Hybrid Water Supply Systems and Conjunctive Use in the Context of Water Sensitive Settlements:

A Case Study of Sekhukhune District Municipality, Limpopo Province

Report to the
Water Research Commission

by

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EXECUTIVE SUMMARY

BACKGROUND

Water crises rank among the top five global risks that pose the highest concern as well as having the greatest impacts in terms of the quality of life and community development. Conventional and centralised water supply systems are either too stretched to meet the demand or inaccessible by the most vulnerable segments of the population who are in rural, peri-urban or informal settlements. As water demands approach the total renewable freshwater availability, each drop of freshwater gets increasingly valuable, hence the need for efficiency and intensity in its management. Given that demand will but continue to increase, there is therefore a need for innovative supply and demand management to achieve economic, environmental and social sustainability. To meet the demand gaps, there is need to develop robust tools to deliver on the alternative, but suitable sources of water sustainably. This can be achieved through a mix of centralised and decentralised water supply systems as well as a mix of conventional and alternative water sources to meet water demand loads sustainably. The mix is referred to as hybrid water supply systems and is situation-dependant, hence it varies from one settlement to another. The tenets of the hybrid water supply and management systems are anchored in the principles that define the Water Sensitive Urban Design (WSUD) and Sustainable Drainage Systems (SuDS). The Water Sensitive Urban Design (WSUD) Framework and Guidelines for South Africa, incorporating the Sustainable Drainage Systems (SuDS), was put in action in 2014. WSUD and SuDS are still new concepts in South Africa and therefore efforts to operationalise WSUD and SuDS require research components to normalise it through the **4Ts** namely, the ongoing development of **T**ools that include manuals, guidelines, etc.; **T**ransfer of knowledge to appropriate officials; application of **T**actics for encouraging WSUD implementation, for instance developing new policies; and **T**esting through trials, for instance pilot studies, small scale developments, etc. The 4Ts are currently work in progress through various studies.

The assumption made in the one source, one system, and one discharge approach is that all water should be treated to the drinking/potable water standard regardless of the purpose for which it will be used (human consumption, industrial use, agriculture, or garden and park watering). This is an inefficient use of money, energy, and water. Matching water quality to its intended function is the future in many cities, and the present in some. For instance, the concept of water that is fit to a purpose has been implemented in the city of Durban, South Africa, to respond to a conflict between water demand for domestic use and economic development under conditions of water scarcity. The eThekwini Water Services developed a strategy to recycle wastewater as an additional water source for industrial use. At operational capacity, the reclamation plant meets 7 percent of Durban's water demand and reduces the wastewater discharge by 10 percent. As a co-benefit, industrial customers reduce their costs by purchasing reclaimed water rather than high-quality, potable water. Further to the fit for purpose water use, a diversity of solutions also is seen to provide flexibility. If water is scarce, then stormwater, greywater, and even wastewater are potentially economically attractive sources.

In the current paradigm shift in water supply and management systems, a high priority is given to the study of alternative water supply which includes the use of centralised water supply system and decentralised water supply system, hybrid water supply systems. Water reclamation and reuse is a well-known practice for creating additional water supplies and, thereby, increasing the security of supply of urban water supply system. Factors affecting the selection of the optimum approach include local hydrology, available water supplies, water demands, local energy and nutrient-management situations, existing infrastructure, and utility governance structure. It is reported that the integration of centralised and decentralised water supply and wastewater management along with water reclamation and reuse, distributed water treatment, and rainwater harvesting, the potential for increased urban water system security and sustainability can be offered. Implementation of these new approaches to urban water and resource management can lead to sustainable solutions, financial stability, using local sustainable water supplies, energy-neutral, responsible nutrients management, and access to clean water and sanitation.

Water supply systems (urban water cycle) are one of the energy consumers in the service delivery cycle, yet there is very little indication in the current literature that the water energy nexus (WEN) has received due attention, especially in the design of rainwater harvesting systems. In most cited instances, water supply systems and energy supply systems have frequently been managed separately. The current attention drawn to WEN has been prompted by the increasing significance of water security, energy efficiency, and economic feasibility of water supply systems. With reference to RWHS and any other water supply system, WEN is increasingly recognised as a principal factor for planning in water resources utilisation and -management. The complex interdependency between water and energy positions new challenges for resources.

Energy consumption and Greenhouse gas emissions (GHG) resulting from setting up a rainwater harvesting systems require that indicators of the extent of Energy Use Potential (EUP) and Global Warming Potential (GWP) be incorporated in the design of rainwater harvesting systems. Rainwater harvesting systems benefit the end users in mitigating water shortages as well as providing an alternative source of water in the hybrid water supply system. However, and inevitably, rainwater harvesting systems, like any other water supply system, accrue adverse impacts that relate to increased consumption of energy. With an increase in population and a consequent increase in water demand, these impacts are bound to increase over time. Planning for the remediation and monitoring of such impacts is therefore integral in the design process of a rainwater harvesting system. Many of the rainwater harvesting systems are designed without taking the factors of energy into consideration. This is a critical gap that needs to be addressed and must therefore be considered in the developed set of frameworks for the rainwater harvesting system.

An integrated rainwater harvesting system design requires the inclusion of WEN as an integral component of the design. In the current documentation on the design of rainwater harvesting systems, there is limited integration of WEN in the design process. Therefore, there is a need to develop a rainwater harvesting system (RWHS) design framework that incorporates WEN and Environmental Risk Scores (ERS). For flexibility in application, the developed generalised domestic rainwater harvesting potential and rainwater harvesting systems selection framework should be characterised as applicable in a range of scenarios, scales, and regions. A subcomponent of the generic framework should then incorporate the WEN analysis as well as the ERS analysis. In this way, a comprehensive RWHS that is not only optimal in process operation and costs, but also environmentally friendly, can be designed. The ERS are derived through an analysis of the contribution of RWHS facilities or components such as HDPE tanks used for storage of harvested rainwater in the release of carcinogens and/or respiratory organics and Greenhouse gas emissions. The use of water treatment chemicals and the potential hazards posed by the treatment residues to the environment are other examples of environmental risks posed by the implementation of a RWHS. The Risk Score is a product of Likelihood of occurrence and Level of impact (ERS = Likelihood of occurrence x Level of impact). The ERS can then be ranked to prioritise the respective risks.

Differentiating stormwater harvesting from rainwater harvesting has been a matter of debate for many years. The main point of departure throughout is the location of capture and point of use. In most literature, stormwater harvesting is depicted as a process that entails the collection, treatment, storage, and use of stormwater runoff from pervious or impervious surfaces. In contrast, rainwater harvesting, in most literature, is considered to be the direct capture of rainwater, mainly from rooftops and onsite (household) point of use. Stormwater harvesting, and reuse is considered a critical tenet of stormwater management. Stormwater harvesting offers an option in the realm of an integrated and sustainable urban water management and can provide multiple benefits/outcomes that include inter alia: (i) flood protection, mitigates flood impacts, and erosion control; (ii) enhancement of urban stream health through the physical abstraction of the contaminated water, a process that improves the flow regime by alleviating the probable deterioration of water quality in the receiving waters (both surface and groundwater resources); (iii) attain and protect natural waterways *in-situ*; (iv) reduces the need to construct new supply development; (v) supports local community values and enhances public amenity and lifestyle values; and (vi) provides an alternative water source fit for compatible end uses.

Stormwater management should be both safe and sustainable by supporting a socially and environmentally responsible use of the harvested stormwater, in which case it would imply the management of both quantity and quality of stormwater in a manner that meets the present needs without compromising the future needs, thus attaining a balance between economic costs, environmental gains, and societal resilience.

Captured stormwater requires a level of treatment depending on the intended end user requirements. Low impact development (LID) and traditional development are two typical configurations of treatment trains that meet the definition of stormwater treatment trains currently utilised by site designers. LID, also referred to as hydrologic source control, endeavours to retain the site's pre-development (pristine) hydrologic regime. This is attained by a combination of impervious area controls with small-scale stormwater Best Management Practices (BMPs), consequently reducing the wet weather flows and the associated nonpoint source pollution (NPSP) and the subsequent stormwater treatment needs. LID systems and practices imitate natural processes that result in the infiltration, evapotranspiration or use of stormwater in order to protect water quality and associated aquatic habitat. They create functional and appealing site drainage that treat stormwater as a resource rather than a waste product. Several practices that adhere to these principles include, but not limited to, rain gardens, bioretention facilities, rain barrels, vegetated rooftops, and permeable pavements. Traditional development typically employs filtration and sedimentation practices such as swales and constructed ponds and wetlands. These practices may or may not treat rainwater close to its source but generally have minor impacts on stormwater volume. Where feasible, LID practices are favoured from a stormwater management practice as they reduce both stormwater volume and pollutant loading. LID practices, however, are often constrained by site factors, such as the existing soil profile (depth to bedrock – depending on whether shallow or deep, this has an impact on infiltration of stormwater and therefore the objective of stormwater volume management is dependent on this as a factor); soil or groundwater contamination (either from agricultural activities, waste disposal, mining or any other economic activity that has an impact on the soil properties and quality of the groundwater – this will impact on use of stormwater for groundwater recharge purposes for example); and space limitations (economic development growth nodes / corridors pose a challenge in developing LID systems, fast expanding urban and peri-urban spaces also pose a challenge in LID systems development).

A combination of LID and traditional BMP (aggregate LID-BMPs) yields the concept of Green Infrastructure (GI). This combination is necessary when developing stormwater treatment trains for larger regional and landscape scales as it provides opportunities to augment the advantages of LID with those of traditional BMPs. As part of the implementation of Water Sensitive Urban Design principles, applications of a combination of Low Impact Development (LID) and Green Infrastructure (GI) have gained traction over the overall sole implementation of traditional stormwater management systems. At both the site and regional scale, LID/GI practices aim to preserve, restore and create green spaces using soils, vegetation, and rainwater harvest techniques.

Given the complexities involved in stormwater management of quantity (volumes), and quality, and with the need to keep environmental sustainability, the systems put in place need to be both reliable and sustainable. There is therefore a need for a well laid-out framework for the harvesting and treatment of stormwater. The framework ought to outline the requirements to identify, select and set up a combination of processes and procedures that translate to a stormwater treatment train. The treatment train being a combination of Best Management Practices (BMPs) and LID systems. In combination to this framework, and for the purposes of reliability and sustainability of the system, there is also a need to develop a framework for monitoring the progress of a stormwater treatment project. A key parameter in this monitoring framework is the Social Indicators (SI). Social indicators for Non-Point Source (NPS) management provide information about awareness, attitudes, constraints, capacity, and behaviours that are expected to lead to water quality improvement and protection.

Good quality surface and groundwater resources are limited in many water management areas, including the Sekhukhune District Municipality (SDM). The water resources are also diminishing due to urbanisation, contamination, and impacts of climate change. On this premise, proper allocation and management of these resources is a critical challenge for satisfying the rising water demands of the SDM. Previous studies in SDM have suggested the conjunctive use of groundwater and surface water resources as an alternative management option in efficient allocation and utilisation of the available water resources in the district. Conjunctive use refers to a coordinated and planned use of surface and groundwater. Literature suggests that it is now recognised that reclaimed wastewater is a water resource developed right at the doorstep of the urban environment. This implies that in a typical contemporary watershed, there are three recognised water resources for water supply, *viz* (i) surface water; (ii) groundwater; and (iii) reclaimed wastewater. Hence in a collective manner, conjunctive use could be referred to as a coordinated and integrated management and wise use of these water resources.

Urban water use through conjunctive use of water from different sources adds a new dimension to the usage and management of water resources as compared to single source use of water. The augmented dimension requires that a set of decisions need to be made at both the application level and the water resource level to enable water users to make the best possible use of all available water. Making such informed decisions requires a set of management tools that can be provided via models such as conjunctive use water management models. Conjunctive use models are developed based on the purpose and objective as well as the technique used. Such models may take different forms, for instance (i) simulation-optimisation models; (ii) simulation and prediction models; (iii) dynamic programming models; (iv) linear programming models; (v) hierarchical optimisation; (vi) nonlinear programming models, and others.

Sekhukhune District Municipality is mainly a rural district with 117 wards and a total of 764 villages. The District is made-up of four Local Municipalities, namely Elias Motsoaledi, Ephraim Mogale, Makhuduthamaga and Fetakgomo Tubatse. The main towns in the district being Burgersfort, Steelpoort, Groblersdal, Marble Hall, Apel, June Furse, Mohlaletsi, Driekop, Penge Mine, Prakiseer, Motetema and Mosterloos. Forty-six percent (46%) of the total area of the SDM is State-owned land (46% of SDM is designated as Municipality Area). Forty-eight percent (48%) is designated as Traditional Authority Area (Department of Rural Affairs and Land Reforms – DRDLR, RSA, 2019). The Traditional Authority Area is made up of villages that are scattered throughout the area. Therefore, providing centralised service delivery is quite a challenge to the municipality. The implication therefore is that service delivery systems are distributed. By extension, development of stormwater and on-site domestic rainwater harvesting systems is also distributed.

As noted in the SDM Development Plan 2021, 10.26% of the households in the district have piped water inside the dwelling; 38.82% of the households in the district have piped water inside the yard; 17.88% of the households in the district have access to communal piped water at RDP-level of service that is less than 200 metres from their dwelling; 16.40% of the households in the district have access to below RDP-level of service of communal piped water located more than 200 m from their dwelling; and 16.64% of the households have no formal piped water. These statistics translate to approximately 33% of households in the district living in below RDP-level service to no service at all that require alternative sources of potable water. This scenario presents an opportunity for the district to explore the on-site domestic rainwater harvesting and stormwater harvesting systems as alternative water supply sources for domestic use.

Sekhukhune District Municipality is an agricultural district hence emphasis is also put on irrigated agriculture. Good quality surface and groundwater resources are limited in SDM. Therefore, proper allocation and management of these resources is a critical challenge for satisfying the rising water demands of the SDM. Previous studies in SDM have suggested the conjunctive use of groundwater and surface water resources as an alternative management option in efficient allocation and utilisation of the available water resources in the district.

This study aimed to develop a set of critical frameworks for hybrid water supply systems that are generic in nature but utilise information for Sekhukhune District Municipality and literature as the basis/functional units of the study. The frameworks developed include the following: a generalised domestic rainwater harvesting potential and rainwater harvesting systems selection framework; framework of water energy nexus (WEN) analysis for a rainwater harvesting system; global warming potential (GWP) analysis framework; and a framework for developing stormwater harvesting systems and monitoring. A Mathematical model for conjunctive use of surface water and groundwater in the SDM was also developed and tested.

Aims:
The following were the aims of the project:
1. To conduct a comprehensive desktop study on hybrid water supply systems in the context of Water Sensitive Settlements and Water Sensitive Urban Design Framework of South Africa
2. To formulate a plausible framework for rainwater harvesting potential and rainwater harvesting systems selection
3. To develop a framework of rainwater energy nexus (RWEN) analysis for a rainwater harvesting system
4. To develop a global warming potential (GWP) analysis framework of a rainwater harvesting system
5. To formulate a plausible framework for developing stormwater harvesting systems and monitoring; and
6. To develop a numerical model to test the potential of conjunctive surface water and groundwater use in Sekhukhune District Municipality.

METHODOLOGY

Scoping for the project provided a comprehensive literature review on hybrid water supply systems and conjunctive water use. Highlights on the challenges and opportunities were identified and documented. In the literature review, a three-prong approach was followed in obtaining the relevant information, viz., (i) current information on the global scale regarding the water situation expressly the urban water cycle was provided. The information collates, probable scenarios of the urban water including the predictions on the resilience of our global urban water supply systems to climate change; (ii) information on water supply systems from the conventional centralised systems to the decentralised systems. Additionally, information on the current paradigm shifts in municipal water supply that combines both centralised and alternative water supply systems that define the Hybrid Water Supply Systems is highlighted. The advantages, disadvantages and challenges of the various systems are also outlined; (iii) information on Conjunctive Use of Groundwater and Surface Water Resources in general is also provided. A case study on the feasibility of utilising groundwater as a major water resource is also outlined where the outcome of the study show that it is feasible to include groundwater as a reliable resource albeit with quality concerns. The section also briefly outlines the pertinent tenets of the conjunctive use of groundwater and surface water in general as well as the probable models that could be applied in the conjunctive use study.

