious (%)	0.47
BMP Vol Capacity (cubic meter)	765
Total Weighted Drainage area (hecter)	85.7931
Total Impervious Percentage (%) weighted by contributing area and volume	0.47
Infiltration Rate (cm per hour)	3.81

Figure E.2: Input Result Sheet part 2

E.3. Removal Tables Sheet

BMP Vol/Drainage Area	Percent Impervious - A Soils (1.6"/hr infilt. Rate) 0.0	0.1	0.3	0.5	0.7	0.9	1.0
0.0000000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.0011478	56.8%	45.3%	22.2%	14.5%	10.7%	8.5%	7.4%
0.0022957	77.6%	63.7%	36.0%	24.8%	18.8%	15.1%	13.2%
0.0034435	88.5%	74.5%	46.4%	33.2%	25.7%	20.9%	18.5%
0.0045845	95.1%	81.6%	54.7%	40.2%	31.7%	26.1%	23.3%
0.0091667	100.0%	93.8%	75.2%	60.5%	50.1%	42.8%	39.1%
0.0137511	100.0%	97.2%	85.8%	72.7%	62.6%	54.8%	50.9%
0.0183333	100.0%	98.5%	91.5%	80.6%	71.4%	63.8%	60.0%
0.0229178	100.0%	99.0%	94.6%	86.0%	77.6%	70.5%	67.0%
0.0275000	100.0%	99.3%	96.5%	89.8%	82.4%	75.7%	72.4%
0.0320845	100.0%	99.5%	97.6%	92.4%	86.0%	79.8%	76.7%
0.0366667	100.0%	99.7%	98.4%	94.3%	88.9%	83.2%	80.4%
0.0412511	100.0%	99.9%	98.8%	95.7%	91.1%	86.0%	83.5%
0.0458333	100.0%	99.9%	99.1%	96.6%	92.8%	88.3%	86.1%
0.0504178	100.0%	100.0%	99.3%	97.4%	94.1%	90.2%	88.2%
0.0550000	100.0%	100.0%	99.5%	98.0%	95.2%	91.7%	90.0%
0.0595845	100.0%	100.0%	99.6%	98.4%	96.0%	92.9%	91.4%
0.0641667	100.0%	100.0%	99.7%	98.7%	96.7%	94.0%	92.6%
0.0687511	100.0%	100.0%	99.7%	98.9%	97.2%	94.8%	93.7%
0.0733333	100.0%	100.0%	99.7%	99.0%	97.6%	95.6%	94.5%
0.0825000	100.0%	100.0%	99.8%	99.3%	98.3%	96.7%	95.8%
0.1000000	100.0%	100.0%	99.8%	99.6%	99.0%	98.0%	97.5%
0.1147842	100.0%	100.0%	99.9%	99.7%	99.3%	98.6%	98.3%
0.1492195	100.0%	100.0%	100.0%	99.8%	99.7%	99.4%	99.2%
0.2000000	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Percent Impervious - A Soils (0.9"/hr infilt. Rate) 0.0	0.1	0.3	0.5	0.7	0.9	1.0
0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
46.1%	36.1%	16.0%	10.2%	7.4%	5.9%	5.1%
67.7%	54.4%	27.6%	18.2%	13.5%	10.7%	9.3%
80.2%	65.8%	37.1%	25.2%	19.0%	15.2%	13.3%
88.0%	73.7%	45.1%	31.4%	24.0%	19.4%	17.1%
100.0%	88.9%	66.6%	50.9%	40.8%	33.8%	30.3%
100.0%	94.3%	78.7%	63.9%	53.2%	45.3%	41.4%
100.0%	96.4%	86.4%	73.0%	62.5%	54.4%	50.3%
100.0%	97.6%	91.1%	79.6%	69.8%	61.7%	57.7%
100.0%	98.4%	93.9%	84.6%	75.4%	67.7%	63.8%
100.0%	98.9%	95.8%	88.3%	79.9%	72.6%	68.9%
100.0%	99.2%	97.1%	91.0%	83.6%	76.6%	73.2%
100.0%	99.4%	97.9%	92.9%	86.5%	80.0%	76.8%
100.0%	99.6%	98.5%	94.4%	88.8%	82.9%	80.0%
100.0%	99.7%	98.8%	95.5%	90.8%	85.3%	82.6%
100.0%	99.8%	99.1%	96.4%	92.3%	87.4%	84.9%
100.0%	99.9%	99.3%	97.2%	93.5%	89.1%	86.9%
100.0%	100.0%	99.5%	97.7%	94.5%	90.6%	88.7%
100.0%	100.0%	99.6%	98.2%	95.3%	91.8%	90.1%
100.0%	100.0%	99.7%	98.5%	96.0%	92.9%	91.3%
100.0%	100.0%	99.7%	99.0%	97.2%	94.5%	93.2%
100.0%	100.0%	99.8%	99.4%	98.4%	96.6%	95.8%
100.0%	100.0%	99.8%	99.6%	99.0%	97.7%	97.1%
100.0%	100.0%	100.0%	99.8%	99.5%	99.0%	98.7%
100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Percent Impervious - B Soils (0.6"/hr infilt. Rate) 0.0	0.1	0.3	0.5	0.7	0.9	1.0
0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
31.7%	25.5%	13.1%	8.6%	6.4%	5.1%	4.4%
48.3%	39.8%	22.9%	15.6%	11.8%	9.4%	8.3%
58.7%	49.5%	31.2%	21.8%	16.7%	13.5%	11.9%
65.7%	56.6%	38.4%	27.4%	21.2%	17.3%	15.3%
79.8%	72.8%	58.8%	45.7%	36.7%	30.6%	27.5%
85.1%	80.5%	71.3%	58.5%	48.8%	41.6%	37.9%
88.2%	85.3%	79.6%	67.8%	58.1%	50.6%	46.8%
90.7%	88.9%	85.3%	74.8%	65.6%	57.9%	54.1%
92.9%	91.7%	89.2%	80.3%	71.4%	64.0%	60.3%
94.5%	93.7%	91.9%	84.5%	76.3%	69.1%	65.4%
95.8%	95.2%	94.0%	87.9%	80.3%	73.3%	69.9%
96.6%	96.2%	95.5%	90.4%	83.6%	77.0%	73.7%
97.1%	96.9%	96.5%	92.3%	86.3%	80.2%	77.1%
97.3%	97.3%	97.2%	93.7%	88.6%	82.9%	80.0%
97.7%	97.7%	97.7%	94.9%	90.5%	85.2%	82.5%
98.0%	98.0%	98.1%	95.8%	91.9%	87.1%	84.8%
98.3%	98.3%	98.4%	96.6%	93.1%	88.9%	86.7%
98.5%	98.6%	98.6%	97.2%	94.1%	90.3%	88.4%
98.8%	98.8%	98.8%	97.6%	94.9%	91.5%	89.8%
99.1%	99.1%	99.2%	98.3%	96.2%	93.4%	92.0%
99.5%	99.5%	99.5%	99.0%	97.9%	95.9%	94.8%
99.6%	99.6%	99.6%	99.4%	98.6%	97.2%	96.5%
100.0%	99.9%	99.7%	99.6%	99.4%	98.8%	98.5%
100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Figure E.3: Removal Table Sheet part 1