In formulating a plausible framework for rainwater harvesting potential and rainwater harvesting systems selection, a summary and a review of hybrid water supply systems was done. The review touches on past, contemporary, and expected futures of water supply systems and the trends of hybrid water supply systems at the local, regional and global scales. It concludes by highlighting the water service delivery scenario (access to water) in the Sekhukhune District Municipality (SDM) and the need for developing alternative water supply systems such as rainwater harvesting and stormwater harvesting. The review recaps on the need for alternative water supply systems in SDM and deals with an overview of the various components of the domestic rainwater harvesting feasibility analysis inter alia the physical, economic/financial, environmental and social aspects. It further discusses the feasibility studies that have been recorded in recent literature with respect to domestic rainwater harvesting. The information gathered therein is then collated to develop a generalised domestic rainwater harvesting potential and rainwater harvesting systems selection framework. The insight into the development of the framework is based on information analysed for the Sekhukhune District Municipality (SDM). The developed framework is however generalised and can be applied in a range of scenarios, scales, and regions. At this stage of the report, it was difficult to obtain the requisite data in form, quantity and quality to evaluate the rainwater harvesting potential in quantity as a case study to verify the implementation of the framework. However, the tenets of the framework are based on sound literature review, desktop study and anchored on verifiable solid theoretical background.

The interdependence between water and energy use in the urban water cycle is strong. In the Water-Energy Nexus (WEN), water supply systems (water cycle) is one of the energy consumers in the service delivery cycle. Energy consumption and Greenhouse Gas (GHG) emissions resulting from setting up a rainwater harvesting system requires that indicators of the extent of Energy Use Potential (EUP) and Global Warming Potential (GWP) be incorporated in the design. In estimating the energy use potential of an anticipated rainwater harvesting system (RWHS), it is imperative to draw parallels to other WEN systems that have been used, especially in developing systems for the urban water system. Following up on this development and as a suggested input in the multi-criteria framework for the selection of an optimal RWHS, the framework for the rainwater-energy nexus, herein referred to as RWEN, is adopted from the body of knowledge of the works of previous studies in the field. Energy intensity (EI), being the unit of energy per unit of water, can be used as a key parameter for assessing the environmental feasibility of different RWHS. The use of EI as a key parameter/indicator for environmental and economic feasibility of designated RWHS is based on its hybrid characteristics in quantifying the energy flows of a water supply system. EI combines the top-down and bottom-up approaches to give a combined quantitative analysis of energy flows of a respective water supply system, i.e. conventional urban as well as rainwater harvesting water supply system energy flows.

There is an established strong correlation between EI and GHG emission, an indicator of GWP analysis for water supply systems. There are several methods of estimating GWP (gCO_2/kWh). For this study, adoption of the International Financial Institutions Technical Working Group on Greenhouse Gas Accounting (IFI TWG) Default Emission Factors is suggested. IFI TWG has developed a set of default values for energy intensity factors for sourcing, conveyance, various treatment technologies, and distribution of water supply systems. The default values are recommended for use in instances where reliable and accurate local data are not available and/or not updated for use in the GHG analysis for any given water supply project. A typical case for this study. The provided default energy intensity information by the IFI TWG, though specific for conventional water supply systems, may be customised and adopted for domestic rainwater harvesting systems. It is a living document maintained by the IFI TWG. Country/region-specific harmonised IFI default grid emission factors is provided as Appendix A of this document. The instructions on how to use this document is provided as Appendix B of this document. The methodologies used to arrive at the information in Appendix A is available as Appendix C of this document.

The social and economic acceptance of any project and/or system cannot be understated. In this framework, an index referred to as the Socio-economic acceptance index (S-eI) is suggested as one of the key parameters of the RWHS selection framework. To obtain this index, a survey of the social perception with regards to the possible uptake of rainwater harvesting as either a primary or secondary source of water needs to be conducted. This element is critical in analysing the probable success of implementing a domestic rainwater harvesting system especially at the envisaged scale. S-eI is developed from a combination of data analyses, based on responses to selected pertinent leading questions such as (i) Is rainwater source a necessary need or an option to be foregone? (ii) is rainwater a dignified source or of lower-grade in comparison to piped water? (iii) is there trust or confidence in the fidelity of the quality and value of rainwater, treated or otherwise? (iv) is there deliberate willingness to adopt RWHS? (iv) is there political will, a deliberate effort to disseminate information or conduct public awareness on the benefits of RWH as an alternative and dignified fit-for-purpose source of domestic water supply? (v) are there set out guidelines, a deliberate move by authorities at all tiers of government (local, regional, and national) to mainstream RWHS as part of the whole with respect to water service delivery?

In the formulation of a framework for developing stormwater harvesting systems and monitoring, the following tasks were completed. Firstly, a review of relevant literature on stormwater harvesting and reuse and some existing case studies of stormwater harvesting and reuse was done. In the literature review, the key issues addressed were; the quantity and quality aspects of harvested stormwater, the need for stormwater harvesting and reuse, the BMPs, typical impacts of stormwater management, the risks associated with using stormwater, technical tools used in stormwater harvesting and reuse studies, challenges in implementing stormwater harvesting and reuse practices, guidelines, policies, and regulations that are formulated to regulate the stormwater management practices, the social impacts and public perceptions in adopting stormwater harvesting and reuse practices. The formulation of the framework for developing stormwater harvesting systems and monitoring followed the concept of developing a Green Infrastructure (GI). GI is an aggregate Low Impact Development (LID) – Best Management Practices (BMPs) system. This combination is necessary as it provides opportunities to augment the advantages of LID with those of traditional BMPs.

The development of a framework for monitoring progress of stormwater harvesting projects was based on common systems used in evaluating and addressing the quality concerns of the stormwater generated during rainfall/precipitation events. This is commonly achieved through an evaluation of the level of contamination of the stormwater through Nonpoint Source (NPS) Pollutants. As an important factor of an effective monitoring schedule of NPS pollution of stormwater, learning more about your watershed is critical. This can be achieved by setting up a system for using social indicators (SI) to help you plan, implement and evaluate Nonpoint Source (NPS) management projects. Social indicators for NPS management provide information about awareness, attitudes, constraints, capacity, and behaviours that are expected to lead to water quality improvement and protection. The guidelines provided in the developed framework of this study provide a roadmap that consolidates the SIs for NPS pollution management under intended outcomes to achieve set goals of the programme. In using this roadmap, a varied list of SIs can be generated that provide important information for planning, implementing, and evaluating NPS pollution projects. The resultant lists are dependent on many factors among them the nature, location, scale, and severity of the programme.

Urban water use through conjunctive use of water from different sources adds a new dimension to the usage and management of water resources as compared to single source use of water. The augmented dimension requires that a set of operation rules need to be put in place to effectively and optimally operationalise and make informed decisions at both the application level and the water resource level. Modelling presents a plausible management tools to employ in making such informed decisions. One such modelling tool for making informed water resources management decisions is a conjunctive use water management model. In this study, a simulation-optimisation model for conjunctive use of surface and groundwater resources is developed and applied through a case study of existing reservoirs for Elias Motsoaledi Local Municipality (EMLM). EMLM is one of four local municipalities of Sekhukhune District Municipality. Elias Motsoaledi Local Municipality was chosen for the case study as it has a better-reticulated network among the other local municipalities and could therefore make for a good reference point in setting the ground for development of operational rules for the effective operationalisation of the conjunctive use of water from different sources. The model was derived by coupling the groundwater simulation model with a multi-objective optimisation programming model to develop a supply-demand conjunctive use water resources management model. The developed conjunctive use management tool was used to idealise an appropriate allocation of surface and groundwater resources of the study area.

For surface water, the study considered the streamflow distribution and storage capacity of reservoirs with weighting for the complex nature of the groundwater flow system such as the geology of the subsurface water basin and hydrology of the surface water system. In the groundwater flow system, safe yield, transmissivity, response recovery time and interaction with existing wells were considered.

In optimisation, an optimisation model with the objective function of minimisation of total deficiency was applied. A key assumption in the model is that the initial facilities for water supply are fixed and are not changed with time. The objective function consists of minimising the total water deficiency while satisfying all water demands in the command area.

RESULTS AND DISCUSSION

GENERAL

A Comprehensive literature review on Hybrid Water Supply Systems and Conjunctive Water Use highlighting the Challenges and Opportunities was successfully done. The information gathered therein was then collated to develop a generalised domestic rainwater harvesting potential and rainwater harvesting systems selection framework. The insight into the development of the framework is based on information analysed for the Sekhukhune District Municipality (SDM). The developed framework, however generalised, can be applied in a range of scenarios, scales, and regions. Based on the literature review, an analysis was done of the global and regional case studies that showcase the successes and challenges, the systems used in the quantification of harvested stormwater, their reliability as well as sustainability. A layout of a framework for the harvesting and treatment of stormwater as well a monitoring framework were successfully developed. A simulation-optimisation conjunctive water use model development was successfully achieved. The developed model was successfully applied to one of the four local municipalities in the Greater Sekhukhune District Municipality to appropriate the allocation of surface and groundwater resources of the study area.

CONCLUSIONS

Scoping

A successful scoping of the study was completed through a comprehensive literature review on Hybrid Water Supply Systems and Conjunctive Water Use highlighting the Challenges and Opportunities. The literature review highlighted the following: (i) current information on the global scale regarding the water situation expressly the urban water cycle; (ii) information on water supply systems from the conventional centralised systems to the decentralised systems, and additionally, information on the current paradigm shifts in municipal water supply that combines both centralised and alternative water supply systems that define the Hybrid Water Supply Systems with an outline of the advantages, disadvantages and challenges of the various systems; and (iii) general information on Conjunctive Use of Groundwater and Surface Water Resources.

Domestic rainwater harvesting frameworks

Based on previous studies, a framework for estimating domestic rainwater harvesting (DRWH) potential was deduced. However, as evidenced in the literature review, glaring gaps in the deduced framework were evident in that most of the hitherto proposed rainwater harvesting potential methodologies primarily concentrated on the quantity of the available rainwater. The flaw in this approach is in the focus on the rainfall element with little attention on other important elements of a rainwater harvesting system such as storage, the intensity of usage, economics (economic feasibility), as well as the environment (environmental impact of rainwater harvesting on the catchment hydrology) and socio-economic acceptability of the selected RWHS. In an attempt to address this gap, the authors developed and proposed a revised framework for estimating DRWH potential and selection of optimal RWHS(s). The presented revised framework addresses and incorporates other determinants such as economic potential (through a life cycle analysis – LCA), social acceptance surveys through the inclusion of the Socio-economic acceptance index (S-eI) and additional environmental indicators such as the energy use potential (EUP) and the Global Warming Potential (GWP) that address the ever-growing need of incorporating the water-energy nexus (WEN) as an integral part of the design of a water supply system. Other elements incorporated in the revised framework include the Environmental Risk Scores (ERS). ERS are derived through an analysis of the contribution of RWHS facilities or components such as HDPE tanks used for storage of harvested rainwater in the release of carcinogens and/or respiratory organics and Greenhouse gas emissions. The development of a revised framework for estimating DRWH potential and selection of optimal RWHS(s) is a major contribution of this study. Other major contributions include: the development of the following submodules of the main framework: a framework of rainwater energy nexus (RWEN) analysis for a rainwater harvesting system; and a global warming potential (GWP) analysis framework of a rainwater harvesting system.

Stormwater harvesting systems and monitoring frameworks
A framework for the harvesting and treatment of stormwater as well a monitoring framework were successfully developed. The stormwater harvesting and treatment framework outlines the requirements to identify, select and set up a combination of processes and procedures that translate to a stormwater treatment train. The treatment train being a combination of Best Management Practices (BMPs), either in parallel or in series, with different processes or a singular BMP that exhibits a combination of processes within its structure such as a constructed wetland. In this case, stormwater treatment entails the processes and procedures to remove or contain stormwater volumes from the point of its generation and reduce or eliminate stormwater pollution load. The framework for monitoring the progress of a stormwater treatment project was also developed. A key parameter in this monitoring framework is the Social Indicators (SI). Social indicators for Non-Point Source (NPS) management provide information about awareness, attitudes, constraints, capacity, and behaviours that are expected to lead to water quality improvement and protection. The inclusion of SIs as a submodule of the stormwater harvesting and treatment framework is also a major contribution of this study as it presents an integrated approach to developing sustainable stormwater harvesting systems through the aggregate LID-BMPs system with a monitoring component that sets parameters that monitor progress of stormwater harvesting projects.

Conjunctive water uses modelling of surface water and groundwater resources
A generic simulation-optimisation conjunctive water use model was successfully developed and applied to the EMLM. In the application, optimal solutions to supplies of scarce water resources of Sekhukhune District Municipality have been achieved through the application of the simulation-optimisation approach. The developed conjunctive use management tool has been used to appropriate the allocation of surface and groundwater resources of the study area. The findings illustrate that daily demand can be reasonably met without leading to over-abstraction of groundwater resources by minimum deficient of water supplies of 6150 litres. From the data used, this deficiency is less than 1 percent of total water demand. The performance of the model shows a marked improvement over current experience in a region where water scarcity has peaked to crisis level. The current reliance on surface water is envisaged to linger into the future as optimal water supplies show more improvement in surface water resources over groundwater at a ratio 43:1, which result in healthy aquifer conditions. However, failure to implement the water supply infrastructure maintenance will result in a water crisis, having a severely negative impact on groundwater resources and water services delivery in the Sekhukhune District Municipality. Generally, the developed conjunctive use management tool can be applied to other local municipals in Sekhukhune District Municipality.

RECOMMENDATIONS

Scoping
In spite of a successful collation of a scoping of the study through a comprehensive literature review on Hybrid Water Supply Systems and Conjunctive Water Use highlighting the Challenges and Opportunities, it should be noted that literature, being a constantly changing element of a document, implies that the contents provided in this document is subject to change as and when new or divergent information is available, verified, justified and authenticated.

Domestic rainwater harvesting frameworks
The proposed revised framework for estimating DRWH potential and selection of optimal RWHS(s) is considered a great improvement of the previously deduced framework. It is however not a panacea framework but subject to further improvements even though in its current form it addresses and incorporates critical elements of a comprehensive design of a RWHS. Elements such as the WEN analysis, GWP, EUP, and S-eI that were hitherto treated in isolation have now been enlisted as key parameters of design and selection of a RWHS. At this stage of the report, it was difficult to obtain the requisite data in form, quantity and quality to evaluate the rainwater harvesting potential in quantity as a case study to verify the implementation of the framework. However, the tenets of the framework are based on sound literature review, desktop study and anchored on verifiable solid theoretical background. It is recommended that case studies in conjunction with a

set of comparative studies should be conducted to evaluate the robustness of the proposed revised framework. The results obtained thereof should then be used a verifiable yardstick to endorse and/or improve the proposed revised framework. An envisaged challenge is to obtain the requisite data in form, quantity and quality to evaluate the rainwater harvesting potential in quantity.

Stormwater harvesting systems and monitoring frameworks

For the aggregate LID-BMPs system developments, studies on cost effectiveness of stormwater treatment trains need to be conducted as there is currently a dearth of information in this regard. The current practice in costing estimation is based on estimation of OPEX and CAPEX of individual BMP practices and processes within a given stormwater management treatment train. However, a system that interrogates multiple stakeholder priorities needs to be put in place. There is need to develop multi-objective-multi-criterion decision-making aid tools for the implementation of SWH systems. Suggested costing comparison studies should consider a holistic approach in which the following are addressed:

- the cost through the life cycle of the BMPs;
- the cost through comparisons of the economy of scale;
- the cost through a comparative analysis of the cost of retrofit versus installation of BMPs in new construction projects; and
- the full cost of the project considering CAPEX, OPEX, cost of land, design, permitting, and contingency in terms of climate action (global change versus climate change).

There is need for conducting case studies to develop a critical body of knowledge that enhance the application of the suggested framework as a stormwater management tool at the watershed scale as well as make improvements on the parameters identified in the framework.

Singular application of conventional stormwater management systems for environmental protection in a treatment train has a higher probability for failure if the resource managers and system designers do not analyse and address all the alterations to flow regimes resulting from storm conventional stormwater drainage systems.