Percent Impervious - B Soils (0.3"/hr infilt. Rate) 0.0	0.1	0.3	0.5	0.7	0.9	1.0
0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
24.3%	19.6%	10.1%	6.7%	5.0%	4.0%	3.5%
39.2%	32.2%	18.4%	12.5%	9.5%	7.6%	6.7%
49.1%	41.3%	25.7%	17.8%	13.6%	11.0%	9.7%
55.9%	47.9%	31.9%	22.6%	17.4%	14.2%	12.5%
70.8%	64.4%	51.5%	39.3%	31.3%	25.9%	23.2%
76.9%	72.6%	64.1%	51.8%	42.5%	35.9%	32.5%
80.5%	78.0%	73.0%	61.2%	51.7%	44.4%	40.7%
83.3%	82.0%	79.4%	68.6%	59.3%	51.7%	47.9%
85.8%	85.2%	84.0%	74.5%	65.4%	57.9%	54.1%
88.3%	88.0%	87.4%	79.3%	70.6%	63.2%	59.5%
90.5%	90.3%	90.0%	83.1%	75.0%	67.7%	64.1%
92.2%	92.1%	92.0%	86.2%	78.7%	71.7%	68.2%
93.4%	93.5%	93.6%	88.7%	81.9%	75.2%	71.9%
94.7%	94.8%	94.8%	90.7%	84.6%	78.3%	75.1%
95.5%	95.6%	95.7%	92.3%	86.9%	80.9%	77.9%
96.1%	96.2%	96.5%	93.6%	88.8%	83.3%	80.5%
96.5%	96.7%	97.1%	94.7%	90.4%	85.3%	82.8%
96.8%	97.1%	97.6%	95.6%	91.8%	87.1%	84.8%
97.2%	97.5%	98.0%	96.4%	92.9%	88.7%	86.6%
97.9%	98.1%	98.5%	97.4%	94.7%	91.2%	89.5%
98.8%	98.9%	99.1%	98.5%	97.0%	94.4%	93.2%
99.3%	99.3%	99.4%	99.0%	98.0%	96.2%	95.2%
99.7%	99.7%	99.6%	99.6%	99.2%	98.4%	98.0%
100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Percent Impervious - C Soils (0.2"/hr infilt. Rate) 0.0	0.1	0.3	0.5	0.7	0.9	1.0
0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
17.1%	15.4%	8.9%	6.1%	4.7%	3.8%	3.3%
28.9%	26.1%	16.5%	11.7%	9.0%	7.3%	6.4%
37.6%	34.0%	23.3%	16.8%	13.0%	10.6%	9.4%
44.1%	40.0%	29.2%	21.5%	16.8%	13.8%	12.3%
60.1%	55.2%	47.7%	37.5%	30.4%	25.4%	22.9%
68.5%	63.9%	60.0%	49.7%	41.5%	35.3%	32.3%
74.5%	70.4%	68.7%	59.1%	50.6%	43.9%	40.5%
79.1%	75.4%	75.2%	66.5%	58.2%	51.2%	47.6%
82.5%	79.4%	80.0%	72.4%	64.4%	57.4%	53.9%
85.3%	82.7%	83.6%	77.2%	69.5%	62.7%	59.3%
87.6%	85.5%	86.5%	81.2%	74.0%	67.3%	64.0%
89.8%	88.0%	88.8%	84.3%	77.8%	71.3%	68.0%
91.7%	90.1%	90.8%	86.9%	81.0%	74.8%	71.8%
93.2%	91.8%	92.3%	89.0%	83.7%	77.9%	75.0%
94.3%	93.2%	93.6%	90.7%	86.1%	80.6%	77.9%
95.4%	94.4%	94.6%	92.2%	88.1%	82.9%	80.4%
96.1%	95.3%	95.4%	93.4%	89.7%	85.0%	82.7%
96.8%	96.1%	96.1%	94.5%	91.1%	86.9%	84.7%
97.3%	96.7%	96.8%	95.3%	92.3%	88.5%	86.6%
97.8%	97.4%	97.7%	96.6%	94.2%	91.0%	89.4%
98.5%	98.3%	98.6%	97.9%	96.6%	94.3%	93.1%
99.0%	98.8%	99.0%	98.6%	97.7%	96.0%	95.2%
99.3%	99.3%	99.5%	99.4%	99.0%	98.3%	98.0%
100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Percent Impervious - D Soils (<0.03"/hr infilt. Rate) 0.0	0.1	0.3	0.5	0.7	0.9	1.0
0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
2.6%	2.3%	1.3%	0.9%	0.7%	0.6%	0.5%
4.3%	3.9%	2.5%	1.8%	1.3%	1.1%	1.0%
5.6%	5.1%	3.5%	2.5%	2.0%	1.6%	1.4%
6.6%	6.0%	4.4%	3.2%	2.5%	2.1%	1.8%
9.0%	8.3%	7.2%	5.6%	4.6%	3.8%	3.4%
10.3%	9.6%	9.0%	7.5%	6.2%	5.3%	4.8%
11.2%	10.6%	10.3%	8.9%	7.6%	6.6%	6.1%
11.9%	11.3%	11.3%	10.0%	8.7%	7.7%	7.1%
12.4%	11.9%	12.0%	10.9%	9.7%	8.6%	8.1%
12.8%	12.4%	12.5%	11.6%	10.4%	9.4%	8.9%
13.1%	12.8%	13.0%	12.2%	11.1%	10.1%	9.6%
13.5%	13.2%	13.3%	12.7%	11.7%	10.7%	10.2%
13.8%	13.5%	13.6%	13.0%	12.1%	11.2%	10.8%
14.0%	13.8%	13.9%	13.4%	12.6%	11.7%	11.3%
14.1%	14.0%	14.0%	13.6%	12.9%	12.1%	11.7%
14.3%	14.2%	14.2%	13.8%	13.2%	12.4%	12.1%
14.4%	14.3%	14.3%	14.0%	13.5%	12.8%	12.4%
14.5%	14.4%	14.4%	14.2%	13.7%	13.0%	12.7%
14.6%	14.5%	14.5%	14.3%	13.8%	13.3%	13.0%
14.7%	14.6%	14.7%	14.5%	14.1%	13.7%	13.4%
14.8%	14.7%	14.8%	14.7%	14.5%	14.1%	14.0%
14.8%	14.8%	14.9%	14.8%	14.7%	14.4%	14.3%
14.9%	14.9%	14.9%	14.9%	14.9%	14.7%	14.7%
15.0%	15.0%	15.0%	15.0%	15.0%	15.0%	15.0%

Figure E.4: Removal Table Sheet part 2

A+ Soil

Soil Type	BMP 1
Soil Type Min Infiltration Rate	1.6
X1	0.00230
X2	0.00344
Y1	0.3
Y2	0.5
Z(Y1X1)	0.36004
Z(Y1X2)	0.46404
Z(Y2X1)	0.24757
Z(Y2X2)	0.33191
Z(X1Yint)	0.26348454
Z(X2Yint)	0.350606436
Z(XintYint)	0.311154804

B+ Soil

Soil Type	BMP 1
Soil Type Min Infiltration Rate	0.6
X1	0.00230
X2	0.00344
Y1	0.3
Y2	0.5
Z(Y1X1)	22.9%
Z(Y1X2)	31.2%
Z(Y2X1)	15.6%
Z(Y2X2)	21.8%
Z(X1Yint)	16.6%
Z(X2Yint)	23.2%
Z(XintYint)	20.2%

C Soil

Soil Type	BMP 1
Soil Type Min Infiltration Rate	0.2
X1	0.00230
X2	0.00344
Y1	0.3
Y2	0.5
Z(Y1X1)	16.5%
Z(Y1X2)	23.3%
Z(Y2X1)	11.7%
Z(Y2X2)	16.8%
Z(X1Yint)	12.4%
Z(X2Yint)	17.7%
Z(XintYint)	15.3%

A- Soil

Soil Type	BMP 1
Soil Type Min Infiltration Rate	0.9
X1	0.00230
X2	0.00344
Y1	0.3
Y2	0.5
Z(Y1X1)	0.27565
Z(Y1X2)	0.37107
Z(Y2X1)	0.18181
Z(Y2X2)	0.25172
Z(X1Yint)	0.195088389
Z(X2Yint)	0.268608062
Z(XintYint)	0.23531596

B Soil

Soil Type	BMP 1
Soil Type Min Infiltration Rate	0.3
X1	0.00230
X2	0.00344
Y1	0.3
Y2	0.5
Z(Y1X1)	18.4%
Z(Y1X2)	25.7%
Z(Y2X1)	12.5%
Z(Y2X2)	17.8%
Z(X1Yint)	13.4%
Z(X2Yint)	18.9%
Z(XintYint)	16.4%

D Soil

Soil Type	BMP 1
Soil Type Min Infiltration Rate	0
X1	0.00230
X2	0.00344
Y1	0.3
Y2	0.5
Z(Y1X1)	2.5%
Z(Y1X2)	3.5%
Z(Y2X1)	1.8%
Z(Y2X2)	2.5%
Z(X1Yint)	1.9%
Z(X2Yint)	2.7%
Z(XintYint)	2.3%

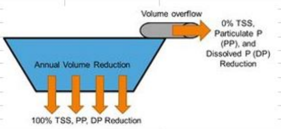
Figure E.5: Removal Table Sheet part 3

E.4. Input Results Sheet Formulas shown

	B	C
1		
2	**Project Name:**	
3	**User Name / Company Name:**	
4	**Date:**	
5	**Project Description:**	
6		
7	**Legend**	
8	**User input cells**	
9	**Calculation cells**	
10	**Constant values**	
11	**Value obtained from another sheet**	
12		
13	Retention Requirment (cm):	2.794
14	Annual Rainfall (cm):	77.724
15	Fraction of annual rainfall events that produce runoff:	0.9
16		
17	**Total Watershed Area**	
18	Land Cover (hecters)	**A soils**
19	Forest/Open Space (hecters) -- undisturbed, protected forest/open space or reforested land	16.1874
20	Managed Turf (hecters) -- disturbed, graded for yards or other turf to be mowed/managed	2.0234
21	Impervious Cover (hecters)	
22		
23		
24		
25	**Infiltration Basin Characteristics**	
26	Required treatment volume (RV) [m³]	=C44
27	Top surface area (A_0) [m²]	929.0304
28	Bottom surface area (Am) [m²]	743.2243
29	Overflow depth (Do) [m]	0.9144
30	Infiltration rate of underlying soils (I_R) [cm/hr]	3.81
31	Required drawdown time (T_D) [hrs]	24
32	Volume reduction capacity of BMP (V) [m³]	=IF(NOT(OR(C26="";C29="";C27="";C28="";C30="";C30=""));ROUND((C27+C28)/2*C29;2);"")
33	**Volume of retention provided by BMP (BMPV) [m³]**	=IF(NOT(C32="");IF(C26="";0;IF(C32>C26;C26;C32));"")
34	Drawdown time of (hours)	=(C29*100)/C30
35	Does it meet required drawdown time	= IF(C34 < C31;"Yes";"No")
36		
37		
38	Total impervious cover (hectars)	=G21
39	Total watershed area (hectars)	=G22
40	Site runoff coefficient, Rv	=IF(G22>0; ((P19+P20+P22)/G22);" Total acres not known ")
41	% Impervious	=IF(C39>0;C38/C39;"")
42		
43		
44	Development volume retention requirement (cubic meter)	=IF(C13>0;ROUND(C38*C13*10000*0.01;2);"Retention requirment empty")
45	Volume removed by BMPs (cubic meter)	=C32
46	Additional volume removal needed to meet requirement (cubic meter)	=IF(NOT(C45="");C44-C45;C44)
47	Percent volume removed	=IF(NOT(C45="");C45/C44;"")
48		
49		
50	Post-developoment annual volume (cubic meter)	=IF(AND(G22>0;NOT(C14=""));ROUND((C14/100)*C15*C40*C39*10000;6);"")
51	Percent annual volume removed	='Removal-tables'!C11
52	Annual volume removed by BMPs (cubic meter)	=IF(NOT(C51="");C51*C50;"")
53		

Figure E.6: Input and Result sheet showing formulas, part 1

	D	E	F	G	J	K	L	M	O	P
10										
11										
12	Notes:									
13	Has to be set by authorit		(Or design storm)							
14	Has to be determined									
15	Number from MIDS shei									
16										
17					**Runoff coef**					
18	**B Soils**	**C Soils**	**D Soils**	**Totals (acres)**	A	B	C	D		
19	8.0937	6.0702	6.0702	=SUM(C19:F19)	0.02	0.03	0.04	0.05	For natural soils	= C19*J19 + D19*K19 + E19*L19 + F19*M19
20	2.0234	2.8328	2.0234	=SUM(C20:F20)	0.15	0.2	0.22	0.25	For managed turf	=C20*J20 + D20*K20 + E20*L20 + F20*M20
21				40.4686	Impervious:					
22			**Total:**	=SUM(G19:G21)	0.95				For imprevious	= G21*J22



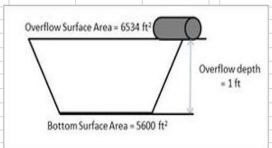


Figure E.7: Input and Result sheet showing formulas, part 2

E.5. Removal Tables Sheet Formulas shown

	A	B	C	D	E	F
1						
2		**Infiltration Basin**			**Infiltration Basin**	**Metric Values**
3		**Inputs from Other Sheets**	**BMP 1**		**Inputs from other sheets**	**BMP 1**
4		Direct Watershed Impervious (%)	=('Inputs-Results'!C41)		Direct Watershed Impervious (%)	=('Inputs-Results'!C41)
5		BMP Vol Capacity (cubic feet)	=('Inputs-Results'!C32)*35.3146667		BMP Vol Capacity (cubic meter)	=('Inputs-Results'!C32)
6		Total Weighted Drainage area (acres)	=('Inputs-Results'!G22) * 2.4710538146717		Total Weighted Drainage area (hecter)	='Inputs-Results'!G22
7		Total Impervious Percentage (%) weighted by contributing area and volume	=C4		Total Impervious Percentage (%) weighted by contributing area and volume	=F4
8		Infiltration Rate (inches per hour)	=('Inputs-Results'!C30) / 2.54		Infiltration Rate (cm per hour)	='Inputs-Results'!C30
9						
10		**Calculations**	**BMP 1**			
11		Volume Reduction	=IF(NOT(C5="");IF(C8>=1.6;C13;C13+((C14-C13)/(C16-C15))*(C$8-C15));0)			
12		BMP Vol/Drainage Area (Max 0.2)	=IF(C5/43560/C6>0.1999999;0.199999999;C5/43560/C6)			
13		Volume Reduction Lower	=INDEX(C$21:C$26;MATCH(C$8;$B$21:$B$26;1);1)			
14		Volume Reduction Upper	=INDEX(C$21:C$26;MATCH(C$8;$B$21:$B$26;1)+1;1)			
15		Infiltration Lower	=INDEX($B$21:$B$26;MATCH(C$8;$B$21:$B$26;1);1)			
16		Infiltration Upper	=INDEX($B$21:$B$26;MATCH(C$8;$B$21:$B$26;1)+1;1)			
17						
18						
19		**Volume Reduction**				
20		**Soil Type Infiltration Rate**	**BMP 1**			
21		0	=K86			
22		0.2	=K71			
23		0.3	=G86			
24		0.6	=G71			
25		0.9	=C86			
26		1.6	=C71			

Figure E.8: Removal Table Sheet showing formulas, part 1

	A	B	C
58		**A+ Soil**	
59		Soil Type	**BMP 1**
60		Soil Type Min Infiltration Rate	1.6
61		X1	=INDEX($B$30:$B$55;MATCH(C$12;$B$30:$B$55);1)
62		X2	=INDEX($B$30:$B$55;MATCH(C$12;$B$30:$B$55)+1;1)
63		Y1	=INDEX($C$30:$I$30;1;MATCH(C$7;$C$30:$I$30))
64		Y2	=INDEX($C$30:$I$30;1;MATCH(C$7;$C$30:$I$30)+1)
65		Z(Y1X1)	=INDEX($C$31:$I$55;MATCH(C$12;$B$31:$B$55);MATCH(C$7;$C$30:$I$30))
66		Z(Y1X2)	=INDEX($C$31:$I$55;MATCH(C$12;$B$31:$B$55)+1;MATCH(C$7;$C$30:$I$30))
67		Z(Y2X1)	=INDEX($C$31:$I$55;MATCH(C$12;$B$31:$B$55);MATCH(C$7;$C$30:$I$30)+1)
68		Z(Y2X2)	=INDEX($C$31:$I$55;MATCH(C$12;$B$31:$B$55)+1;MATCH(C$7;$C$30:$I$30)+1)
69		Z(X1Yint)	=C65+((C67-C65)/(C64-C63))*(C$7-C63)
70		Z(X2Yint)	=C66+((C68-C66)/(C64-C63))*(C$7-C63)
71		Z(XintYint)	=C69+(C70-C69)/(C62-C61)*(C$12-C61)
72			
73		**A- Soil**	
74		Soil Type	**BMP 1**
75		Soil Type Min Infiltration Rate	0.9
76		X1	=INDEX($B$30:$B$55;MATCH(C$12;$B$30:$B$55);1)
77		X2	=INDEX($B$30:$B$55;MATCH(C$12;$B$30:$B$55)+1;1)
78		Y1	=INDEX($J$30:$P$30;1;MATCH(C$7;$J$30:$P$30))
79		Y2	=INDEX($J$30:$P$30;1;MATCH(C$7;$J$30:$P$30)+1)
80		Z(Y1X1)	=INDEX($J$31:$P$55;MATCH(C$12;$B$31:$B$55);MATCH(C$7;$J$30:$P$30))
81		Z(Y1X2)	=INDEX($J$31:$P$55;MATCH(C$12;$B$31:$B$55)+1;MATCH(C$7;$J$30:$P$30))
82		Z(Y2X1)	=INDEX($J$31:$P$55;MATCH(C$12;$B$31:$B$55);MATCH(C$7;$J$30:$P$30)+1)
83		Z(Y2X2)	=INDEX($J$31:$P$55;MATCH(C$12;$B$31:$B$55)+1;MATCH(C$7;$J$30:$P$30)+1)
84		Z(X1Yint)	=C80+((C82-C80)/(C79-C78))*(C$7-C78)
85		Z(X2Yint)	=C81+((C83-C81)/(C79-C78))*(C$7-C78)
86		Z(XintYint)	=C84+(C85-C84)/(C77-C76)*(C$12-C76)
87			