Conjunctive water uses modelling of surface water and groundwater resources

The developed conjunctive use management tool can be applied to other local municipals in Sekhukhune District Municipality. However, reliable and continuous data may be an impediment in many of the local municipalities due to a lack of funding and technical skills for implementation of efficient groundwater and surface water monitoring networks. Future planning and budget allocation should therefore make provision for this risk. The current model is developed for conjunctive use of surface water and groundwater only. However, with the availability of “new tap” water sources such as rainwater harvesting, stormwater harvesting, water conservation and demand management, etc., the appropriation rules will definitely change and new modules will need to be added to the model to accommodate the “new tap” water sources.

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS & ABBREVIATIONS

ADWG:	Australian Drinking Water Guidelines
AHP:	Analytical Hierarchy Process
APDR:	Area Precipitation per Demand Ratio
ASAL:	Arid to Semi-Arid Land
ASR:	Aquifer Storage and Recovery
ASTR:	Aquifer Storage Transfer and Recovery
BCR:	Benefit-Cost-Ratio
BMP:	Best Management Practices
BOD_5:	5-day Biochemical Oxygen Demand
CAPEX:	Capital Expenditure
CFU:	Colony-Forming Unit
CN:	Cycle Number
COD:	Chemical Oxygen Demand
CoJ:	City of Johannesburg
CPI:	Corruption Perception Index
CSP:	Concentrated Solar Power
DEF:	Default Emission Factors
DF:	Dilution Factor
DRDLR:	Department of Rural Affairs and Land Reforms
DRWH:	Domestic Rainwater Harvesting
DWA:	Department of Water Affairs
DWS:	Department of Water and Sanitation
ECAM:	Energy Performance and Carbon Emissions Assessment and Monitoring
EF:	Emission Factor
EI:	Energy Intensity
EMCs:	Even Mean Concentrations
EMLM:	Elias Motsoaledi Local Municipality
EOCs:	Emerging Organic Contaminants
EQS:	Environmental Quality Standards
ERS:	Environmental Risk Scores
EU:	European Union
EUP:	Energy Use Potential
FTWs:	Floating Treatment Wetlands
FU:	Functional Unit
GDP:	Gross Domestic Product
GHG:	Greenhouse Gas

GI:	Green Infrastructure
GIS:	Geographic Information System
GRIP:	Groundwater Resource Information Project
GWP:	Global Warming Potential
GWTW:	Groblersdal Water Treatment Works
HDPE:	High Density Polyethylene
HE:	Hydro-Economic classification
HPC:	The Heterotrophic Plate Count
IBNET:	The International Benchmarking Network
ICRA:	Catalan Institute for Water Research
IEA:	International Energy Agency
IFI TWG:	International Financial Institutions Technical Working Group on Greenhouse Gas Accounting
IGSM:	Integrated Groundwater and Surface water Model
IPCC:	Intergovernmental Panel on Climate Change
IRR:	Internal Rate of Return
ISO:	International Organisation for Standardisation
IWA:	International Water Association
IWA PI:	International Water Association Performance Indicators
LC:	Levelized Cost
LCA:	Life Cycle Assessment
LCC:	Life Cycle Costing
LID:	Low Impact Development
MAP:	Mean Annual Precipitation
MRV:	Monitoring, Reporting and Verification
MUSIC:	Model for Urban Stormwater Improvement Conceptualisation
NDCs:	Nationally Determined Contributions
NPSP:	Nonpoint Source Pollution
NPV:	Net Present Value
NRW:	Non-Revenue Water
OECD:	Organization for Economic Cooperation and Development
OPEX:	Operational Expenditure
POE:	Point-Of-Entry
POU:	Point-Of-Use
PP:	Payback Period
RCP:	The Representative Concentration Pathways
RDP:	Reconstruction and Development Programme
RHADESS:	Rainwater Harvesting Decision Support System

RMSE: Root Mean Square Error
ROI: Return on Investment
RSA: Republic of South Africa
RUE: Rainwater Use Efficiency
RWEN: Rainwater Energy Nexus
RWHS: Rainwater Harvesting Systems
RWTW: Roossenekal Water Treatment Works
SDM: Sekhukhune District Municipality
S-eI: Socio-economic acceptance Indicators
SI: Social Indicators
SIV: System Input Volume
SLAMM: Source Loading and Management Model
SSP: Shared Socio-economic Pathways
SuDs: Sustainable Drainage Systems
SUSTAIN: System for Urban Stormwater Treatment and Analysis Integration
SWH: Stormwater Harvesting
SWHS: Stormwater Harvesting Systems
SWMM: Stormwater Management Model
TDS: Total Dissolved Solids
TN: Total Nitrogen
TP: Total Phosphorus
TS: Total Solids
TSS: Total Suspended Solids
UCM: Urban Catchment Model
UNESCO: United Nations Educational, Scientific and Cultural Organization
UNFCCC: United Nations Framework Convention on Climate Change
UNICEF: United Nations Children's Fund
US EPA: United States Environmental Protection Agency
WaCCliM: Water and Wastewater Companies for Climate Mitigation
WDN: Water Distribution Network
WEF: Water Environment Federation
WEN: Water Energy Nexus
WEST: Water-Energy Sustainability Tool
WFaS: The Water Futures and Solutions
WHO: World Health Organisation
WRC: Water Research Commission
WSE: Water Saving Efficiency
WSUD: Water Sensitive Urban Design

WTW: Water Treatment Works

WWTP: Wastewater Treatment Plant

WWTW: Wastewater Treatment Works

GLOSSARY

It is believed that the terminologies used in this report are comprehendible to the target audience and therefore an inclusion of an elaborate glossary would not add value to the report. Further, most of the terminologies applied bear minimal double meanings as to confuse or mislead the reader.

CHAPTER 1: BACKGROUND

1.1 INTRODUCTION

Water crises ranks among the top five global risks that pose the highest concern as well as having the greatest impacts in terms of the quality of life and community development. Conventional and centralised water supply systems are either too stretched to meet the demand or inaccessible by the most vulnerable segments of the population who are in rural, peri-urban or informal settlements. As water demands approach the total renewable freshwater availability, each drop of freshwater gets increasingly valuable hence the need for efficiency and intensity in its management. Given that demand will but continue to increase, there is therefore, a need for innovative supply and demand management to achieve economic, environmental and social sustainability. To meet the demand gaps, there is need to develop robust tools to deliver on the alternative but suitable sources of water sustainably. This can be achieved through a mix of centralised and decentralised water supply systems as well as a mix of conventional and alternative water sources to meet water demand loads sustainably. The mix is referred to as hybrid water supply systems and is situation dependant hence varies from one settlement to another. The tenets of the hybrid water supply and management systems are anchored in the principles that define the Water Sensitive Urban Design (WSUD) and Sustainable Drainage Systems (SuDS). The Water Sensitive Urban Design (WSUD) Framework and Guidelines for South Africa, incorporating the Sustainable Drainage Systems (SuDS) was put in action in 2014. WSUD and SuDS are still new concepts in South Africa and therefore, efforts to operationalise WSUD and SuDS require research components to normalise it through the **4Ts** namely, the ongoing development of **T**ools that include manuals, guidelines, etc.; **T**ransfer of knowledge to appropriate officials; application of **T**actics for encouraging WSUD implementation for instance developing new policies; and **T**esting through trials for instance pilot studies, small scale developments, etc. The 4Ts are currently work in progress through various studies.

The assumption made in the one source, one system, and one discharge approach is that all water should be treated to the drinking/potable water standard regardless of the purpose for which it will be used (human consumption, industrial use, or garden and park watering). This is an inefficient use of money, energy, and water. Matching water quality to its intended function is the future in many cities, and the present in some. For instance, the concept of water that is fit to a purpose has been implemented in the city of Durban, South Africa, to respond to a conflict between water demand for domestic use and economic development under conditions of water scarcity. The eThekwini Water Services developed a strategy to recycle wastewater as an additional water source for industrial use. At operational capacity, the reclamation plant meets 7 percent of Durban's water demand and reduces the wastewater discharge by 10 percent. As a co-benefit, industrial customers reduce their costs by purchasing reclaimed water rather than high-quality, potable water. Further to the fit for purpose water use, a diversity of solutions also is seen to provide flexibility. If water is scarce, then stormwater, greywater, and even wastewater are potentially economically attractive sources.

In the current paradigm shift in water supply and management systems, a high priority is given to the study of alternative water supply which includes the use of centralised water supply system and decentralised water supply system, hybrid water supply systems. Water reclamation and reuse is a well know practice for creating additional water supplies and, thereby, increase the security of supply of urban water supply system. Factors affecting the selection of the optimum approach include local hydrology, available water supplies, water demands, local energy and nutrient-management situations, existing infrastructure, and utility governance structure. It is reported that integrating centralised and decentralised water supply and wastewater management, along with water reclamation and reuse, distributed water treatment, and rainwater harvesting, can offer the potential for increased urban water system security and sustainability. Implementation of these new approaches to urban water and resource management can lead to sustainable solutions, financial stability, using local sustainable water supplies, energy-neutral, responsible nutrients management, and access to clean water and sanitation.

Water supply systems (urban water cycle) are one of the energy consumers in the service delivery cycle, yet, there is very little indication in the current literature that the water energy nexus (WEN) has received due attention especially in the design of rainwater harvesting systems. In most cited instances, water supply systems and energy supply systems have frequently been managed separately. The current attention drawn to WEN has been prompted by the increasing significance of water security, energy efficiency, and economic feasibility of water supply systems. With reference to RWHS and any other water supply system, WEN is increasingly recognized as a principal factor for planning in the water resources utilisation and management. The complex interdependency between water and energy positions new challenges for resources.

Energy consumption and Greenhouse gas (GHG) emissions resulting from setting up a rainwater harvesting systems requires that indicators of the extent of Energy Use Potential (EUP) and Global Warming Potential (GWP) be incorporated in the design of rainwater harvesting systems. Rainwater harvesting systems benefit the end users in mitigating water shortages as well as providing an alternative source of water in the hybrid water supply system. However, and inevitably, the rainwater harvesting systems, like any other water supply system accrue adverse impacts that relate to increased consumption of energy. With an increase in population and a consequent increase in water demand, these impacts are bound to increase over time. Planning for the remediation and monitoring of such impacts is therefore integral in the design process of a rainwater harvesting system. Many of the rainwater harvesting systems are designed without taking the factors of energy into consideration. This is a critical gap that needs to be addressed and is therefore considered in the developed set of frameworks for the rainwater harvesting system.

An integrated rainwater harvesting system design requires the inclusion of WEN as an integral component of the design. In the current documentation on the design of rainwater harvesting systems, there is limited integration of WEN in the design process. There is therefore a need to develop a rainwater harvesting system (RWHS) design framework that incorporates WEN and Environmental Risk Scores (ERS). For flexibility in application, the developed generalised domestic rainwater harvesting potential and rainwater harvesting systems selection framework should be characterised as applicable in a range of scenarios, scales, and regions. A subcomponent of the generic framework should then incorporate the WEN analysis as well as the ERS analysis. In this way, a comprehensive RWHS that is not only optimal in process operation and costs but also environmentally friendly can be designed. The ERS are derived through an analysis of the contribution of RWHS facilities or components such as HDPE tanks used for storage of harvested rainwater in the release of carcinogens and/or respiratory organics and Greenhouse gas emissions. The use of water treatment chemicals and the potential hazards posed by the treatment residues to the environment are, but other examples of environmental risks posed by the implementation of a RWHS. The Risk Score is a product of Likelihood of occurrence and Level of impact (ERS = Likelihood of occurrence x Level of impact). The ERS can then be ranked to prioritise the respective risks.

Differentiating stormwater harvesting from rainwater harvesting has been a matter of debate for many years. The main point of departure through is the location of capture and point of use. In most literature, stormwater harvesting is depicted as a process that entails the collection, treatment, storage, and use of stormwater runoff from pervious or impervious surfaces. In contrast, rainwater harvesting, in most literature, is considered as the direct capture of rainwater mainly from rooftops and onsite (household) point of use. Stormwater harvesting, and reuse is considered a critical tenet of stormwater management. Stormwater harvesting offers an option in the realm of an integrated and sustainable urban water management and can provide multiple benefits/outcomes that include inter alia: Flood protection, mitigates flood impacts, and erosion control; Enhancement of urban stream health through the physical abstraction of the contaminated water, a process that improves the flow regime by alleviating the probable deterioration of water quality in the receiving waters (both surface and groundwater resources); Attain and protect natural waterways *in-situ*; Reduces the need to construct new supply development; Supports local community values and enhances public amenity and lifestyle values; and Provides an alternative water source fit for compatible end uses.

Stormwater management should be both safe and sustainable by supporting a socially and environmentally responsible use of the harvested stormwater. In which case it would imply the management of both quantity and quality of stormwater in a manner that meets the present needs without compromising the future needs, thus, attaining a balance between economic costs, environmental gains, and societal resilience.

Captured stormwater requires a level of treatment depending on the intended end user requirements. Low impact development (LID) and traditional development are two typical configurations of treatment trains that meet the definition of stormwater treatment trains currently utilised by site designers. LID, also referred to as hydrologic source control, endeavours to retain the site's pre-development (pristine) hydrologic regime. This is attained by a combination of impervious area controls with small scale stormwater Best Management Practices (BMPs) and consequently reducing the wet weather flows and the associated nonpoint source pollution (NPSP) and the subsequent stormwater treatment needs. LID systems and practices imitate natural processes that result in the infiltration, evapotranspiration or use of stormwater in order to protect water quality and associated aquatic habitat. They create functional and appealing site drainage that treat stormwater as a resource rather than a waste product. Several practices that adhere to these principles include but not limited to rain gardens, bioretention facilities, rain barrels, vegetated rooftops, and permeable pavements. Traditional development typically employs filtration and sedimentation practices such as swales and constructed ponds and wetlands. These practices may or may not treat rainwater close to its source but generally have minor impacts on stormwater volume. Where feasible, LID practices are favoured from a stormwater management practice as they reduce both stormwater volume and pollutant loading. LID practices, however, are often constrained by site factors, such as the existing soil profile (depth to bedrock – depending on whether shallow or deep, this has an impact on infiltration of stormwater and therefore the objective of stormwater volume management is dependent on this as a factor); soil or groundwater contamination (either from agricultural activities, waste disposal, mining or any other economic activity that has an impact on the soil properties and quality of the groundwater – this will impact on use of stormwater for groundwater recharge purposes for example); and space limitations (economic development growth nodes / corridors pose a challenge in developing LID systems, fast expanding urban and peri-urban spaces also pose a challenge in LID systems development).

A combination of LID and traditional BMP (aggregate LID-BMPs) yields the concept of Green Infrastructure (GI). This combination is necessary when developing stormwater treatment trains for larger regional and landscape scales as it provides opportunities to augment the advantages of LID with those of traditional

BMPs. As part of the implementation of Water Sensitive Urban Design principles, applications of a combination of Low Impact Development (LID) and Green Infrastructure (GI) have gained traction over the overall sole implementation of traditional stormwater management systems. At both the site and regional scale, LID/GI practices aim to preserve, restore and create green spaces using soils, vegetation, and rainwater harvest techniques.

Given the complexities involved in stormwater management of quantity (volumes), and quality, and with the need to keep environmental sustainability, the systems put in place need to be both reliable and sustainable. There is therefore a need for a well laid out framework for the harvesting and treatment of stormwater. The framework ought to outline the requirements to identify, select and set up a combination of processes and procedures that translate to a stormwater treatment train. The treatment train being a combination of Best Management Practices (BMPs) and LID systems. In combination to this framework, and for the purposes of reliability and sustainability of the system, there is also a need to develop a framework for monitoring the progress of a stormwater treatment project. A key parameter in this monitoring framework is the Social Indicators (SI). Social indicators for Non-Point Source (NPS) management provide information about awareness, attitudes, constraints, capacity, and behaviours that are expected to lead to water quality improvement and protection.

Good quality surface and groundwater resources are limited in many water management areas including the Sekhukhune District Municipality (SDM). The water resources are also diminishing due to urbanisation, contamination, and impacts of climate change. On this premise, proper allocation and management of these resources is a critical challenge for satisfying the rising water demands of the SDM. Previous studies in SDM have suggested the conjunctive use of groundwater and surface water resources as an alternative management option in efficient allocation and utilisation of the available water resources in the district. Conjunctive use refers to a coordinated and planned use of surface and groundwater. Literature suggests that it is now recognised that reclaimed wastewater is a water resource developed right at the doorstep of the urban environment. This implies that in a typical contemporary watershed, there are three recognised water resources for water supply meaning: surface water; groundwater; and reclaimed wastewater. Hence in a collective manner, conjunctive use could be referred to as a coordinated and integrated management and wise use of these water resources.

Urban water use through conjunctive use of water from different sources adds a new dimension to the usage and management of water resources as compared to single source use of water. The augmented dimension requires that a set of decisions need to be made at both the application level and the water resource level to enable water users to make the best possible use of all available water. Making such informed decisions requires a set of management tools that can be provided via models such as conjunctive use water management models. Conjunctive use models are developed based on the purpose and objective as well as the technique used. Such models may take different forms for instance, simulation-optimisation models; Simulation and prediction models; Dynamic programming models; Linear programming models; Hierarchical optimisation; Nonlinear programming models and others.

Sekhukhune District Municipality is a mainly rural district with 117 wards and a total of 764 villages. The District is made-up of four Local Municipalities, namely; Elias Motsoaledi, Ephraim Mogale, Makhuduthamaga and Fetakgomo Tubatse. The main towns in the district being: Burgersfort, Steelpoort, Groblersdal, Marble Hall, Apel, June Furse, Mohlaletsi, Driekop, Penge Mine, Prakiseer, Motetema and Mosterloos. 46% of the total area of the SDM is State-owned land (46% of SDM is designated as Municipality Area). 48% is designated as Traditional Authority Area (Department of Rural Affairs and Land

Reforms – DRDLR, RSA, 2019). The Traditional Authority Area is made up of villages that are scattered throughout the area. Therefore, providing centralised service delivery is quite a challenge to the municipality. The implication therefore is that service delivery systems are distributed. By extension, development of stormwater and on-site domestic rainwater harvesting systems is also distributed.

As noted in the SDM Development Plan 2021, 10.26% of the households in the district have piped water inside the dwelling; 38.82% of the households in the district have piped water inside the yard; 17.88% of the households in the district have access to communal piped water at RDP-level of service that is less than 200 m from their dwelling; 16.40% of the households in the district have access to below RDP-level of service of communal piped water located more than 200 m from their dwelling; and 16.64% of the households have no formal piped water. These statistics translate to approximately 33% of households in the district living in below RDP-level service to no service at all that require alternative sources of potable water. This scenario presents an opportunity for the district to explore the on-site domestic rainwater harvesting and stormwater harvesting systems as alternative water supply sources for domestic use.

Sekhukhune District Municipality (SDM) is an agricultural district hence emphasis is also put on irrigated agriculture. Good quality surface and groundwater resources are limited in SDM. Therefore, proper allocation and management of these resources is a critical challenge for satisfying the rising water demands of the SDM. Previous studies in SDM have suggested the conjunctive use of groundwater and surface water resources as an alternative management option in efficient allocation and utilisation of the available water resources in the district.

This study intended to develop a set of critical frameworks for hybrid water supply systems that are generic in nature but utilise information for Sekhukhune District Municipality and literature as the basis/functional units of the study. The frameworks developed include the following: a generalised domestic rainwater harvesting potential and rainwater harvesting systems selection framework; framework of water energy nexus (WEN) analysis for a rainwater harvesting system; global warming potential (GWP) analysis framework; and a framework for developing stormwater harvesting systems and monitoring. Mathematical model for conjunctive use of surface water and groundwater in the SDM was also developed and tested.

1.2 PROJECT AIMS

The following were the aims of the project:

1. To conduct a comprehensive desktop study on hybrid water supply systems in the context of Water Sensitive Settlements and Water Sensitive Urban Design Framework of South Africa
2. To formulate a plausible framework for rainwater harvesting potential and rainwater harvesting systems selection
3. To develop a framework of water energy nexus (WEN) analysis for a rainwater harvesting system
4. To develop a global warming potential (GWP) analysis framework of a rainwater harvesting system
5. To formulate a plausible framework for developing stormwater harvesting systems and monitoring, and
6. To develop a numerical model to test the potential of conjunctive surface water and groundwater use in Sekhukhune District Municipality

1.3 SCOPE AND LIMITATIONS

The project titled: Hybrid Water Supply Systems and Conjunctive Use in the Context of Water Sensitive Settlements: A Case Study of Sekhukhune District Municipality, Limpopo Province was conceived as a multifaceted project to build on the Water Sensitive Urban Design (WSUD) for South Africa: Framework and Guidelines document. The focus was more on developing frameworks for hybrid water supply systems for rural and peri-urban settlements based on the tenets of the overarching South Africa Framework and Guidelines document. The study also explored the development of a conjunctive water use model for the allocation and management of surface and groundwater resources in an area with competing water demands from limited sources.

Sekhukhune District Municipality (SDM) was chosen for the study because of its uniqueness and challenges it faces in water service delivery. Firstly, official statistics show that approximately 33% of households in the district live below RDP-level service to no service at all that require alternative sources of potable water. Secondly, official reports indicate that 48% of the SDM land is designated as Traditional Authority Area (Department of Rural Affairs and Land Reforms – DRDLR, RSA, 2019). The Traditional Authority Area is made up of villages that are scattered throughout the area. Consequently, providing centralised service delivery is quite a challenge to the municipality. The scenario thus renders SDM subject to a distributed service delivery system and by extension, development of stormwater and on-site domestic rainwater harvesting systems is also distributed. The populace that requires alternative sources of water for domestic use is significant. This situation presents an opportunity for the district to explore the on-site domestic rainwater harvesting and stormwater harvesting systems as alternative water supply sources for domestic use. With the SDM management's goal of providing water and sanitation services to all, the ideal and optimal system to adopt would thus be a hybrid water supply system.

As an agricultural district, SDM has a high demand for water for irrigated agriculture, in an area where good quality surface and groundwater resources are limited. In an effort to strike a workable balance in water allocation and management, previous studies in SDM have suggested the conjunctive use of groundwater and surface water resources as an alternative management option in efficient allocation and utilisation of the available water resources in the district.

The study envisaged the formulation and development of generic but robust frameworks for the development of rainwater harvesting and stormwater harvesting systems in a typical rural and/or a peri-urban settlement. Such systems are imagined to draw parallels with a typical setup of an urban settlement in terms of basic design parameters and requirements such as energy use potential (EUP) and global warming potential (GWP) that must be integral to a sustainable water-energy nexus (WEN). This was considered a major contribution of this study.

The formulation and application of a simulation model for conjunctive surface and groundwater use was to showcase the robustness of modelling as a water allocation and management tool in an area with competing water demands from limited sources. Even though use was made of the existing sources, *viz*., surface water and groundwater, the developed model can be extended to include other "new taps" such as the rainwater harvesting and stormwater harvesting.

At this stage of the study, the resulting frameworks have not been tested for robustness in application but have been structured based on solid scholarly information and data. However, a set of case studies are suggested to accomplish this goal. Case studies, if conducted, will also provide additional information, and/or input to improve the structure of the frameworks for rainwater and stormwater harvesting systems as well as the parameters that define the simulation model for conjunctive use of water resources. A major challenge in testing the frameworks for rainwater and stormwater harvesting as well as extension of the modelling study is in obtaining sufficient, reliable and quality data from the local municipalities. The lack of adequate funding and human resource capacity with the requisite skills set is a key contributor to the dearth of information and relevant data to accomplish this task.

Given the multifaceted nature of the study, the report is presented in four major parts. Part 1 is the scoping component whereby we define the key parameters of the project. Part 2 presents information on the formulation of a framework for determining a domestic rainwater harvesting potential as well as a framework for rainwater harvesting system selection. The resulting framework includes a revision of the deduced framework based on contemporary literature, practices, and case studies. This is one of the major contributions of the study. Further contributions of the study to the body of knowledge in this regard involves the formulation of submodules for inclusion of parameters that define the water-energy nexus (WEN) as an integral component in the design, operation and maintenance of rainwater harvesting systems. The section further illustrates the steps to include a socio-economic acceptance as an index (S-eI) in the design of socially acceptable rainwater harvesting systems. This is an important factor for the success of any rainwater harvesting system project in the community. Part 3 of the report presents information on the formulation of a framework for developing stormwater harvesting systems and monitoring. In this part of the report, the concept of Green Infrastructure (GI) is illustrated and how it is applied in the framework formulation. The section also provides information on the setup of a framework for monitoring progress of stormwater harvesting projects through monitoring nonpoint source pollutants concentrations and using Social Indicators (SI) as key aids in planning, implementation and evaluation of nonpoint source management projects. Part 4 of the report presents information and the basis for the formulation of a simulation model for conjunctive use of water (surface water and groundwater). It also presents the results of a case study in Elias Motsoaledi Local Municipality (EMLM), one of the four local municipalities that constitute the SDM.

CHAPTER 2: SCOPING

2.1 INTRODUCTION

2.1.1 Global water situation

Water is an essential, precious natural resource for the survival and well-being of human kind. Over time it is not only precious but increasingly critical resource. Despite its essence, the availability and access to the freshwater is increasingly under threat. According to The World Economic Forum's "Global Risks 2014" report, water crises is identified as one of the top five global risks posing the highest concern (World Economic Forum, 2014). In the report, water crises were ranked as the third biggest risk in terms of impact; however, strictly speaking, four of the identified top 10 risks are water-related. They are: water crises, climate change mitigation and adaptation, extreme weather events, and food crises (Arup, 2014). In addition to increasing water scarcity and pollution, rapid population growth, and urbanisation in combination with a fixed supply of total renewable water resources are key elements posing fundamental challenges to the global water cycle, with a particular pressure on the urban water supply. It is estimated that the growing food demands and increasing standards of living raised global water use approximately 8 folds from 500 to 4000 km^3 per year (Wada et al., 2016). As stated in Arup (2015), since 1950, cities have increased their water usage five-fold. This increase is reported not only as a result of population growth but considerably through increased per capita demand. Despite the call for an integrated water resources management whereby the city "urban" and rural systems are considered holistically, there is increased decoupling of urban and rural systems. This trend undermines the perceived holistic consideration of the global water cycle, where urban areas are continuously considered as isolated entities.

A holistic approach is however encouraged in order for the cities to succeed in a world characterised by resource concerns and constraints. Climate change is likely to make the challenge even more daunting, as it will increase the variability of water supplies with the effect that traditional water sources become less reliably available. At the same time, climate extremes are likely to increase, which may increase the likelihood of water related disasters reflected in more frequent floods and droughts (van den Berg, 2014). As stated in Arup (2014) the 2030 Water Resources Group predicts a global gap between safe freshwater demand and supply at 40% by 2030 if business-as-usual water management continues. This gap, it is predicted will imply that the safe freshwater supply will not support the predicted population by 2030. To make the most of water scarcity, the populace will have to improve the way it uses its available water resources significantly so that it can deal with the challenges ahead (van den Berg, 2014; Sapkota et al., 2015). At present, cities growingly struggle to access enough water supplies to sustain their populace yet over half of the world's cities with more than 100 000 inhabitants are situated in areas experiencing water scarcity. Studies have identified global drivers of change linked to the future of urban water utilities. A study by Arup's Foresight + Research + Innovation team identified about 100 trends (Arup, 2014). These trends were identified from global megatrends through to the sector specific drivers of change linked to the future of urban water utilities. Figure 2.1 is a depiction of the drivers and trends of change linked to the future of urban water utilities. These trends include the future of urban water access, supply and services (Arup, 2014). All these attributes need to be considered when managing the water cycle holistically. The identified drivers of change assist water managers, decision makers, scientists and all stakeholders dealing with water related matters to identify risks and opportunities as well as help us to get a better understanding of the long-term issues and consequently prime us for future scenarios.

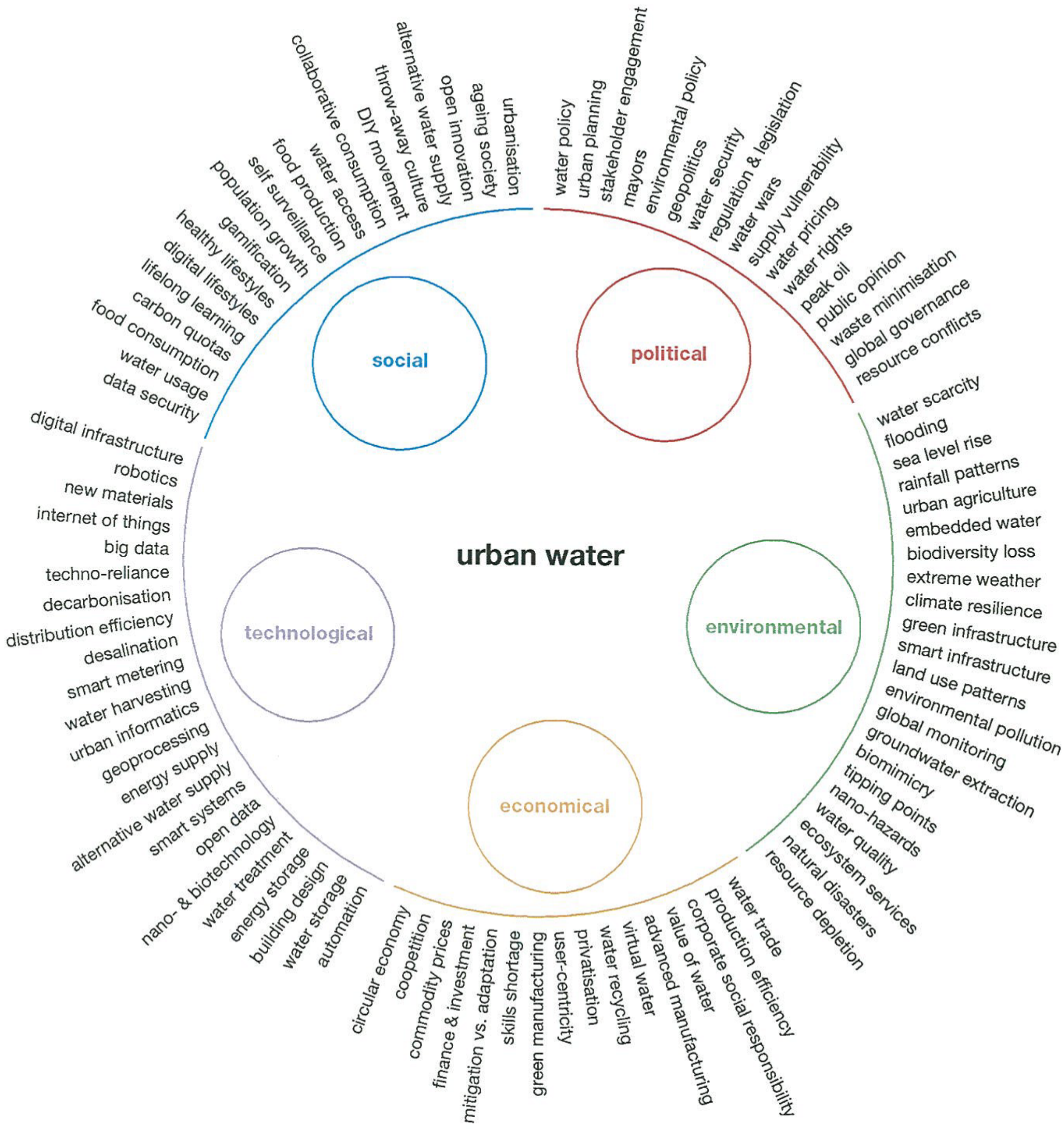


Figure 2.1 Drivers and trends of change linked to the future of urban water utilities (Arup, 2014)

2.1.2 Top ten trends for sub-Sahara Africa

In the proceedings of a workshop on Science and Technology-based Scenarios for sub-Saharan Africa, held in Windhoek, Namibia in March 2006, ten main trends in drinking water supply were identified. The ten main trends in drinking water supply in Southern and sub-Saharan Africa that were identified are as listed below (Swartz and Offringa, 2006):

1. Population Growth;
2. Urbanisation;
3. Degradation of Source Water Quality;
4. Climate Change: Water Resource Quantity (Water Stress);
5. Life-style Choices: Point-of-use Systems and Bottled Water;
6. Increasing Cost of Energy;
7. Better Access to Communication Technology and Information;
8. Increase in Water-borne Diseases;
9. Degradation of Infrastructure; and
10. Political Tensions over Water.