Figure E.9: Removal Table Sheet showing formulas, part 2

	F	G	H	I	J	K
58	**B+ Soil**				**C Soil**	
59	Soil Type	**BMP 1**			Soil Type	**BMP 1**
60	Soil Type Min Infiltration Rate	0.6			Soil Type Min Infiltration Rate	0.2
61	X1	=INDEX($B$30:$B$55;MATCH(C$12;$B$30:$B$55);1)			X1	=INDEX($B$30:$B$55;MATCH(C$12;$B$30:$B$55);1)
62	X2	=INDEX($B$30:$B$55;MATCH(C$12;$B$30:$B$55)+1;1)			X2	=INDEX($B$30:$B$55;MATCH(C$12;$B$30:$B$55)+1;1)
63	Y1	=INDEX($Q$30:$W$30;1;MATCH(C$7;$Q$30:$W$30))			Y1	=INDEX($AE$30:$AK$30;1;MATCH(C$7;$AE$30:$AK$30))
64	Y2	=INDEX($Q$30:$W$30;1;MATCH(C$7;$Q$30:$W$30)+1)			Y2	=INDEX($AE$30:$AK$30;1;MATCH(C$7;$AE$30:$AK$30)+1)
65	Z(Y1X1)	=INDEX($Q$31:$W$55;MATCH(C$12;$B$31:$B$55);MATCH(C$7;$Q$30:$W$30))			Z(Y1X1)	=INDEX($AE$31:$AK$55;MATCH(C$12;$B$31:$B$55);MATCH(C$7;$AE$30:$AK$30))
66	Z(Y1X2)	=INDEX($Q$31:$W$55;MATCH(C$12;$B$31:$B$55)+1;MATCH(C$7;$Q$30:$W$30))			Z(Y1X2)	=INDEX($AE$31:$AK$55;MATCH(C$12;$B$31:$B$55)+1;MATCH(C$7;$AE$30:$AK$30))
67	Z(Y2X1)	=INDEX($Q$31:$W$55;MATCH(C$12;$B$31:$B$55);MATCH(C$7;$Q$30:$W$30)+1)			Z(Y2X1)	=INDEX($AE$31:$AK$55;MATCH(C$12;$B$31:$B$55);MATCH(C$7;$AE$30:$AK$30)+1)
68	Z(Y2X2)	=INDEX($Q$31:$W$55;MATCH(C$12;$B$31:$B$55)+1;MATCH(C$7;$Q$30:$W$30)+1)			Z(Y2X2)	=INDEX($AE$31:$AK$55;MATCH(C$12;$B$31:$B$55)+1;MATCH(C$7;$AE$30:$AK$30)+1)
69	Z(X1Yint)	=G65+((G67-G65)/(G64-G63))*(C$7-G63)			Z(X1Yint)	=K65+((K67-K65)/(K64-K63))*(C$7-K63)
70	Z(X2Yint)	=G66+((G68-G66)/(G64-G63))*(C$7-G63)			Z(X2Yint)	=K66+((K68-K66)/(K64-K63))*(C$7-K63)
71	Z(XintYint)	=G69+(G70-G69)/(G62-G61)*(C$12-G61)			Z(XintYint)	=K69+(K70-K69)/(K62-K61)*(C$12-K61)
72						
73	**B Soil**				**D Soil**	
74	Soil Type	**BMP 1**			Soil Type	**BMP 1**
75	Soil Type Min Infiltration Rate	0.3			Soil Type Min Infiltration Rate	0
76	X1	=INDEX($B$30:$B$55;MATCH(C$12;$B$30:$B$55);1)			X1	=INDEX($B$30:$B$55;MATCH(C$12;$B$30:$B$55);1)
77	X2	=INDEX($B$30:$B$55;MATCH(C$12;$B$30:$B$55)+1;1)			X2	=INDEX($B$30:$B$55;MATCH(C$12;$B$30:$B$55)+1;1)
78	Y1	=INDEX($X$30:$AD$30;1;MATCH(C$7;$X$30:$AD$30))			Y1	=INDEX($AL$30:$AR$30;1;MATCH(C$7;$AL$30:$AR$30))
79	Y2	=INDEX($X$30:$AD$30;1;MATCH(C$7;$X$30:$AD$30)+1)			Y2	=INDEX($AL$30:$AR$30;1;MATCH(C$7;$AL$30:$AR$30)+1)
80	Z(Y1X1)	=INDEX($X$31:$AD$55;MATCH(C$12;$B$31:$B$55);MATCH(C$7;$X$30:$AD$30))			Z(Y1X1)	=INDEX($AL$31:$AR$55;MATCH(C$12;$B$31:$B$55);MATCH(C$7;$AL$30:$AR$30))
81	Z(Y1X2)	=INDEX($X$31:$AD$55;MATCH(C$12;$B$31:$B$55)+1;MATCH(C$7;$X$30:$AD$30))			Z(Y1X2)	=INDEX($AL$31:$AR$55;MATCH(C$12;$B$31:$B$55)+1;MATCH(C$7;$AL$30:$AR$30))
82	Z(Y2X1)	=INDEX($X$31:$AD$55;MATCH(C$12;$B$31:$B$55);MATCH(C$7;$X$30:$AD$30)+1)			Z(Y2X1)	=INDEX($AL$31:$AR$55;MATCH(C$12;$B$31:$B$55);MATCH(C$7;$AL$30:$AR$30)+1)
83	Z(Y2X2)	=INDEX($X$31:$AD$55;MATCH(C$12;$B$31:$B$55)+1;MATCH(C$7;$X$30:$AD$30)+1)			Z(Y2X2)	=INDEX($AL$31:$AR$55;MATCH(C$12;$B$31:$B$55)+1;MATCH(C$7;$AL$30:$AR$30)+1)
84	Z(X1Yint)	=G80+((G82-G80)/(G79-G78))*(C$7-G78)			Z(X1Yint)	=K80+((K82-K80)/(K79-K78))*(C$7-K78)
85	Z(X2Yint)	=G81+((G83-G81)/(G79-G78))*(C$7-G78)			Z(X2Yint)	=K81+((K83-K81)/(K79-K78))*(C$7-K78)
86	Z(XintYint)	=G84+(G85-G84)/(G77-G76)*(C$12-G76)			Z(XintYint)	=K84+(K85-K84)/(K77-K76)*(C$12-K76)
87						

Figure E.10: Removal Table Sheet showing formulas, part 3

F

Performance Curve Development

For the MIDS calculator the performance curves were developed using the P8 model. P8 is an open source model for the prediction of the generation and transport of stormwater runoff pollutants in urban areas. P8 performs continuous water-balance and mass-balance calculations on among others Devices, i.e. BMP's [192, 193]. The P8 model was used to calculate the run off from several hypothetical 4 hectare watershed areas with varying levels of imperiousness, soil types and BMP, infiltration pond, volumes. For the simulation a 50-year hourly precipitation data set was used together with an daily temperature data set, both from Minneapolis-St. Paul. Because the P8 model requires hourly precipitation and daily temperature data. Bio retention basins were used to simulate the amount of water infiltrated by each BMP. The basins were varied in size in addition to a variation in infiltration rates based on the underlying soils. Then the bio-retention basins were modelled using each of the drainage characteristic combinations of: soil types and impervious surfaces. The results from all the model simulation were the total percent annual runoff reduction based on the ratio between pond volume and watershed area, plus the percentage of imperiousness of the watershed area and infiltration rate of the pond, also know as the performance curves. Agency [151] contains a more extensive description of the generation of performance curves.

G

Estimation of Clogging Rate

G.1. Tool for Estimation of Clogging Rate

With the INOWAS tool 'T01. SAT basin infiltration capacity reduction database' of the technical University of Dresden stakeholders can estimate how fast a specific pond will clog and how that will affect the infiltration rate. The INOWAS Tool seems to be a promising approach for collaboration in the field of stormwater infiltration. However, it was not possible to find the references of the studies that are considered in the tool. This is problematic since the clogging rate is not only dependent on the parameters considered by INOWAS but also the solids concentration which is not reported within the tool. This tool is therefore not advised to be used in the framework at hand, but nevertheless the tool is explained in this Appendix since it might prove itself useful in the future.

The Tool can be accessed via this link: https://inowas.com/tools/t01-sat-basin-infiltration-capacity-reduction-database/

G.2. Explanation of the Tool

There are six parameters that influence the infiltration rate:

1. Hydraulic loading rate (HLR)
2. Hydraulic loading cycle (HLC)
3. Infiltration time
4. Hydraulic conductivity
5. Climate conditions
6. Experimental scale

From the analysis of above mentioned factors three decision making tools are obtained:

1. Infiltration capacity decrease diagram
2. Infiltration capacity reduction bar
3. Proportion of infiltration capacity phases

Since clogging rates are highly site specific and variable it is difficult to assess them by calculation or modelling. The INOWAS data tool allows the user to adjust the filters in a search engine (see Figure G.1) to match their field measurements. Based on the filter settings the tool will show studies that match the filter settings and the studie's reported reduction of infiltration rate are shown. Figure G.1 shows the user interface and the search engine of the INOWAS tool. The following paragraphs explain the different hydraulic parameters and how they are linked.

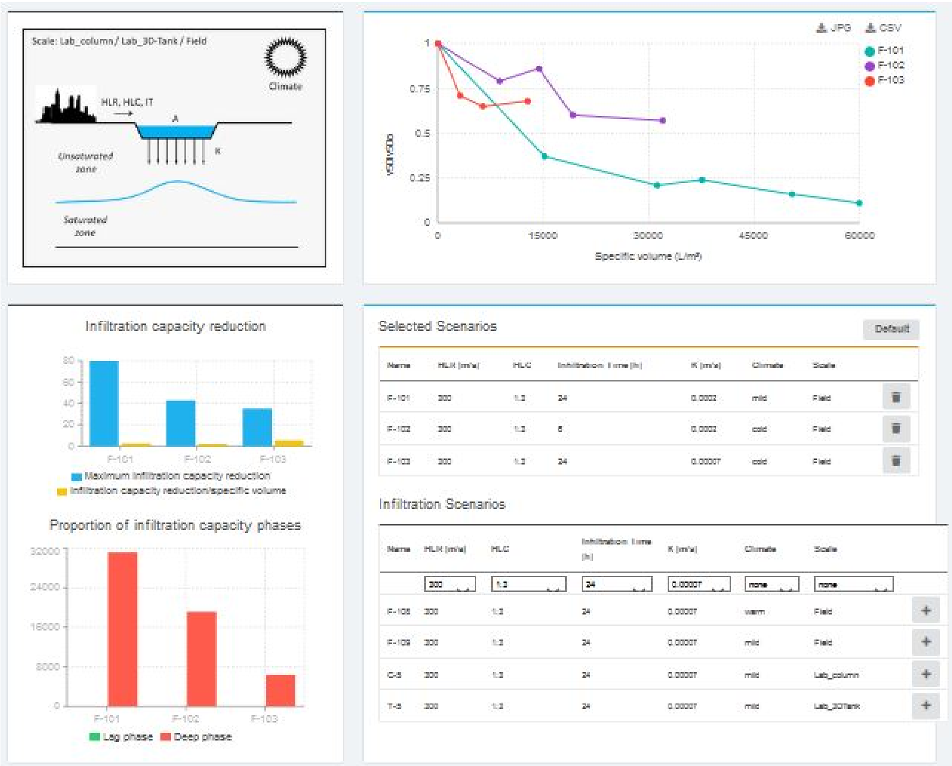


Figure G.1: Screenshot of the 'T01. SAT basin infiltration capacity reduction database'

Hydraulic Loading Rate The Hydraulic Loading Rate is the volume of water that is planned/possible to be infiltrated. The HLR is dependent on the hydraulic capacity which is a site specific parameter itself dependent on soil texture and bulk density which is dependent on the availability of water and the hydraulic conductivity (see chapter 11). The HLR (m/a) is the water column that is infiltrated above 1 m^2 in 1 year. Multiplying the HLR with the surface area of the pond and dividing by the number of days one can expect rainfall, will give the amount that is infiltrated per square meter per day. This number is the required infiltration rate per day.