The report summarises that the most important trends that will affect Southern and sub-Sahara Africa are:

1. High population growth and large-scale urbanisation;
2. Deterioration of source water quality;
3. Climate change and its effect on sustainable water supply; and
4. The cost and availability of energy.

An excerpt of sections of the report depicting the Trends, Implication for Water Industry and the Adaptive Strategies is summarised in Table 2.1

Table 2.1 A summary of the top ten trends in drinking water supply in sub-Saharan Africa, implications for water industry and the identified adaptive strategies (Developed with material from Swartz and Offringa, 2006)

Trend	Implication for Water Industry	Adaptive Strategies
Population Growth	• Substantial increase in water demand will require exploitation of alternative water resources inter alia groundwater exploitation, water reclamation and reuse, rainwater harvesting, desalination of seawater and brackish water. • Large scale interventions from central government will be required to assist local authorities and communities to supply water for drinking purposes. • There will be increasing tensions regarding the allocation of water, from community level through to international level where water resources are shared. The question is who gets what, why and how much? This is already a real problem for many countries in sub-Saharan Africa. • Ballooning population size will also result in sanitation backlogs and pollution of water sources, requiring in many cases additional water treatment technologies to produce water complying with health requirements (WHO). The international community is expected to play a major role in supplying these technologies, of which Europe and China will play a major role. Innovative systems will be required. • The trend will be more towards centralised water treatment rather than decentralised treatment in the rural and peri-urban areas. In the more affluent societies in the cities there will be increasing use of household water treatment systems (point-of-use and point-of-entry) and there will be very active competition in the marketing and supply of these systems.	• Effective water demand management will be critical. Better regional cooperation will be necessary (political cooperation between countries sharing water sources). • Innovative solutions for exploitation of alternative water resources and treatment technologies (to enhance existing systems) will be required.
Urbanisation	• Strain on existing infrastructure with the implication that the requirements for new services and infrastructure will overwhelm the supply side. With concomitant degradation of existing infrastructure, it will place huge financial and capacity strains on the on the local authorities to satisfy the demands.	• Use of alternative water resources, such as water reclamation and reuse; seawater desalination in coastal cities; reducing water losses by better water conservation and demand management;

Trend	Implication for Water Industry	Adaptive Strategies
	• Due to economic strains, international funding will indeed be necessary required in order to address the backlogs. • Upgrades and extensions to large water treatment plants and distribution systems will be required, and in many cases more advanced technologies (e.g. membranes and advanced oxidation) will also be needed to treat the poorer raw water quality, new contaminants and micro pollutants. However, bear in mind that the bottleneck is almost always in the distribution system. • Greater emphasis will be placed on urban water supply in research and development programmes. Research on how to improve urban water demand management will receive high priority.	• Life-improvement programmes and development in rural areas as “pull factors” with the purpose of countering the urbanisation trend. • Meet the millennium development goals (MDGs) in rural areas.
Degradation of Source Water Quality	• Improved and appropriate technologies will be required to treat the poorer raw water quality since the conventional treatment systems of coagulation/flocculation, sedimentation, filtration and chlorination will in many cases not be adequate to ensure safe water. The occurrence of emerging contaminants and increase in water-borne diseases such as malaria, cholera and typhoid (and also diseases that had previously been eradicated or suppressed such as smallpox, dengue fever, Ebola fever and tuberculosis that are likely to re-emerge) will require more advanced treatment technologies, such as membrane treatment and advanced oxidation. • The poorer quality drinking water supplied to households in the cities (not only from inadequate treatment but also from quality deterioration in the distribution systems) will lead to more consumers in the affluent societies using point-of-use (POU) treatment systems, which will be marketed on large scale in these areas. This will be especially the case in the highly populated areas such as Johannesburg/Pretoria and Cape Town in South Africa. • The gradual increase in organic content (NOM) of surface waters will lead to expedited research in treatment technologies that can reduce these compounds cost-effectively, and that will be sustainable over the long term.	• Better source protection; major effort to reach MDGs, thereby improving sanitation services and reducing pollution of water resources; • Development of cost-effective sustainable treatment systems and technologies applicable to Africa conditions and that of developing countries; • Major programmes to improve operation and maintenance of both new and existing technologies; • Assessment of steps and processes needed to improve measurement processes, monitoring, database development and data analysis.

Trend	Implication for Water Industry	Adaptive Strategies
	• To improve the sustainability of existing treatment systems to treat the poorer raw water quality will need interventions to improve the operation and maintenance of these systems. Some privatisation in this market sector is expected to realise.	
Climate Change: Water Resource Quantity (Water Stress)	• For drought periods, strict water conservation and demand management measures will be required. These will include: allocation of water; and water restrictions. Water restrictions have already been implemented in a number of towns in the western parts of South Africa. • Increased focus on alternative water supply options and technologies, such as seawater desalination (Cape Town metropole; Swakopmund planning for this; also areas in the southern parts of the continent). • Increased research and development of rainwater harvesting and water reclamation and reuse as alternative water supply options. There has been a significant increase in marketing of desalination technologies in the sub-continent, notably in South Africa. New competitors are entering the market. • The central government will work towards implementing improved water conservation and demand management programmes, particularly in the urban areas. • Increasing migration – particularly to southern Africa and South Africa – is placing further stress on this region's scarce water supplies.	• Greater emphasis will be required on the use of alternative water sources such as desalination, water reclamation and reuse, rainwater harvesting; • Flood protection to protect water treatment plants against possible damage during flooding, thereby ensuring uninterrupted water supply and acceptable drinking water quality.
Life-style Choices (Point-of-use Systems and Bottled Water)	• A wide variety of point-of-use (POU) water treatment devices have appeared on the market in South Africa (and some other African countries), and there are very strong marketing drives. Often misleading statements are made regarding the quality of tap water, or what the treatment device can achieve. This has generally resulted in decline in consumer confidence in many areas in South Africa. • Effective communication with consumers will be required to restore the confidence in water supply authorities; however, the water suppliers will need to ensure that water of high quality is not only produced at the treatment plant, but actually delivered at the tap at	• Improve communication with consumers. • Improve quality control through effective operation and monitoring, especially in the rural areas where this is generally lacking.

Trend	Implication for Water Industry	Adaptive Strategies
	households (i.e. much more focus should be placed on eradicating the deterioration of water quality that takes place in the distribution systems).	
Increasing Cost of Energy	• Emphasis will need to be placed on energy efficient water treatment technologies, or on development of alternative energy technologies which will ensure affordable and sustainable treatment systems for developing countries with limited sources. Research on renewable energy sources will therefore have to be fast-tracked. • For rural and remote areas, research on treatment systems that requires no electricity will be a high priority. The proposed application of membrane technologies in rural areas will need to strive towards using low or no energy, such as gravity fed systems (low-pressure systems).	• Develop water treatment technologies that are energy efficient. • Develop renewable energy resources that could be used in combination with small-scale water treatment technologies for rural and remote areas (decentralisation).
Better Access to Communication Technology and Information	• More sophisticated treatment technologies and accompanying control systems will be within reach of the rural and remote communities. This is currently evidenced by the widespread use of cellular telephones world-wide. There are tailor-made applications (Apps) for various functions to complement smart phone utilisation.	• It will be possible to supply treatment technologies to rural and remote areas in Africa that can be controlled remotely via telemetry and communication technology, which should ensure improved sustainability of these systems through rapid corrective action during plant upsets.
Increase in Water-borne Diseases	• There is a need for technologies that can effectively prevent any pathogens, viruses, parasites, emerging micro pollutants from occurring in the treated water consumed by communities. • Re-contamination in the distribution network should be prevented by implementing effective monitoring systems. • General health improvement drive needed by governments to ensure adequate sanitation provision and water supply.	• There should be increased environmental awareness. • Water source protection should be high priority. • Development and application of technologies that can prevent pathogens, parasites, et cetera occurring in the treated water, that is, the use of barrier treatment systems such as membranes.

Trend	Implication for Water Industry	Adaptive Strategies
Degradation of Infrastructure	• Water supply authorities will not be able to ensure continued provision of acceptable quality water. • The end-users will have less confidence in the water supply authorities, and increased use of point-of-use systems and bottled water will prevail. This is currently the situation in South Africa. The problem is being addressed on a national scale with strong campaigns to consumers to trust the water from the distribution system. • Donors may become tired of continually having to fund solutions for Africa's many problems and shift from the donation of funds to market (investment and commercial) opportunity funding.	• Asset and facility management programs should be improved where in existence and immediately implemented where none existent; • Prioritise on capacity building in preventative maintenance programs and management thereof by the authorities; • Prioritise on funding allocation (this requires proper, extensive, and inclusive consultation process in conjunction with sound informed judgement) ; and • Provide capacity to improved project and financial management.
Political Tensions over Water	• Increased perception of the value of water. Affluent consumers are generally prepared to pay more for better quality water. • Improved water conservation and demand management methods needed. • Intervention by central government to ensure better service delivery and regain the confidence of consumers in (especially) problems areas. • Partisan political interests prevent regional collaboration between countries, while party politics within many countries use access to water to force or coerce political support.	• Increasing need for science and technology to provide relevant technical input to help inform decision-making.

A quick analysis of the presentation in Table 2.1 shows that the identified top ten trends will pose challenges in the provision of water in five different fronts thus: Social; Economical; Political; Technological; and Environmental. On the social front, it is evident that there will be a great rise on the level of affordability of the basic needs which will be pertinent. On the economic front, appropriate and affordable technology will be a point of focus with the emphasis on low running cost technology. As a partnership, it will be expected that the users pay the running costs. Coupled to this, there will be pressure to produce and use renewable energy sources at a lower cost (green economy). Regarding the politics, the pressure will be to develop and exploit alternative water and energy sources. The impact of global warming will be substantial, leading to water shortages in certain areas and flooding in other areas. On the technological front, the challenge will be to match the treatment technologies with the constantly emerging new micro-pollutants in order to attain a reasonable water quality requirement by the end user (customer tap). Finally, on the environmental front, all said and done, the environmental sustainability is paramount hence a proper and delicate balance must be maintained throughout the product lifecycle (water) from the source abstractions through the treatment processes and finally to the customer tap. A delicate balance of quality and quantity within reasonable and affordable economies of scale is a great challenge to be overcome.

2.1.3 Water supply and sanitation: Climate change considerations

Climate change and variability is already a threat to water supplies and sanitation. This is recognised as one of the defining challenges for the 21st century. The process of climate change has been confirmed to be ongoing and some further changes are now considered unavoidable. Most impacts will be experienced through more droughts, floods, and less predictable rainfall and water flows. These will place established water and sanitation services together with future gains in access and service quality at real risk. It is acknowledged that climate change is not happening in isolation hence it is best understood as an additional factor in a complex network of interactions as summarised in Figure 2.2. Technologies and planning are needed that can adapt to cope with multiple threats, rather than to climate change alone (WHO, 2009).

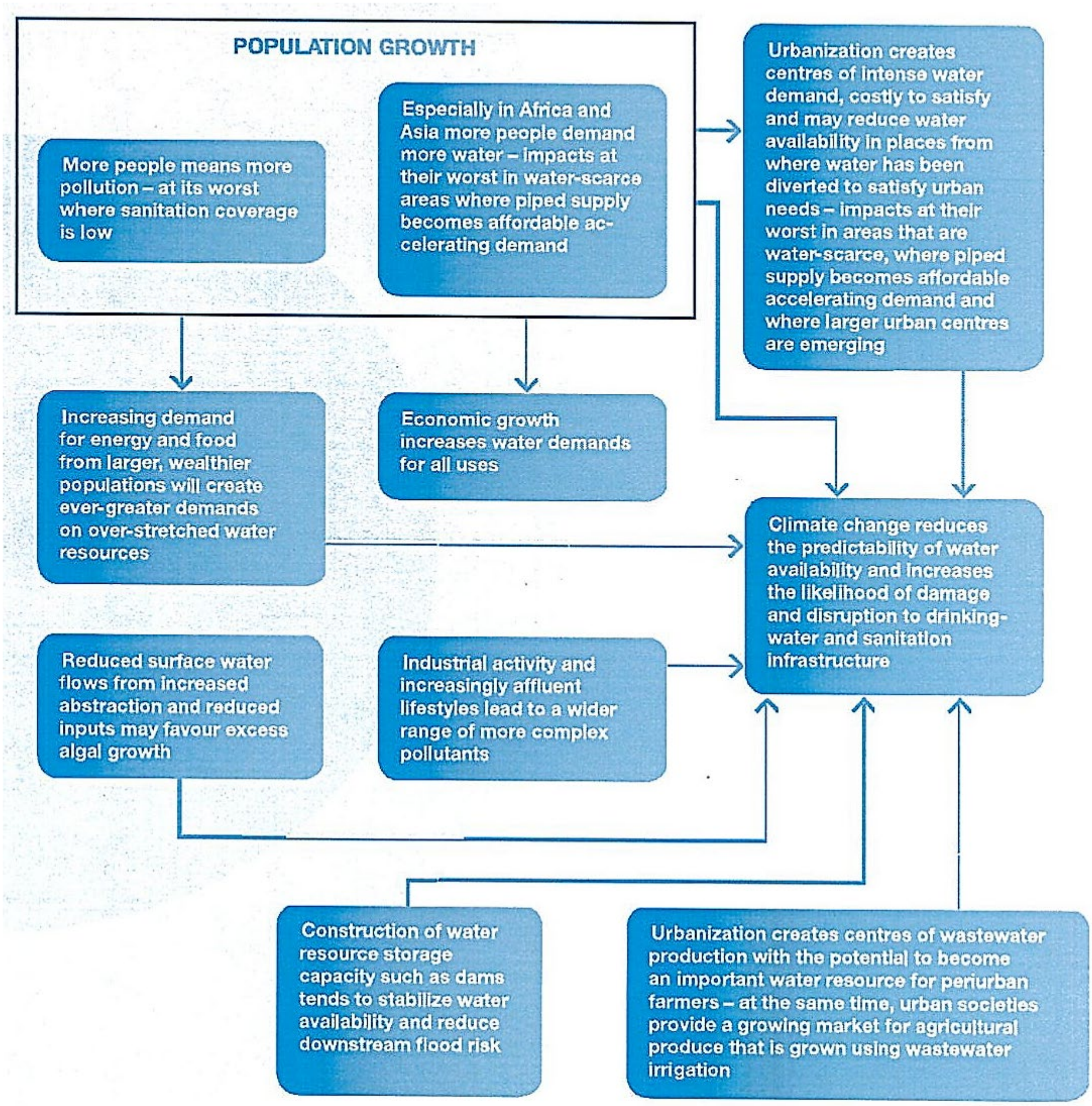


Figure 2.2 Impacts of climate change in a context of multiple challenges (adapted from WHO, 2009)

According to a World Health Organization (WHO) study, all drinking water technologies will be vulnerable to climate change and all have some adaptive potential (WHO, 2009). A wide range of potential climate change impacts on water supply technologies abound. Such include flood damage to infrastructure, increased contamination, deteriorating water quality, increased treatment requirements and reduced water availability. Figure 2.3 presents a summary of identified resilience of water technology to climate change as considered applicable by 2030.

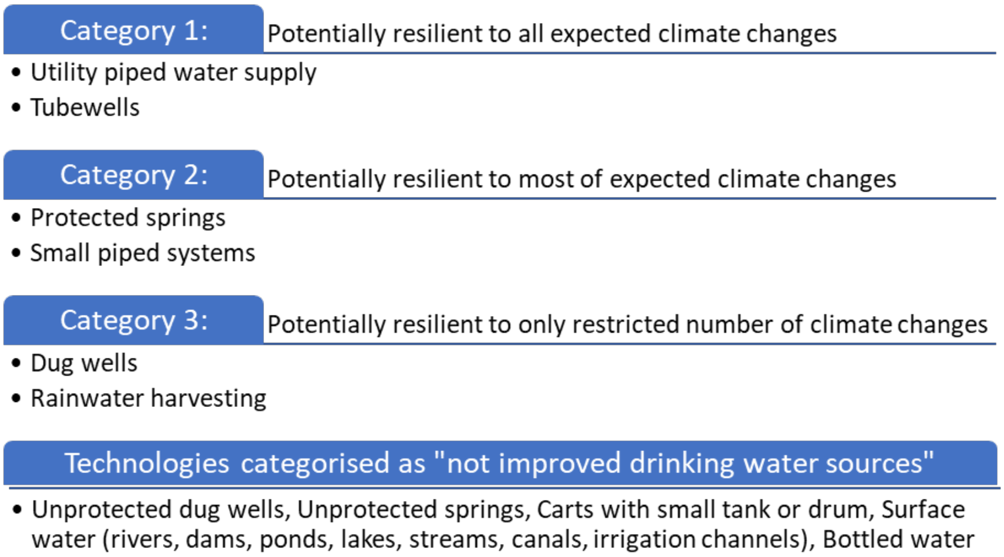


Figure 2.3 Resilience of water technology to climate change: applicability by 2030 (adapted from WHO, 2009)

Climate change will affect individuals, groups and countries differently since their sensitivities or vulnerabilities to climate change impacts differ according to their respective capacities to adapt. South Africa, already a water-stressed country, is likely to experience significant impacts as a result of global climate change and other stress factors such as pollution, land-use and unsustainable water use (DWS, 2015). Depending on its resilience, countries develop adaptation strategies differently. South Africa, in response to mitigate impacts of global climate change has developed a Climate Change Response Strategy document for the Water Sector. The purpose of the document is to inform on probable coping strategies as a way of building resilience and reducing vulnerability. Table 2.2 presents excerpts from the strategy document with regards to water supply and sanitation, groundwater development and alternative water supply sources.

Table 2.2: Some Climate Change Adaptation Measures for the Water Sector in South Africa (Excerpts from the Climate Change Response Strategy for the Water Sector, DWS, 2015)

Table 2.2 Some Climate Change Adaptation Measures for the Water Sector in South Africa (Excerpts from the Climate Change Response Strategy for the Water Sector, DWS, 2015)

Multi-purpose water storage

Adaptation measure:	
National	• Build capacity and awareness around climate change impacts on infrastructure for planners and engineers. • Test Department of Water and Sanitation: Water Resources infrastructure plans against no regrets/low regrets framework and against most recent climate change impact scenarios to ensure that the appropriate infrastructure decisions are being made. • Plan for developing new water resources including dams, water re-use, desalination and other additional water resources. • Ensure all national and municipal dams have written operating rules in place, including clear rules for drought conditions.
WMA	Refurbish government irrigation schemes to reduce water wastage.

Water supply and sanitation

Adaptation measure:	
National	• WRC to invest in research regarding optimal technologies capable of adapting to the range of climate scenarios across the country. • DWS with the WRC will develop a municipal handbook on climate change and a simple tool for the rapid assessment of the vulnerability of water services institutions to climate change. • Update design guidelines for WWTW and WTW to take account of climate change, including changing water temperature.
WMA	• Support municipal water conservation and demand management programmes.
Local	• Water Services Authorities to reduce physical water loss according to DWS targets. • Municipal planning to acknowledge the effects of climate change in order to minimise its impact to water services delivery.

Groundwater development

Adaptation measure:	
National	• Develop new groundwater sources to supply water and secure appropriate recharge including artificial recharge where appropriate. • Develop tools to understand and determine the effect of climate change on groundwater.
WMA	Monitor groundwater systems and ensure appropriate maintenance plan is in place.
Local	Monitor groundwater systems and ensure appropriate maintenance plan is in place.

***Alternative water supply sourc**es*

Adaptation measure:	
National	Continue to investigate alternate water supplies as part of the reconciliation studies.
Local	Investigate the feasibility of alternative water sources such as rainwater harvesting, fog water harvesting, desalination, recycling, etc. to augment municipal water supply.

Key:
DWS – Department of Water and Sanitation; WMA – Water Management Area; WRC – Water Research Commission; WTW – Water Treatment Works; WWTW – Wastewater Treatment Works

2.1.4 Future urban water: Scenarios

Water scarcity, pollution, rapid population growth and urbanisation are among major factors posing fundamental challenges to the global water cycle, with a particular pressure on the urban water supply (Lambert and Vassarotti, 2015). Urban water systems are in a period of stress and uncertainty and will experience rapid and significant changes in the coming decades (Pinkham, 2015). In order to sustain growing food demand and increasing standard of living, Wada et al. (2015) commentates that the global water use increased by nearly 6 times during the last 100 years and this figure continues to grow. Lambert and Vassarotti (2015) indicate that the growth in demand is not only through population growth but considerably through increased per capita demand and cities progressively struggle to access sufficient water supplies to sustain their population. Compounding this growing pressure on water resources is the element of climate change and its attributes that include rising temperatures, extreme weather events, rising sea levels and reduction in river flows as well as uncertainty in groundwater levels. It is further estimated that a global gap of 40% between safe freshwater demand and supply will exist by 2030 if business-as-usual water management continues. The soaring water use worsens water scarcity conditions already prevailing in semi-arid and arid regions consequently raising the uncertainty for sustainable food production and economic development. Arup (2015) and Wada et al. (2015) indicate that planning for future development and investments require that we prepare projections of water supply and demand balances for the future. However, estimations are complicated since the key drivers of change for the future of urban water is a combination of interaction of social, technological, economic, environmental, and political factors while only limited knowledge and observational data is available about freshwater resources and how they are being used (Wada et al., 2015). Given the combination of interactions stated above, it implies that managing water at a local scale has global impacts and global developments have local impacts. To the water managers and policy makers, new risks and uncertainties are further created by the climate change and the ever changing and unpredictable global economic environment.

Scenario building and visioning exercises are valuable tools for understanding change and planning strategies for the future (Pinkham, 2015). Scenario building offers a creative and flexible way of preparing for an uncertain future. According to Lambert and Vassarotti (2015), scenarios can be used to explore the viability of different strategies, inspire innovation and assist in long-term planning for a more sustainable and resilient urban water system. Several authors have attempted to develop generic scenarios to pattern the present and future of the water systems. For instance, Pinkham and Chaplin (1996) in their work for the Rocky Mountain Institute built a set of scenarios of general interest to managers, policy makers, and the citizens concerned with community water systems. Wada et al. (2015) developed scenarios for modelling global water use for the 21st century. In their work, Wada et al. (2015), focus on the water use in the various sectors whereby they assess the state of the art for estimating and projecting water use regionally and globally through what is known as The Water Futures and Solutions (WFaS) initiative. A critical component of the WFaS analysis is the assessment of global water supply and demand balances, both now and into the future, and the state-of-the art methods used to understand the extent of water resource challenges faced around the world (Wada et al., 2015). It is indicative that the estimation of global sectoral water-use or withdrawals is considered a highly uncertain component of global water assessments. However, the work by Wada et al. (2015), provides the first multi-model analysis of global water use for the 21st century. The analysis is based on water scenarios designed to be consistent with the community-developed shared socio-economic pathways being prepared for the latest Intergovernmental Panel on Climate Change (IPCC) assessment report. The global water scenarios used are based on the following: the Shared Socio-economic Pathways (SSP), the Representative Concentration Pathways (RCPs) as well as the Hydro-Economic (HE) classification. The uniqueness of the WFaS initiative is that apart from following the SSP and RCP narratives of scenario building and assumptions, it incorporates the HE classification. The SSPs were developed by the climate change community with a focus of the key elements for climate policy analysis. This implies less or no information is given related to the water sector. The WFaS assessment uses the three global water models that include both water supply and demand, namely H08, PCR-GLOBWB and WaterGAP. The HE classification describes different conditions in terms of a country's or region's ability to cope with water-related risks and its exposure to complex hydrological conditions, which affect its development in the scenarios (Wada et al., 2015).

2.1.4.1 Water futures and solutions (WFaS) scenario approach: scenario assumptions

<u>HE scenario assumptions</u>

Within WFaS, qualitative scenarios of water availability and demand are being developed that are broadly consistent with scenarios being developed for other sectors and that incorporate feedback from stakeholders where possible (Wada et al., 2015). The SSP narratives were enhanced with relevant crucial dimensions of the main water use sectors, i.e. agriculture, industry, and domestic for the development of a first set of assumptions applied in global water models. This is achieved for various conditions in terms of a country or region's ability to cope with water-related risks and its exposure to complex hydrological conditions. For this purpose, a hydro-economic (HE) classification has been developed, assigning each country in a two-dimensional space of coping capacity and hydrologic complexity (Wada et al., 2015). A brief description of the HE and SSPs is presented in the following section. For more detailed description reference is made to Wada et al. (2015).

The HE classification is derived from two broad dimensions representing (i) a country's economic and institutional capacity to address water challenges, and (ii) each country's magnitude/complexity of water challenges in terms of water availability and variability within and across years. The following are considered under each dimension:

<u>Economic-institutional coping capacity:</u>

1. GDP per capita (purchasing power parity corrected) as a measure of economic strength and financial resources that could be invested in risk management; and
2. The Corruption Perception Index (CPI) indicator as a measure of institutional capacity to adopt good governance principles (efficiency, effectiveness, transparency, accountability, inclusiveness, rule of law) in governance and management of risks.

<u>Hydrological complexity:</u>

1. Total renewable water resources per capita as a measure of water availability;
2. Ratio of total water withdrawal to total renewable water resource availability as a proxy for relative intensity of water use;
3. The coefficient of variation over 30 years of monthly runoff as a proxy for both inter- and intra-annual variability of water resources; and
4. The share of external (from outside national boundaries) to total renewable water resources as a measure for the dependency of external water resources.

To develop water scenarios assumptions, countries are grouped into classes. Wada et al. (2015) grouped countries in a space of four categorised the level of HE development challenges as follows:

- HE-1: hydro-economic 1 (water secure, poor)-this class includes countries characterised as low-to-mid income and regarded as having only moderate hydrological challenges;
- HE-2: hydro-economic 2 (water secure, rich)-this class represents countries of mid-to-high income and with moderate hydrological challenges;
- HE-3: hydro-economic 3 (water stress, rich)-this class represents countries that have mid-to-high income and are facing substantial hydrological challenges; and
- HE-4 (water stress, poor)-this class comprises countries with low-to-mid income and substantial hydrological challenges; hence, countries require large economic development in a context of severe water challenges.

Figure 2.4 presents a graphical representation of the HE classes

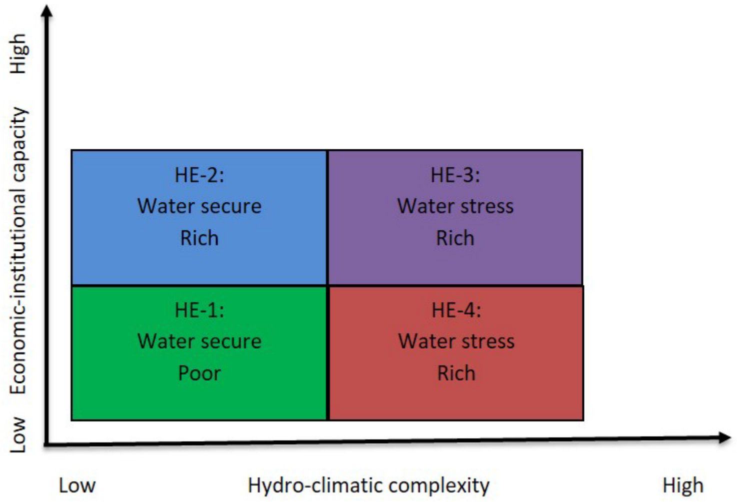


Figure 2.4 : Hydro-economic quadrants for human-natural water development challenges (Adapted from Wada et al. (2015)).

SSP scenario assumptions

Each SSPs storyline was scrutinised for developments relevant for each water use sector, i.e. agriculture, industry and domestic. Coupled with the developments, the accompanying probable implications of each development was also indicated. Table 2.3 presents a summary of the SSPs per sector and their probable implications. For this study, five SSPs were identified as developed in O'Neill et al. (2015), and Wada et al. (2015). The SSPs are numbered SSP1 through to SSP5 and are described as follows:

- SSP1: sustainability-taking the green road;
- SSP2: middle of the road;
- SSP3: regional rivalry-a rocky road;
- SSP4: inequality-a divided road; and
- SSP5: fossil-fuelled development; taking the highway.

Table 2.3 Summary of SSP narratives, attributes and implications (Developed with information adapted from O'Neill et al. (2015) and Wada et al. (2015))

Sector	SSP narrative	Attributes	Implications
Agricultural	SSP1: Sustainability-taking the green road	• Sustainability concerns; more stringent environmental regulation implemented; • Rapid technological change; • Energy efficiency and improved resource efficiency; • Relatively low population growth; emphasis on education; • Effective institutions; • Wide access to safe water; • Emphasis on regional production; • Some liberalisation of agricultural market; and • Risk reduction and sharing mechanisms in place.	• Improved agricultural productivity and resource use efficiency; • Quite rapid reduction of prevailing yield gaps toward environmentally sustainable and advanced technology yield levels; • Improving nutrition with environmentally benign diets with lower per capita consumption of livestock products; • Enforced limits to groundwater over-exploitation; • Large improvements in irrigation water use efficiency where possible; • Reliable water infrastructure and water supply; • Enhanced treatment and reuse of water; • Concern for pollution reduction and water quality, implying widespread application of precision farming and nutrient management; • Risk management and related measures implemented to reduce and spread yield risks

	SSP2: Middle of the road	• Most economies are politically stable; • Markets are globally connected but they function imperfectly; • Slow progress in achieving development goals of education, safe water, and health care; • Technological progress but no major breakthroughs; • Modest decline in resource use intensity; • Population growth levels off in the second half of the century; • Urbanization proceeds according to historical trends; • Consumption is oriented towards material growth; • Environmental systems experience degradation; • Significant heterogeneities exist within and across countries; • Food and water insecurity remain in areas of low-income countries; • Barriers to entering agricultural markets are reduced only slowly; • Moderate corruption slows effectiveness of development policies.	• Modest progress of agricultural productivity; • Slow reduction of yield gaps, especially in low-income countries; • Increasing per capita consumption of livestock products with growing incomes; • Persistent barriers and distortions in international trade of agricultural products; • No effective halt to groundwater over-exploitation; • Some improvements in water use efficiency, but only limited advances in low-income countries; • Some reduction of food insecurity due to trickle down of economic development; • Food and water insecurities remain as problems in some areas of low-income countries; • No effective measures to prevent pollution and degradation by agricultural practices; environmental risks caused by intensive application of fertilizers and agrochemicals, and intensive and concentrated livestock production systems; and • Only moderate success in reducing climate risks and vulnerability

	SSP3: Regional rivalry-a rocky road	• Growing concerns about globalization and focus on national/regional issues and interests; • Markets (agriculture, energy) are protected and highly regulated; • Global governance and institutions are weak; • Low priority for addressing environmental problems; • Slow economic growth; • Low investment in education and technology development; • Poor progress in achieving development goals of education, safe water, health care; • Increase in resource use intensity; • Population growth low in developed, high in developing countries; overall large increase; • Urbanization proceeds slowly; disadvantaged continue to move to unplanned settlements; • Serious degradation of environmental systems in some regions; • Large disparities within and across countries; and • Weak institutions contribute to slow development	• Poor progress with agricultural productivity improvements in low-income countries due to lack of investment and education; • Widespread lack of sufficient investment and capacity for yield gap reduction in developing countries; • Growing protection of national agricultural sectors and increasing agricultural trade barriers; • Low priority to halt environmental degradation caused by agriculture (erosion, deforestation, poor nutrient management, water pollution and exploitation); • Widespread pollution and deterioration of ecosystems; • Continued deforestation of tropical rainforests; • Only modest improvements in irrigation water use efficiency; • Persistent over-exploitation of groundwater aquifers; • widespread lack of access to safe water and sanitation; • Unreliable water and energy supply for agricultural producers; • Food and water insecurity persist as major problems in low-income countries; and • High population growth and insufficient development leave behind highly vulnerable human and environmental systems.