Hydraulic Loading Cycle The Hydraulic Loading Cycle is the relation between wetting phase and dry phase with the first number being the unit of wetting time. For instance an HLC of 1:2 would indicate that the dry phase is double as long as the infiltration time.

Infiltration Time

The Infiltration time is the time that is needed to infiltrate the water in each cycle before the dry phase begins. The infiltration time is given in hours. Based on the infiltration time and the HLC the dry phase can be calculated.

Hydraulic Conductivity

The hydraulic conductivity (K) is the capacity of the soil to conduct water through the soil pores. A smaller pore space increases the infiltration time and thus to a better filtration of TSS. This might lead to faster clogging if HLC and TSS loading are unfavorable. The hydraulic conductivity is given in m/s.

Climate Conditions

Since the database contains data from all over the world the hydraulics are influenced by seasonal climate variations. The climate influences the reduction of the infiltration capacity by influences bacterial growth and activity through availability of solar radiation and variations in temperature. Furthermore, infiltration is dependent on the viscosity of the water which is itself a function of temperature.

Experimental Scale The reduction of infiltration capacity is also dependent on the scale of the experiment, thus the user can choose from the three categories: field, lab 3D tank and lab column experiments.

H

Mounding Calculation

H.1. Hantush equation

Calculating the Mounding is solving the Hantush analytical equation for 'growth and decay of groundwater mounds in response to uniform percolation' underneath an infiltration cells [194].

Hantush (1967) proposed assumptions to create boundary conditions that allow usage of the a Laplace transform with respect to time plus the Fourier cosine transform with respect to x and y to derive an integral that can be solved. These assumptions help solving the general two-dimensional groundwater flow equation [142, 194]. The resulting equation to calculate the groundwater mound is as follows:

$$h^2 - h_i^2 = (w/2k)(vt)\{S*(\frac{l+x}{\sqrt{4vt}}, \frac{a+y}{\sqrt{4vt}}) + S*(\frac{l+x}{\sqrt{4vt}}, \frac{a-y}{\sqrt{4vt}}) + S*(\frac{l-x}{\sqrt{4vt}}, \frac{a+y}{\sqrt{4vt}}) + S*(\frac{l-x}{\sqrt{4vt}}, \frac{a-y}{\sqrt{4vt}})\} \quad (H.1)$$

where:

$$S*(\alpha,\beta) = \int_0^1 erf(\frac{\alpha}{\sqrt{\tau}})erf(\frac{\beta}{\sqrt{\tau}})d\tau \quad (H.2)$$

Where:

h is the height of water table above impermeable layer at a given time after recharge begins
h_i is the initial head (height of the water table above impermeable layer)
w is the recharge (infiltration) rate
K is the horizontal hydraulic conductivity
v is the diffusivity, where $v = Kb/Sy$
b is the average thickness of the aquifer
Sy is the specific yield
t is the time elapsed since start of recharge
l is the half-length of the recharge basin or the recharge project area in y direction
a is the half-width of the recharge basin or the recharge project area in x direction
x is the distance from the centre of the recharge basin in the x direction
y is the distance from the centre of the recharge basin in the y direction
α is $(l+x)/(\sqrt{4vt})$ or $(l-x)/(\sqrt{4vt})$
β is $(a+y)/(\sqrt{4vt})$ or $(a-y)/(\sqrt{4vt})$
τ the dummy variable of integration
erf the error function

The above equation contains an integral that cannot be solved explicitly and has to be solved using iterative numerical methods.

H.2. Mounding Calculator

Online mounding calculators and mounding calculator spreadsheets can help solve the Hantush equation. One calculator is provided by Inowas and can be accessed via inowas.com [141]. The online mounding calculator accepts user supplied values and solves the Hantush analytical equation automatically. Furthermore the calculator has a user friendly interface, see Figure H.1. The Inowas online calculator requires the following values:

- Magnitude of recharge rate, w (m/d)
- Basin/Pond length, L (m)
- Basin/Pond width, W (m)
- Initial saturated aquifer thickness (groundwater level), h_i (m)
- Specific yield, Sy (-)
- Horizontal Hydraulic conductivity, K (m/d)
- Duration of infiltration period, t (d)

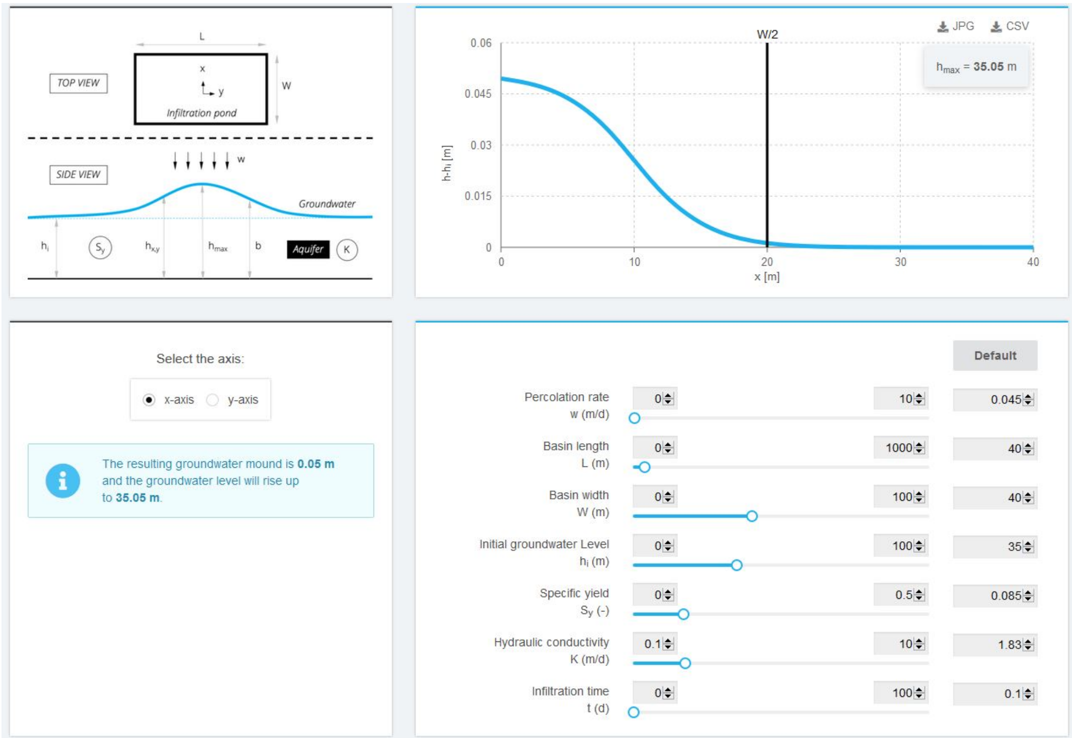


Figure H.1: Inowas Mounding Calculator Interface

H.2.1. Hydraulic Conductivity

The horizontal hydraulic conductivity, K is in units of length per time (L/T). The ability of aquifers to transmit water from areas with higher water levels, or water head, to lower water levels depends on the horizontal hydraulic conductivity and the aquifer thickness. These two multiplied give the aquifer transmissivity.

The horizontal hydraulic conductivity of aquifers can range over several orders of magnitude. These large variations of hydraulic conductivity make it a more important and controlling variable compared to the aquifer thickness when calculating the Mounding associated with water infiltration. Because aquifer thickness can easily be measured. The horizontal hydraulic conductivity is often measured by conducting an aquifer test [142].

H.2.2. Specific Yield

The specific yield indicates how much water the unsaturated zone can store. Specific yield is related to the porosity of a soil, more specific, the void space of a soil. Only not all void space can be used for water storage because water adheres to grains of sediment, called specific retention, and reduces the amount of storage during the recharge event. Thus the specific yield is the total porosity minus the specific retention. Specific yield and specific retention are often expressed as percentages [142].

The porosity can be determined based on desktop study or field measurements, for this see the fieldwork manual B. Based on the present soil types the specific retention can be determined from literature.

H.2.3. Recharge

The recharge of the aquifer or groundwater depends generally on infiltration, storage of the ground and evaporation and transpiration. Typically most precipitation does not become recharge. It is stored in the soil zone and eventually leaves via evaporation or plant transpiration. Recharging of the ground water can occur in response to individual precipitation events in places with shallow water tables [195]. For the mounding analysis the constant infiltration rate and recharge rate are assumed to be the same. Neglecting the evaporation and transpiration effects and storage of water in the soil. The assumption is founded on the difference between infiltration of precipitation and centralised infiltration of precipitation via a infiltration cell, and the given that water table levels are relatively shallow in the Cape Flats during the winter.

The constant infiltration rate can be determined via infiltration tests, for this see the fieldwork manual B.