	SSP4: Inequality-a divided road	• Inequalities within and between countries increase; fragmentation increases; • Wealth and income increasingly concentrate at the top; • Global governance and institutions are weak; • Public expenditures focus on and benefit a small, highly educated elite; • Polarization creates a mixed world with income inequality increasing; • Political and economic power becomes more concentrated in a small political and business elite; • Increasing price volatility in biomass and energy markets; • Well-educated elite induces technical progress and efficiency improvements; • A world that works well for the elite but where development stagnates or decreases opportunities for those left behind; • Low fertility in developed countries. High fertility and high urbanization in low- and middle-income countries; • Large disparities of incomes and well-being within and across countries; • Poor access to institutions by the poor; and • No adequate protection for those losing out in development; these groups lose assets and livelihoods.	• In part, the trend is towards large, technologically advanced and profitable farms. Yet, at the same time, there is also poor progress of agricultural productivity in low income farm households due to lack of investment and education; • Land and water grabbing to the benefit of elites and large international agro-complexes; • Efficient irrigation systems used for profitable and internationally traded cash crops. Little improvements in irrigation efficiencies of the low-income farm sector; • In low-income countries, food and water insecurity persist as major problems outside the privileged elites; • High population growth in developing countries and polarizing development leave behind highly vulnerable rural systems; • No adequate protection for those losing out in development; these groups lose assets and livelihoods; and • Co-existence of well-organized agricultural production and marketing chains, run by the elite, and widespread subsistence and landless dwellers in rural areas.

	SSP5: Fossil-fueled development-taking the highway	• The world is developing rapidly, powered by cheap fossil energy; • Economic success of emerging economies leads to convergence of incomes; • Decline in income inequality within regions; • World views oriented towards market solutions; • Developing countries follow the development model of the industrial countries; • Rapid rise in global institutions; • Strong rule of law; lower levels of corruption; • Accelerated globalization and high levels of international trade; • Policies emphasizing education and health; • Consumerism, resource-intensive status consumption, preference for individual mobility; • Population peaks and declines in the 21st century; • Strong reduction of extreme poverty; • Very high global GDP; continued large role of manufacturing sector; • All regions urbanize rapidly; • Widespread technology optimism; high investments in technological innovations; and • Local environmental problems addressed effectively; however, lack	• Agro-ecosystems become more and more managed in all world regions; • Large increases in agricultural productivity; diffusion of resource-intensive management practices in agriculture; • Large improvements in irrigation water use efficiency; • Enhanced treatment and reuse of water; • High per capita food consumption and meat-rich diets globally; • Land and environmental systems are highly managed across the world; • Large reduction of agricultural sector support measures; • Global agricultural markets are increasingly integrated and competitive; • Improved accessibility due to highly engineered infrastructures; • Large-scale engineering of water infrastructure to manage and provide reliable water supply; and • Economic use of land is given priority over nature protection and sustainability of ecosystems.

		of global environmental concern and solutions	
Industry (electricity water use efficiency)	SSP1: Sustainability-taking the green road	• Reduced overall energy demand over the longer term; • lower energy intensity, with decreasing fossil fuel dependency; • Relatively rapid technological change is directed toward environmentally friendly processes, including energy efficiency and clean energy technologies; favourable outlook for renewables – increasingly attractive in the total energy mix; • Strong investment in new technologies and research improves energy access; and • advances alternative energy technologies	• Reduction in energy demand will decrease the demand for water from the energy sector substantially even if world population, primary energy production, and electricity generation were to increase; • A shift away from traditional biomass toward less consumptive energy carriers, as well as the changing energy mix in electricity generation, could lead to water savings; • A favourable outlook for renewables will cause big structural and efficiency shifts in the choice of technology, with variable consequences for water use intensity and efficiency, depending on the renewable type. For example, an expanding output of biofuels will lead to a rise in water consumption, whereas a shift towards photovoltaic solar power or wind energy will lead to a decrease in water use intensity; • Higher energy efficiency could translate into a relatively lower water demand and improvements in water quality, following high standards that commit industry to continually improving environmental performance; and • Overall, structural and technological changes will result in decreasing water use intensities in the energy sector. For example, the widespread application of water-saving technologies in the energy sector will significantly reduce the amount of water used not only for fuel extraction and processing, but also for electricity generation.

	SSP2: Middle of the road	• Continued reliance on fossil fuels, including unconventional oil and gas resources; • Stabilization of overall energy demand in the long run; • Energy intensity declines, with slowly decreasing fossil fuel dependency; • Moderate pace of technological change in the energy sector; and • Intermediate success in improving energy access for the poor.	• Reliance on fossil fuels may lead to only minor structural and efficiency shifts in technology; • Stabilization of overall energy demand in the long run will lead to little or no change in water demand for fuel extraction, processing and electricity generation; • A decline in energy intensity will lower water demand; • A moderate pace in technological change will cause minor structural and efficiency shifts in technology, and ultimately water use intensity will change only slightly; • Weak environmental regulation and enforcement trigger only slow technological progress in water use efficiencies; • Regional stress points will increase globally. Power generation in regional stress points will likely have to deploy more and more technologies fit for water-constrained conditions to manage water-related risks, though this can involve trade-offs in cost, energy output and project siting; and • In general, if historic trends remain the same, water use intensities will continue to decrease in the most developed regions. However, there will be slow progress in Africa, Latin America and other emerging economies.

	SSP3: Regional rivalry-a rocky road	• Growing resource intensity and fossil fuel dependency; • Focus on achieving energy and food security goals within their own region; • Barriers to trade, particularly in the energy resource and agricultural markets; • Use of domestic energy results in some regions increases heavy reliance on fossil fuels; and • Increased energy demand driven by high population growth and little progress in efficiency.	• Barriers in trade may trigger slow technological progress in water use efficiencies. A moderate pace in technological change will cause minor structural and efficiency shifts in technology, and ultimately water use intensity will change only slightly; • Reliance on fossil fuels may lead to only minor structural and efficiency shifts in technology; • An increase in energy intensity will increase water demand, whereas little progress in efficiency would trigger increased water demand as energy use intensifies; and • Weak environmental regulation and enforcement hamper technological progress in water use efficiencies; hence, very slow progress in water-saving technologies

	SSP4: Inequality-a divided road	• Oligopolistic structures in the fossil fuel market leads to underinvestment in new resources; • Diversification of energy sources, including carbon intensive fuels like coal and unconventional oil, but also low-carbon energy sources like nuclear power, largescale CSP (concentrated Solar power), large hydroelectric dams, and large biofuel plantations; • A new era of innovation that provides effective and well-tested energy technologies; and • Renewable technologies benefit from the high technology development	• A move towards more water-intensive power generation will lead to a rise in water consumption. However, new technologies in processing primary energy, especially in the thermal electricity generation, as well as an increased use of renewable energy and improved energy efficiency, will have an impact on water savings; • Rapid technical progress could trigger water efficiency improvements in the energy sector, which then will translate into a decrease in water use intensities. However, the progress will be mainly in richer regions, whereas the energy sector in low-income counties may stagnate, with little progress in decreasing water use intensities; • Regional stress points will increase globally. Power generation in regional stress points will likely have to deploy more and more technologies fit for water constrained conditions to manage water-related risks, though this can involve trade-offs in cost, energy output and project siting; and • For additional implication: ref. implications for both SSP1 and 2 depending on the energy path. Continued use of nuclear power and large-scale CSPs, for instance, will intensify water use.

	SSP5: Fossil-fueled development-taking the highway	• Adoption of energy-intensive lifestyles; • Strong reliance on cheap fossil energy and lack of global environmental concern; • Technological advancements in fossil energy mean more access to unconventional sources; and • Alternative energy sources are not actively pursued	• The structure of the energy sector is driven by market forces, with water-intensive energy sources and technologies persisting into the future. Nevertheless, a rapid technological change may lower water use intensities; • The combined effect of structural and technological changes results in only moderate decreases in manufacturing water use intensities; • The development of unconventional oil and gas resources, which also raises notable water-quality risks, will increase water use intensity in the energy sector, especially for fuel extraction and processing; and • Regional stress points will increase globally. Power generation in regional stress points will likely have to deploy more and more technologies fit for water-constrained conditions to manage water-related risks, though this can involve trade-offs in cost, energy output and project siting.
Industry (Manufacturing)	SSP1: Sustainability-taking the green road	• Improved resource-use efficiency; • More stringent environmental regulations; • Rapid technological change is directed toward environmentally friendly processes; • Research and technology development reduce the challenges of access to safe water; and • Risk reduction and sharing mechanism	• The importance of the manufacturing sector in the overall economy decreases further due to the increasing importance of the non-resource using service sector; • Manufacturing industries with efficient water use and low environmental impacts are favoured and increase their competitive position against water-intensive industries; and • Enhanced treatment, reuse of water, and water-saving technologies; widespread application of water-saving technologies in industry

	SSP2: Middle of the road	• The SSP2 world is characterized by dynamics similar to historical developments; • Moderate awareness of environmental consequences from natural resource use; • Modest decline in resource intensity; • Consumption oriented towards material growth; • Technological progress but no major breakthrough; and • Persistent income inequality (globally and within economies).	• Manufacturing GVA further declines in relative terms; • Moderate and regionally different decreases of manufacturing water use intensities; • Following historic trends, water use intensities further decrease in the most developed regions, but there is less progress in Africa, Latin America and other emerging economies; and • Weak environmental regulation and enforcement trigger only slow technological progress in water use efficiencies.
	SSP3: Regional rivalry-a rocky road	• Low priority for addressing environmental problems; • Resource-use intensity is increasing; • Low investment in education and technological development; • Persistent income inequality (globally and within economies); and • Weak institutions and global governance	• Manufacturing GVA in relative terms (% of GDP) declines slower than historic trends; • Weak environmental regulation and enforcement hamper technological progress in water use efficiencies; • Very slow progress in water-saving technologies; and • Water use intensities increase only marginally, primarily in the most developed regions.
	SSP4: Inequality-a divided road	• Increasing inequality in access to education, a well-educated elite; • Rapid technological progress driven by a well-educated elite; • Persistent income inequality (globally and within economies); and • Labour-intensive, low-tech economy persists in lower income, poorly educated regions	• Manufacturing GVA in relative terms (% of GDP) declines in economically rich regions, but decreases very slowly in poorer regions; • Rapid technical progress triggers water efficiency improvements in manufacturing. However, the progress is mainly implemented in rich regions; and • The manufacturing sector in low-income, poorly educated regions stagnates, with little progress in decreasing water use intensities.

	SSP5: Fossil-fueled development-taking the highway	• A continued large role of the manufacturing sector; • Adoption of the resource- and energy-intensive lifestyle around the world; • Robust growth in demand for services and goods; • Technology, seen as a major driver for development, drives rapid progress in enhancing technologies for higher water use efficiencies in the industrial sector; • Local environmental impacts are addressed effectively by technological solutions, but there is little proactive effort to avoid potential global environmental impacts	• Manufacturing GVA in relative terms (% GDP) declines only slowly; • The structure of the manufacturing sector is driven by economics with water-intensive manufacturing industries persisting into the future; • Yet, there is rapid technological change in the manufacturing industry contributing also to lowering the manufacturing water intensities; and • The combined effect of structural and technological changes results in only moderate decreases in manufacturing water use intensities

Domestic	SSP1: Sustainability-taking the green road	• Inequality reduction across and within economies; • Effective and persistent cooperation and collaboration across the local, national, regional and international scales and between public organizations, the private sector and civil society within and across all scales of governance; • Policies shift to optimize resource use efficiency associated with urbanizing lifestyles; • Consumption and investment patterns change towards resource-efficient economies; • Civil society helps drive the transition from increased environmental degradation to improved management of the local environment and the global commons; • Research and technology development reduce the challenges of access to safe water; • Emphasis on promoting higher education levels, gender equality, access to health care and to safe water, and sanitation improvements; • Investments in human capital and technology lead to a relatively low population; and • Better-educated populations and high overall standards of living confer resilience to societal and	• Management of the global commons (including water) will slowly improve as cooperation and collaboration of local, national, and international organizations and institutions, the private sector, and civil society become enhanced; • Decreasing population will ease the pressure on scarce water resources; • Increasing environmental awareness in societies around the world will favour technological changes towards water-saving technologies; • Industrialized countries support developing countries in their development goals by providing access to human and financial resources and new technologies; • Achieving development goals will reduce inequality both across and within countries, with implications for improving access to and water quality in poor households, especially the urban slums; and • Higher levels of education will in poor urban slums improve awareness of household water management practices and in rich households induce behavioural changes towards efficient water use.

		environmental changes with enhanced access to safe water, improved sanitation, and medical care.	
	SSP2: Middle of the road	• Moderate awareness of the environmental consequences of choices when using natural resources; • Relatively weak coordination and cooperation among national and international institutions, the private sector, and civil society for addressing environmental concerns; • Education investments are not high enough to rapidly slow population growth; • Access to health care and safe water and improved sanitation in low-income countries makes unsteady progress; • Gender equality and equity improve slowly; • Consumption is oriented towards material growth; • Conflicts over environmental resources flare where and when there are high levels of food and/or water insecurity; and • Growing energy demand leads to continuing environmental degradation.	• Weak environmental awareness triggers slow water security and progress in water use efficiencies; • Global and national institutions, and lack of cooperation and collaboration, make slow progress in achieving sustainable development goals; • Growing population and intensity of resource aggravates degradation of water resources; • Access to health care, safe water, and sanitation services are affected by population growth and heterogeneities within countries; and • Conflicts over natural resource access and corruption trigger the effectiveness of development policies. •

	SSP3: Regional rivalry-a rocky road	• Societies are becoming more skeptical about globalization; • Countries show a weak progress in achieving sustainable development goals; • Environmental policies have very little importance. • Weak cooperation among organizations and institutions; • Global governance, institutions and leadership are relatively weak in addressing the multiple dimensions of vulnerability; • Low investment in education and in technology increases socio-economic vulnerability; • Growing population and limited access to health care, safe water and sanitation services challenge human and natural systems; • Gender equality and equity change little over the century; and • Consumption is material intensive and economic development remains stratified by socio-economic inequalities.	• National and regional security issues foster stronger national policies to secure water resource access and sanitation services; • Material-intensive consumption triggers higher levels of domestic water use; • Limited development in human capital results in inefficient use of water for households, especially in growing urban slums; • National rivalries between the countries slow down the progress towards development goals and increase competition for natural resources; and • Rational management of cross-country watersheds is hampered by regional rivalry and conflicts over cross-country shared water resource increase.

	SSP4: Inequality-a divided road	• Increasing inequalities and stratification both across and within countries; • Limited environmental awareness and very little attention given to global environmental problems and their consequences for poorer social groups; • Power becomes more concentrated in a relatively small political and business elite; • Vulnerable groups lack the capacity and resources to organise themselves to achieve a higher representation in national and international institutions; • Low-income countries lag behind and in many cases struggle to provide adequate access to water, sanitation and health care for the poor; • Economic uncertainty leads to relatively low fertility and low population growth in industrialized countries; • In low-income countries, large numbers of young people result from high fertility rates; • People rely on local resources when technology diffusion is uneven; • Socio-economic inequities trigger governance capacity and challenge progress towards sustainable goals; and	• Although water-saving technologies have been developed in high-income areas, low-income countries cannot benefit, as they lack financial resources for investments; • This results in prevailing unequal access to clean drinking water and sanitation; • Such inequalities are especially large in the growing urban conglomerates; • As social cohesion degrades, conflict and unrest over uneven distribution of scarce clean water resources become increasingly common, especially in mega-cities; and • As the poor and vulnerable lack the capacity to organise themselves, they have few opportunities to access water resources and security.

		• Challenges to land use management and to adapt to environmental degradation are high.	

	SSP5: Fossil-fueled development-taking the highway	• Global economic growth promotes robust growth in demand for services and goods; • Developing countries aim to follow the fossil- and resource-intensive development model of the industrialized countries; • Rise in global institutions and global coordination; • Social cohesion, gender equality and political participation are strengthened, resulting in a gradual decrease in social conflicts; • Higher education and better health care accelerate human capital development; • Investments in technological innovation are very high; • While local environmental impacts are addressed effectively by technological solutions, there is relatively little effort to avoid potential global environmental impacts due to a perceived trade off with progress on economic development; and • Environmental consciousness exists on the local scale, and is focused on end-of-pipe engineering solutions for local environmental problems that have obvious impacts on well-being, such as air and water pollution, particularly in urban settings.	• Access to water and management of domestic water use becomes more and more widespread in all world regions; • Development policies, combined with rapid economic development, lead to a strong reduction of extreme poverty and significantly improved access to safe drinking water and piped water access; and • Large improvements in water use efficiencies of household water appliances (toilets, shower).