H.2.4. Other Inputs

The other four remaining inputs can be directly measured or determined via a desktop study. The Basin dimensions, length and width, can be directly measured at the site or determined via LiDAR. For the LiDAR dimension survey see subsection 8.3.3.

The initial saturated aquifer thickness can be obtained by measuring the distance to the groundwater table, for the see B. The Cape Flats aquifer is an unconfined aquifer. Obtaining the thickness of this aquifer at the location can be done via desktop study, this can be done via GIS. Subtracting the distance to the water table from the aquifer thickness will give the initial saturated aquifer thickness.

The duration of the infiltration period can be matched with the duration of a storm event or the required drawdown time.

I

Annual Yield Measurement in Open Channels

To determine the current Annul Yield of a pond one can apply a simple mass balance given that, in this case, the inflow and overflow are known. These can be directly measured by installing measurement devices at the inlet and outlet. In this section the application of the sensor is discussed for open channel flows or flows in big tubes that never fully fill up.

A crump weir should be constructed and placed in the open channel leading to the pond. The sensor should be mounted above the crump weir, see figure I.1.

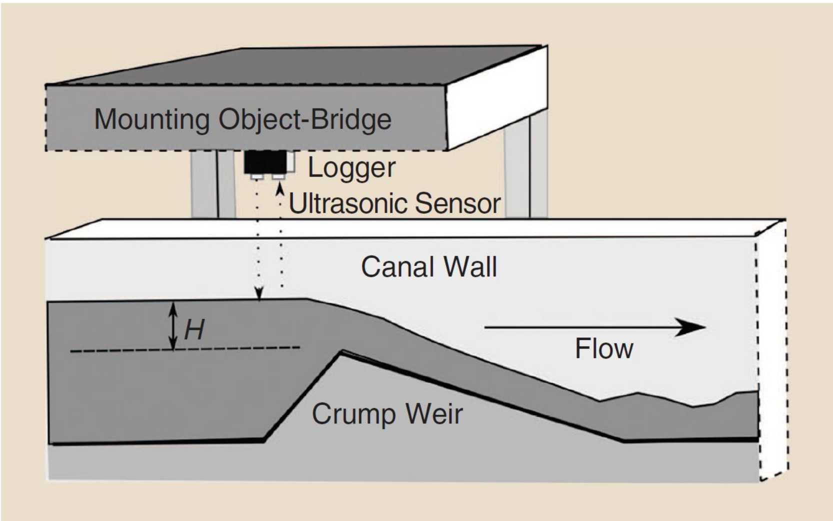


Figure I.1: Ultrasonic level sensor and crump weir setup to monitor the open channel flow

The sensor measures the distance to the water every 6 minutes. The water level over the crest can be calculated by subtracting the measured distance to the water from the known distance between the sensor and the weir crest. With the water level over the weir the discharge can be calculated with the following equation:

$$Q = C_d C_v b g^{\frac{1}{2}} h^{\frac{1}{2}} \tag{I.1}$$

Where:

Q is the flow rate

C_d is the discharge coefficient
C_v is the velocity coefficient
b is the width of the weir
g is the gravitational acceleration
h is the water level above the weir or depth of water above the weir

By multiplying the flow rate, Q, with the corresponding time interval will give the amount of inflow. If this is done for the full year the device is installed one obtains the annual inflow. When a sensor and crest are installed at the outflow the same measurement method can provide the outflow per year. Both inflow and outflow then can give an indication of the current yield of the pond. Only evaporation is neglected, which has a negative impact on the yield.

J

Annual Yield Measurement in Pipes

To determine the current Annul Yield of a pond one can apply a simple mass balance given that, in this case, the inflow and overflow are known. These can be directly measured by installing measurement devices at the inlet and outlet.

A smart low-cost remote-monitoring flow sensor containing low-cost off-the-shelf sonar devices is proposed. These devices are used to gauge river/water height as a proxy for flow rates. The logged data is transmitted to a centralised server in order to facilitate real time data analysis [99]. In this section the application of the sensor is discussed for fully and partially filled pipe flows. First fully filled pipe flow measurement is discussed after which partially full pipe flows are discussed.

J.0.1. Flow Measurement for Full Pipes

The flow measurement for fully filled pipes can be conducted via the Venturi effect [100]. The Venturi effect describes the reduction of fluid pressure that results when fluids passes through a constricted section. Via the pressure difference and other parameters the flow velocity can be calculated. For this a Venturi Tube is needed with a constricted area and two vertical tubes, see Figure J.1. One can use the height difference between fluid levels in vertical tubes to determine the pressure difference between the constricted, location 2, and non constricted, location 1. Thus a part of the tube has to be replaced with a Venturi tube.

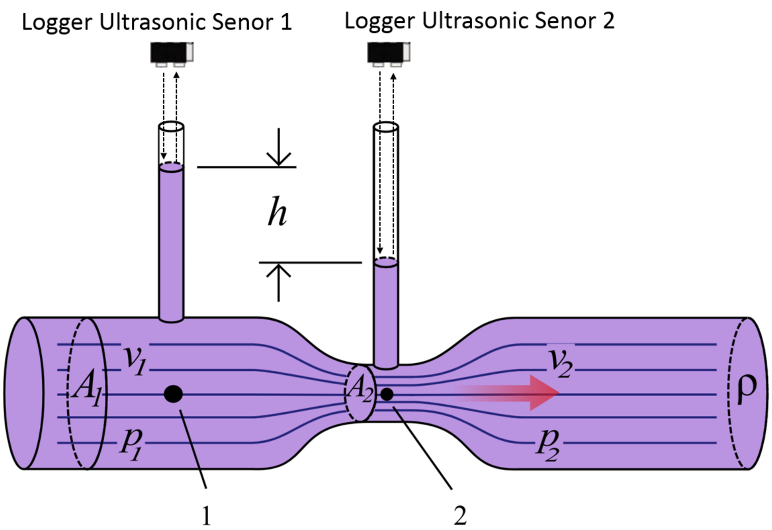


Figure J.1: Ultrasonic level sensors and Venturi Tube setup to monitor fully filled pipe flow, by author

Above the vertical tubes, tube 1 and tube 2, two smart low-cost sensors, sensor 1 and sensor 2, have to be mounted, see Figure J.1. The two sensors can determine the difference between the height of water between the two vertical tubes. The flow velocity can be calculated from the height difference delta H, the areas of the constricted and non constricted part (A_1 and A_2) plus gravitational constant via the following formula:

$$V_1 = \sqrt{\frac{2g\Delta h}{(A_1/A_2)^2 - 1}} \tag{J.1}$$

$$Q = V_1 * A_1 \tag{J.2}$$

Where:

V_1 is the flow speed at location 1
g is the gravitational acceleration
A_1 is the tube surface perpendicular to the flow at location 1
A_2 is the tube surface perpendicular to the flow at location 2
Δh is the distance between the two water levels in the vertical tubes
Q is the flow rate trough the tube

By multiplying the flow rate, Q, with the corresponding time interval will give the amount of inflow. If this is done for the full year the device is installed one obtains the annual inflow. When the amount of outflow at the outlet is also known, both inflow and outflow then can give an indication of the current yield of the pond. Only evaporation is neglected, which has a negative impact on the yield.

J.0.2. Flow Measurement for partially filled Pipes

The flow measurement for partially filled pipes can be conducted via the Manning equations, provided that the flow in the pipe is uniform [101].

The Manning equation can be used for uniform partially full pipe flow calculations, which occurs for a constant flow rate of water through a pipe of constant diameter, surface roughness and slope. Under these conditions the water will flow at a constant depth [101]. The equation for this conditions is:

$$Q = \frac{KAR^{2/3}S^{1/2}}{n} \tag{J.3}$$

Where:

Q is the flow rate
A is the cross-sectional area normal to the flow direction
R is the hydraulic radius (cross-section area divided by wetted perimeter), A/P
S is the slope of the channel at the point of measurement
n is the surface Manning Roughness coefficient
K is the constant dependent upon units, for SI units $K = 1$

The hydraulic radius depends on the wetted perimeter, which in turn depends on: cross-sectional area of flow (A) and wetted perimeter (P), these are calculated in two different ways depending on how full the pipe is. Calculation for situations where the tube is less than half full and calculation for situation where the tube is more than half full. The measurements (m) taken with the low cost sensor can help determine this, m > radius of tube or m < radius of tube . The measurements will also provide the height (h) of the water, for the case of less than half full flow, see Figure J.2, or provide the distance (h) from the water surface to the top of the pipe for more than half full flow, see Figure J.3.

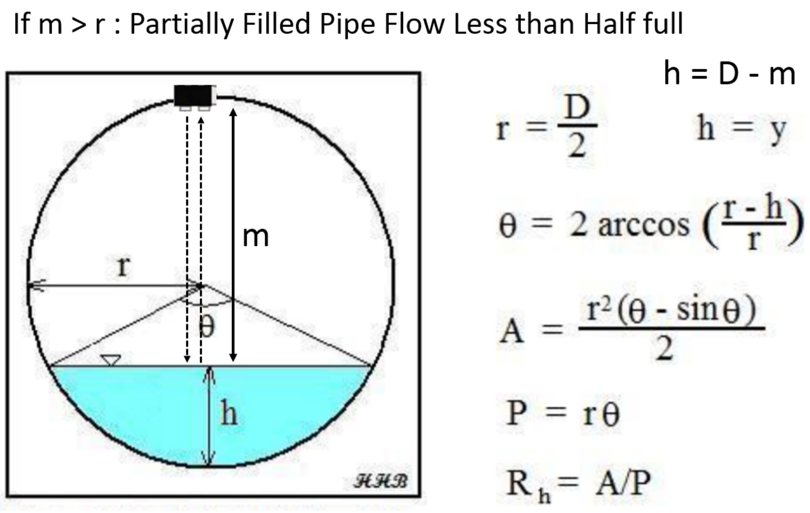


Figure J.2: Equations for A and P for partially full pipe flow under less than half full flow condition, adapted from [101]

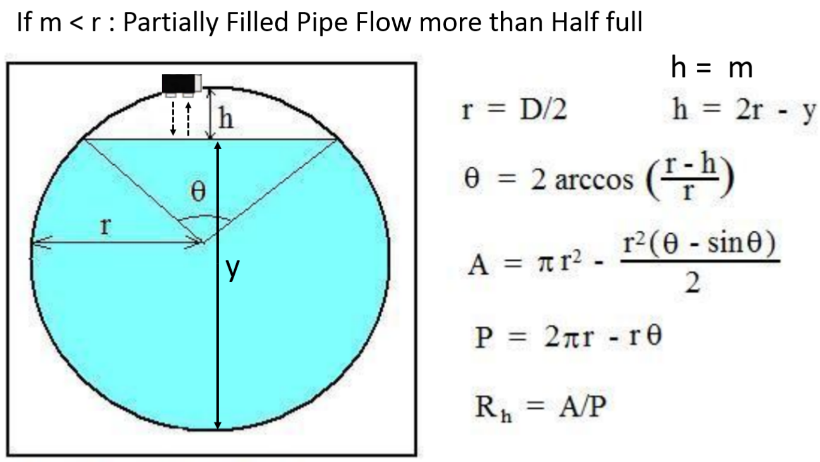


Figure J.3: Equations for A and P for partially full pipe flow under more than half full flow condition, adapted from [101]

By multiplying the flow rate, Q, with the corresponding time interval will give the amount of inflow. If this is done for the full year the device is installed one obtains the annual inflow. When the amount of outflow at the outlet is also known, both inflow and outflow then can give an indication of the current yield of the pond. Only evaporation is neglected, which has a negative impact on the yield.

K

Green Infrastructure Flexible Model

GIFmod is open source and freely available via www.gifmod.com. It contains the distribution package of GIFMod including examples and a detailed manual [154].

K.1. User Guide

This appendix provides an overview of the model's capabilities and a brief introduction to the GIFMOD interface. The capabilities of the GIFMOD are presented in Figure K.1.

GIFMOD Capabilities		
Hydraulic Modelling	water balance equations	Van Genuchten-Maulem (unsaturated flow)
		Darcy Equation (saturated porous media flow)
		Diffusive wave equation (surface water flow)
		Penman model (evaporation)
		Priestly Tailor model (evaporation)
		Aerodynamic model (evaporation)
	use of user defined equations	
	use of evaporation time series	
Particle Transport Modelling	modelling of multiple classes of particles with different transport properties	mobile phase
		reversibly attached phase
		irreversibly attached phase
		attached to air-water interface
	Langmuirian blocking function	
	Exchange rates between phases	
Coupled Dissolved and Particle-associated Reactive Transport Modelling	advective-dispersive transport	dissolved species
		mobile particles
	mass transfer between	aqueous phase
		solid phase (soil/particulate phases)
	user defined biogeochemical transformation processes	Peterson matrix
		Arrhenius equation
		physical parameters (e.g. moisture content, light intensity)
	settling velocities	
Transport Modeling Capability	parameter estimation	deterministic (Genetic algorithm)
		probalistic (Markov Chain Monte-Carlo)

Figure K.1: Capabilities of the GIFMOD, created after [105]

K.1.1. General Approach

Massoudieh et al. [105] gives following general working procedure in their manual:

1. Creating a project in solution explorer and setting (or accept the default values) the basic project options for the analysis.
2. Drawing the visual representation of the GI by using blocks that represent spatial components (e.g. pond, stream, etc.) and connectors (interfaces between the spatial components).
3. Editing of the block and connector properties which together built up the GI system.
4. Adding of time series as well as hydraulic and water quality data.
5. Setting up the water quality component of the model (if water quality aspect included).
6. If parameter estimation intended, set up the define parameters and observed data.
7. Running the model forward (or inverse for parameter estimation).
8. Viewing of the results.

K.1.2. Example Model for Infiltration Basin

In this section it is briefly explained how to create a simple model of an infiltration basin in GIFMOD [154]. The explanation is kept short to provide a quick-start for the program. For a more extensive explanation of the software and all functions and possibilities please read the manual of Massoudieh et al. [105]. In the following short manual the numbering refers to Figure K.2:

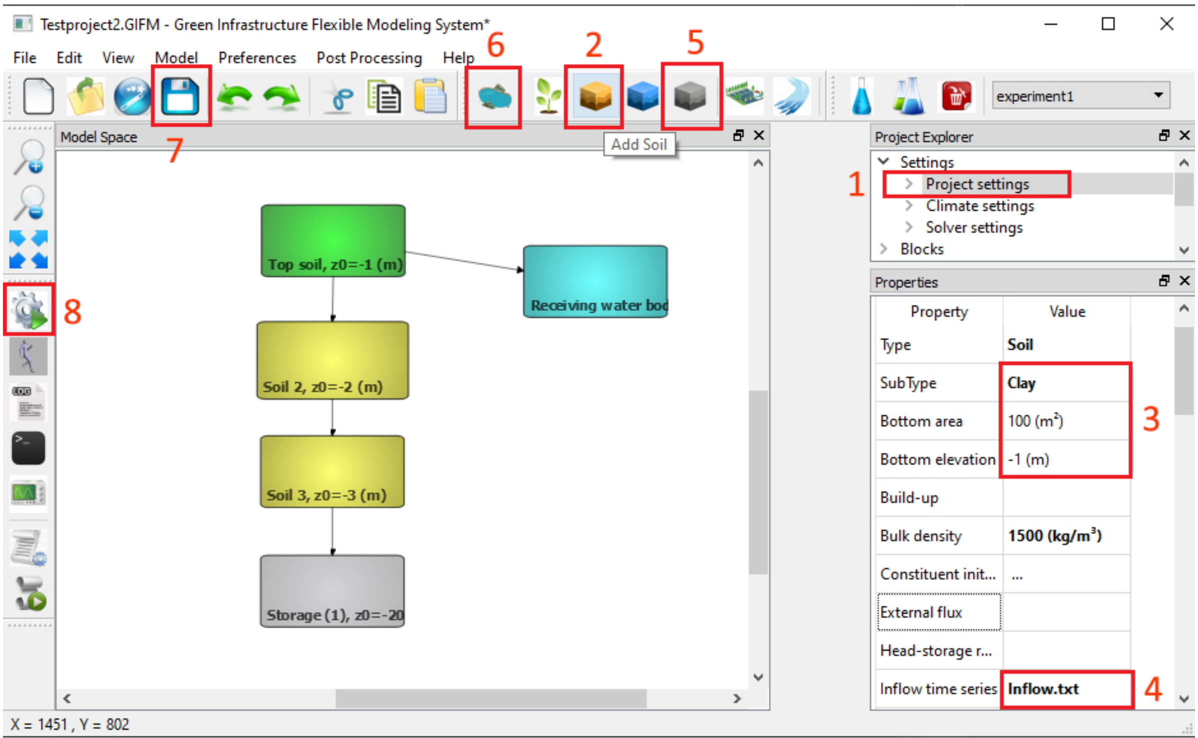


Figure K.2: User interface and simple hydraulic model example of an infiltration basin in GIFMOD [154]

1. Click on project settings and define the model duration in the 'properties'-window by clicking on 'simulation end time' and choosing an end date of the simulation. The actual date does not matter, the program will use the amount of days between start and end. Furthermore, check if 'Perform mass balance check', 'Perform particle transport simulation' and 'Perform water quality solution' are checked with 'Yes' if desired.
2. Click on 'Add Soil' and place one or more soil layers in the canvas and link them by drawing connectors between them. Connect the new block with the existing blocks by drawing a line between them. Adjust

the flow type (pipe, darcy, rating curve, etc.) and other settings of the connector under 'properties'.

3. Click on the soil layers and define the soil type, bottom surface, bottom elevation, depth of the block. By defining the soil type, saturated hydraulic conductivity and other soil specific parameters are automatically filled in. It is also possible to use user defined soil types.
4. Add an inflow time series. This must be a data with the'.txt' format with comma delimited entries for time step and inflow. Examples for inflow time series can be found in the example repository of the software.
5. Add a storage block if wished and adjust its settings in the 'properties' window. Connect the new block with the existing blocks by drawing a line between them. Adjust the flow type (pipe, darcy, rating curve, etc.) and other settings of the connector under 'properties'.
6. Add a receiving water body in form of a pond (or a stream). Add a connector and adjust the settings for the spatial elements (pond and connector) within the 'properties'-window as in the step 5.
7. Save the project
8. Run the project and right-click on the spatial element to see the model outputs 'Plot inflow properties' or 'Plot Hydraulic Results'. If errors occur check the 'log file' and correct the red entries under 'properties' of the spatial elements and connectors. If a water quality model is included those outputs can be checked in the same way, however a more extensive input file is required and 'Particles' and 'Reactions' have to be defined in the 'Project Explorer' under 'Water quality'. For an explanation of how that works, please read the GIFMOD manual of Massoudieh et al. [105].

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GIFMod groundwater recharge simulation

This Appendix reports on the set up of a stormwater pond and infiltration pond model. Both used to simulate the groundwater recharge over a period of 14 months. These models were made to demonstrate the potential of GIFMod to model specific Green Infrastructure and to simulate infiltration and groundwater recharge, in this context a stormwater detention pond with clay lining and an infiltration pond with a sand top soil. For a general introduction and GIFMod user guide refer to Appendix K.

L.1. Rain garden model

The model has been based on one of the worked-out examples on the GIFMod site [154]. The model futures a rain garden which can drain directly into the receiving water or indirectly via an underground storage. Figure L.1 shows the model in the GIFMod interface.

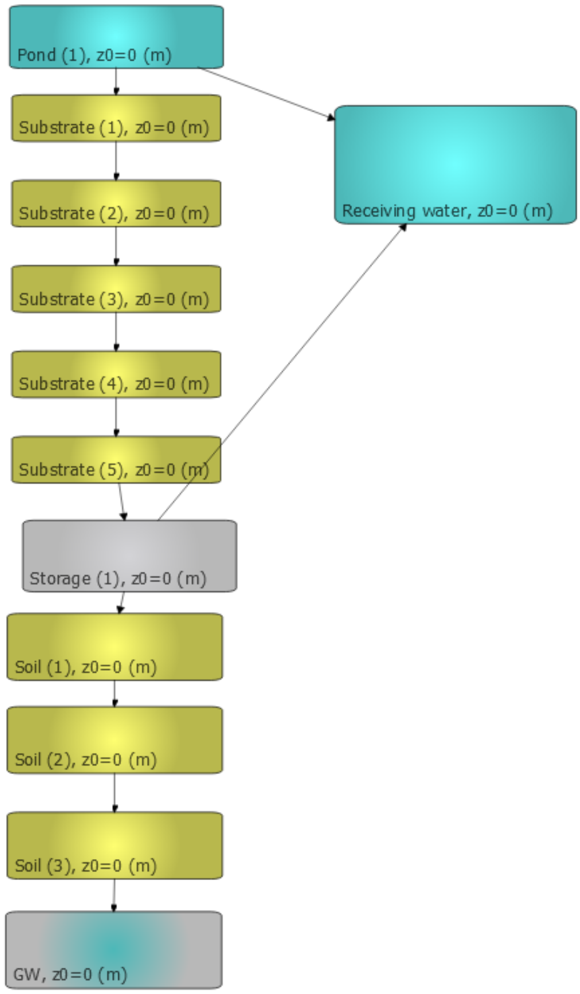

Figure L.1: GIFMOD raingarden model, created after [154]

L.2. Changes to model to make a stormwater pond model

A catchment with an area 300 m^2 which drains to pond at height 0.7 m through a pipe with diameter 0.2m was added. Note bottom of the pond is at height 0m. Secondly, the underground storage space was replaced by a soil layer, called Soil z0. The underground storage space drain to receiving water was removed. Thirdly the drain from Pond(1) to receiving water is lowered, with an begin height of and the diameter changed to 0.05 m. Lastly the following soil types are assigned to the layers. Substrate 1 = clay, Substrate 2 = clay, Substrate 3 = clay, Substrate 4 = sandy loam, Substrate 5 = sandy loam, Soil z0 = Sand, Soil 1 = Sand, Soil 2 = Sand and Soil 3 = Sand. Figure L.2 shows the storm water pond model in the GIFMod interface.

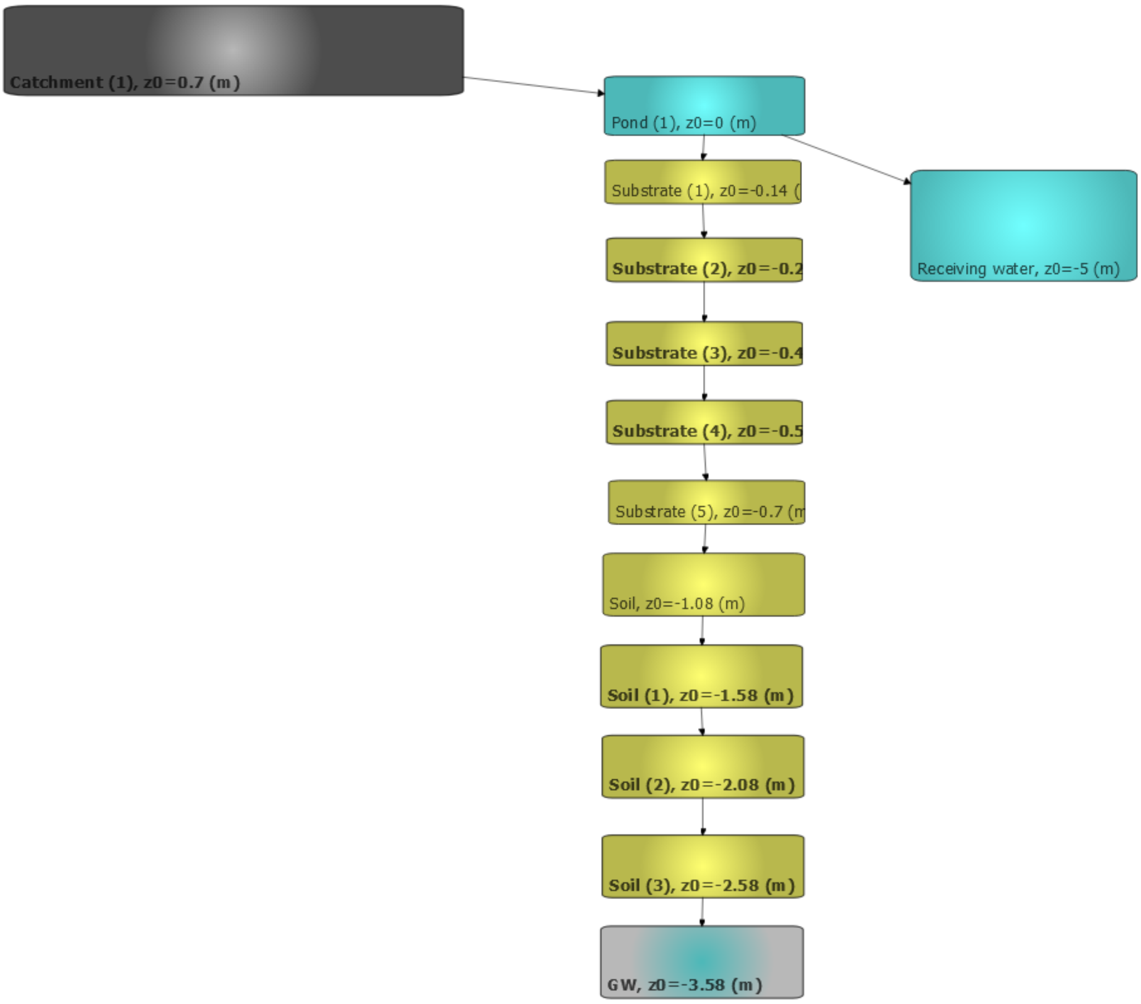

Figure L.2: GIFMOD stormwater pond model

This model resembles a stormwater pond with a bottom area of 354.52 m^2 and clay lining up to -0.4 m (0.4 meters below the pond surface). The pond receives direct water via inflow time series Inflow.txt and from a catchment area of 300 m^2 which also receives water directly via inflow time series Inflow.txt. Furthermore, the pond follows an evaporation via the Evaporation.txt time series. Besides the clay lining the low elevated outflow pipe with a diameter smaller than the inflow pipe is characterising for a stormwater detention pond.

After running the model to simulate 14 months the flow from Soil(3) to Gw (Groundwater) was plotted, recharge of the groundwater. Acquiring the simulated infiltration was done by plotting the flow from Pond(1) to Substrate(1). The flow plot of Soil(3) to Gw is presented in subsection 7.3.5 under Annual Yield Calculation: GIFMod.

L.3. Changes to model to make an infiltration pond model

The Stormwater pond model was changed in the following ways to model an infiltration pond. Firstly the soil types of layers: Substrate 1, -2 and -3 have been changed to sand. Secondly the outflow pipe height to the receiving water has been increased from 0.05m to 0.6m. No figure of the model is included as the graphical GIFMod interface representation does not deviate from the stormwater pond model, see Figure L.2.

This model resembles an infiltration pond with a bottom area of 354.52 m^2 and no clay lining up to -0.4 m (0.4 meters below the pond surface) but a sand substrate. The pond receives direct water via inflow time series Inflow.txt and from a catchment area of 300 m^2 which also receives water directly via inflow time series Inflow.txt. Furthermore, the pond follows an evaporation via the Evaporation.txt time series. A high elevated outflow pipe at 0.6m allows the pond to fill up and empty its content as infiltration or lose it as evaporation.

Again the model was used to simulate 14 months and the flow from Soil(3) to Gw (Groundwater) was plotted, recharge of the groundwater. Also acquiring the simulated infiltration was done by plotting the flow from Pond(1) to Substrate(1). The flow plot of Soil(3) to Gw is presented in subsection 7.3.5 under Annual Yield Calculation: GIFMod.