Lambert and Vassorotti (2014) developed scenarios for the future of urban water utilities in 2040. The later work resonates with South Africa given that it was developed in Australia which bears a lot of climatic similarities with South Africa. It is insinuated that while the scenarios are based on Sydney Water, their implications are relevant to a wide range of other utilities. The scenarios developed are thus discussed in detail in the sections that follow.

2.1.4.2 The future of urban water: scenarios for urban water utilities in 2040: Assumptions

As earlier stated, the drivers of change that are most probable to occur are in general social, technological, economic, environmental and political. The assumptions used in the development of the scenarios are thus derived from these drivers of change. The assumptions are as follows:

1. Developed world: the assumption here is that the scenarios take a developed economy as a baseline;
2. Urbanisation: it is assumed that there is continuing growth of the urban populations;
3. Climate change: it is assumed that there is evidence of increasing frequency and intensity of extreme weather events;
4. Volatility: it is assumed that volatility is experienced in supply of water as a resource and that there is an overall increasing resource scarcity;
5. Efficiency: it is assumed that there is an efficient management of the utility irrespective of who owns the utility; and
6. Smart utilities: it is also assumed that there is a visible shift towards smarter utilities and technological progression is in place.

2.1.4.3 The future of urban water: scenarios for urban water utilities in 2040: Scenarios

Lambert and Vassarotti (2015) opine that the variation in future urban utility systems and experiences to a greater extent reflect two critical variables: Centralised versus Decentralised system and Separated versus Integrated utilities. The centralised versus decentralised system demonstrates the degree to which services and utilities are operated either a central point or separated locations while the separated versus the integrated utilities demonstrates the level to which utilities are cooperating across different types of utilities. Based on this premise, the scenario variables are developed as presented in Figure 2.5.

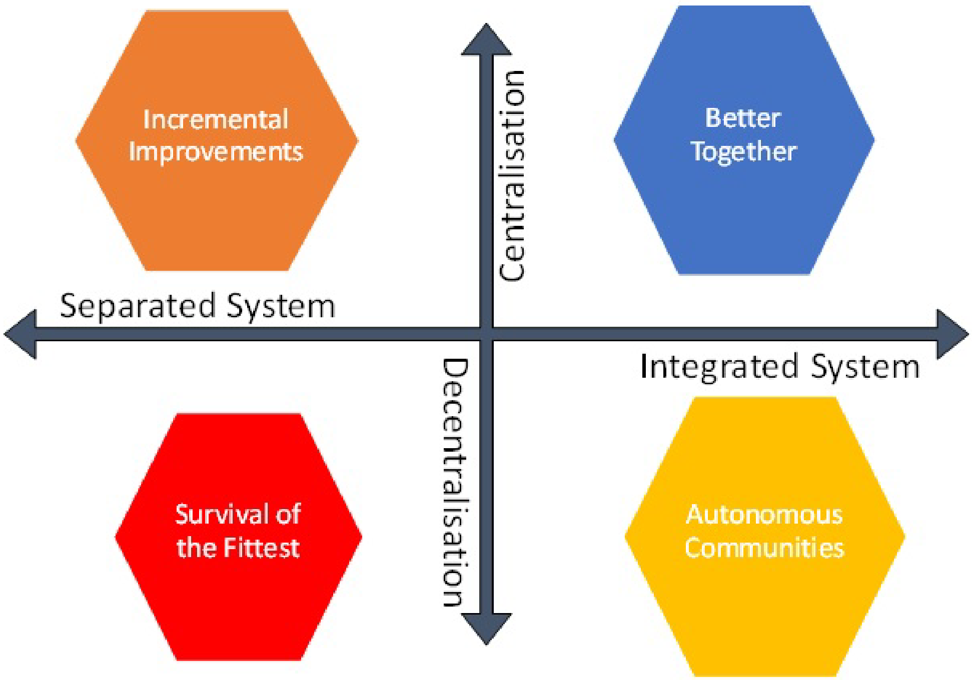


Figure 2.5 Scenario variables (adapted from Arup, 2014)

Table 2.4 is a summary description of each scenario variable as they appear in the respective quadrants.

Table 2.4 Summary of the scenario variables (information adapted from Arup, 2014; Lambert and Vassarotti, 2015)

Scenario variable	Description	Attributes	
		Item	**Description**
Incremental Improvements	Describes a world with little change to existing assets and operations. A centralised water supply system with a separated provision of utilities.	***Economy***	Slow economic growth coupled with economic uncertainty
		Consumers	Price driven consumption with little customer engagement and little concern for sustainability
		Industry	Focus on profit maximisation and conforming to regulation
		Technology	Focus on resource efficiency through limited deployment of smart solutions and utilisation of advanced technologies to deal with the consequences of climate change
		Energy	Continued overreliance on fossil fuels, but some expansion in renewable power generation
		Resources	Focus on efficiency, driven by price and scarcity, but little behaviour changes at the consumption level
		Environment	Unpredictable and extreme weather conditions continuously challenge the resilience of urban systems in need for upgrade

Scenario variable	Description	Attributes	
		Governance	Regulatory environment focuses on facilitating economic growth and reactive climate change related measures
Scenario variable	**Description**	**Attributes**	
Better Together	A scenario where industry and utilities better collaborate across a centralised system. A centralised water supply system with an integrated provision of utilities.	**Item**	**Description**
		Economy	Moderate to high economic growth driven by investment in clean technologies
		Consumers	Engagement between consumer and utilities enabled by smart systems to reduce consumption
		Industry	Focus on resource efficiency, circular economy, coopetition, and coordinated investments
		Technology	Application of smart systems to enable efficiency and effective integration across utilities and customers
		Energy	Maximised use of renewable energy, fully integrated with water and food supply
		Resources	Use of resources is monitored and there is a drive for reuse, recycling and avoidance
		Environment	Green infrastructure increases the resilience of urban systems while still having to deal with consequences of climate change
		Governance	Regulatory environment focuses on facilitating effective cooperation across utilities and efficiency measures
Scenario variable	**Description**	**Attributes**	
Autonomous Communities	Depicts a world in which households, communities and industry developed independence in water collection, processing and distribution while considering the interrelation of water, energy and food systems. A decentralised water supply system with an integrated provision of utilities.	**Item**	**Description**
		Economy	Moderate to high economic growth and an increase in independently operating businesses
		Consumers	Customer experience focused on independence, sharing, open networks and resource efficiency
		Industry	Clusters, autonomous systems and resource trading across industries with a focus on circular systems
		Technology	Virtual management of a decentralised network and increased use of data and advanced technologies on the community scale

Scenario variable	Description	Attributes	
		Energy	Dominated by small-scale and decentralised renewables operated by virtual power plants
		Resources	High resource prices and increasing scarcity foster local systems, including collection and supply
		Environment	Unpredictable weather conditions with green infrastructure measures implemented on the local scale dealing with weather events
		Governance	Focus on local and regional governance and a collaborative model
Scenario variable	**Description**	**Attributes**	
		Item	**Description**
Survival of the fittest	Replicates a scenario with greater competition for limited resources and restrictions to supply with high disparities in usage behaviour and access. A decentralised water supply system with a separated provision of utilities.	***Economy***	Prolonged period of recession and a lack of investment increases competition for capital and resources
		Consumers	Accessibility and price-driven consumer behaviour increases inequality
		Industry	Lack of reliable water supply forces extreme efficiency measures and some private water networks
		Technology	Smart technologies are deployed to monitor and control the restricted water consumption
		Energy	High energy prices and a failed shift to renewables
		Resources	Utilities fail to manage supply constraints effectively forcing restrictions on resource usage
		Environment	Continued environmental degradation and frequent extreme weather events, including an increase in droughts
		Governance	Strong restrictions on consumption and supply with access rights at the city scale

Each scenario with its attributes is expected to have a differentiated impact on the water resources, services and utilities management. A generalised impact analysis emanating from this study has been itemised under three key topical themes that is customer service and experience, infrastructure development and usage, and general governance. Table 2.5 is a summary depiction of such impacts on urban water utilities.

Table 2.5 Summary of the envisaged implication of each scenario described in Table 2.3 on urban water utilities (information adapted from Arup, 2014; Lambert and Vassarotti, 2015)

Scenario variable	Implication for Urban Water Utilities		
	Customer	Infrastructure	Governance
Incremental Improvement	1. Focus on customer services that are user-centric and that provide greater personal choice and control over service levels and pricing; 2. Expansion of water services that focus on meeting the requirements of individual customers and that engage people at the community level; and 3. Demand for higher levels of transparency and information in relation to metering, billing and customer satisfaction	1. Increased deployment of digital infrastructures and data analytics to manage, reduce or eliminate system peaks and fluctuating demand patterns; 2. Deployment of sensing technologies and metering to increase the quantity and quality of system information and enable real-time applications for asset management and customer service; and 3. Greater focus on existing assets, energy performance, and integrated infrastructure as part of maintenance and operating plans.	1. Higher levels of cooperation and integration between water, energy and telecommunication companies with a focus on integrated planning and maintenance; 2. Focus on deregulation and greater competition, both within the water sector and across complimentary utilities; and 3. Strategic focus on upgrading, improving and digitising existing assets in order to achieve better customer engagement and service feedback.
Better Together	1. Emphasis on creating a seamless customer experience across multiple integrated utilities, including shared billing, pricing and customer services; 2. Focus on maximising customer satisfaction and engagement through digital experiences, gamification and	1. Integration and sharing of assets and infrastructure across multiple utilities, including water, energy, waste and telecommunications; 2. Creation of smart and self-learning water distribution networks that is enabled by sensors and automation across water collection, processing,	1. Better cooperation between urban utilities through collaborative planning, integrated asset management, shared protocols and open data; 2. Emergence of third-party service providers that focus on integration and cooperation between customers, systems components and

Scenario variable	Implication for Urban Water Utilities		
	Customer	**Infrastructure**	**Governance**
	community-based water systems; and 3. Exploitation of synergies between multiple utilities and service offerings, with a focus on finding more efficient ways to meet customer requirements.	distribution and consumption; and 3. Implementation of green infrastructure solutions on a city and regional scale, with a focus on minimising the impacts of droughts, flooding and storm water.	utility providers; and 3. Increase in prices for service provision in order to enable investment in infrastructure improvements coupled with a higher number of investments that are shared by multiple utilities
Autonomous Communities	1. Greater focus on services that enable customers to manage and maintain autonomous water systems at building, community or cluster level; 2. Shift from customers that pay for the delivery of services to those that pay for the cost of installing and maintaining local infrastructure, either individually or collaboratively; and 3. Utility services focus on assisting with end-user system design, installation, information, maintenance and emergency response.	1. Provision of planning and infrastructure services that enable communities to develop, run and maintain autonomous urban water systems; 2. Shift to clusters of autonomous and self-regulated water networks that operate at a building or community level, independent of the wider grid; and 3. Increased deployment of digital infrastructure to facilitate resource trading and information sharing across a large number of autonomous urban water networks.	1. Governance and operation of autonomous systems and small-scale water networks through cooperatives, virtual networks and community platforms; 2. Change in legislation and building regulations to enable greater autonomy and smaller-scale applications in water collection, storage, treatment and distribution; and 3. Increase in small- and medium-sized utilities that focus on providing information, system design, installation, and maintenance services to autonomous communities.
Survival of the Fittest	1. Development of applications to provide customers with real-time data and information	1. Expansion of technology and systems to manage and minimise the impact of extreme	1. Implementation of differential water pricing and services according to availability of

Scenario variable	Implication for Urban Water Utilities		
	Customer	Infrastructure	Governance
	about water consumption, availability and pricing; 2. Increased disparity in the type of water services delivered to urban customers as service models are increasingly influenced by variable pricing and service packages; and 3. Usage of smart technologies within households, industry and networks to enforce, monitor and control efficient use, distribution and recycling of water.	fluctuations in water availability, including fast shifts from too much water to too little; 2. Focus on advances in decentralised and centralised water storage solutions, coupled with intelligent demand management and higher water recycling and reuse rates; and 3. Increased focus on monitoring and reducing illegal water trade and theft, coupled with a reduction in leakages and wastage across the existing network	supply, service plans, and customer behaviour; 2. Greater focus on autonomous and community-based water systems, where service and infrastructure levels are determined by private investors and income power; and 3. Resettlement of communities and industries into areas where resources are available and risks associated with urban water scarcity are reduced.

Analysis of the proceedings above does indicate that scenarios can aid water system managers and policy makers explore various pathways that the future might take. As a tool, scenario building is necessary in order to make sense of the many drivers of change in the water infrastructure, the governance of water as a scarce resource as well as the perception and expectations of the end-user (the customer). Pinkham (2006) indicates that some of those drivers will emanate from within the water sector while others will come from outside, from developments beyond the control of water managers. However, what is clear is that crucial changes, both physical and institutional will need to be faced in the urban water infrastructure. Deductions from the scenario analyses outcomes also indicate that urban water utilities encompassing water, wastewater, and stormwater service requirements can be disaggregated into many quality, quantity, and reliability attributes. Different end-uses, customer classes, and locations do have varying sets and subsets of needs that current one-size-fit-all infrastructure does not always meet effectively or efficiently (Pinkham, 2006; Arup, 2015). It is also important to bear in mind that there are many more technological and institutional ways to satisfy the various sets and subset of needs than current infrastructure systems and institutions provide hence from the scenario building, probable permutations on future operations, performance and how “water business” is carried out could developed for the purposes of informed decision making.

2.2 WATER SUPPLY SYSTEMS

2.2.1 Urban water supply systems

Urban hydraulic systems are dated in the Bronze Age (2800-1100 BC) (Mays, Koutsoyiannis and Angelakis, 2007; Angelakis and Zheng, 2015). According to Ashley and Cashman (2006), the first major water infrastructure systems were constructed around 3000 BC by the Egyptians and the Sumerians. Around this time China was formally irrigating and by 2000 BC Egypt was maintaining large dams. In the subsequent age, up to the birth of Christ, the Romans, Persians and others built major water supply and sanitation structures (Ashley and Cashman, 2006; Mays et al., 2007; Angelakis and Zheng, 2015). Some of these infrastructures have survived the elements to date. The advancements in urban hydraulic systems were largely in response to urbanisation and the growth of towns and cities (Ashley and Cashman, 2006).

Presently, a casual turn of the tap provides clean water which is a valuable resource. Engineering advances in managing this resource vis-à-vis water treatment, supply, and distribution systems changed life profoundly in the twentieth century, virtually eliminating waterborne diseases in developed nations, and providing clean and abundant water for communities, farms, and industries (UNESCO, 2005). As stated by the US National Academy of Engineering (National Academy of Engineering, 2016), water supply systems are among the five greatest achievements of engineering in the twentieth century. As populations continually move to urban areas for improved opportunities and a higher standard of living, and as cities merge to form megacities, the design and management of water supply systems serving these urban areas becomes an increasingly important part of regional integrated water resources planning and management (UNESCO, 2005).

Urban water infrastructure typically includes water collection and storage facilities at source sites, water transport via aqueducts (canals, tunnels and/or pipelines) from source sites to water treatment facilities; water treatment, storage and distribution systems; urban drainage works; and wastewater system, including stormwater and sanitary drainage, treatment, effluent disposal and management of residual sludge. Stormwater (or rainwater) systems manage runoff from rainfall and irrigation to avert flooding and consequent problems thereof. Stormwater systems are progressively needed to manage both quantity and quality of runoff. As runoff is generated and channelled, it amasses numerous contaminants found on streets, plots, feed lots, and parking lots in the urban environment. (Ashley and Cashman, 2006). Also, closely related to the water distribution is the fire protection systems that provide cities with on-demand, high-pressure water to combat fires. In early twentieth century cities, fire protection was often a critical component of water infrastructure projects, motivating greater centralisation to protect buildings primarily constructed of wood (Melosi, 2011).

Urban water management strategies evolve with changes in technology, environmental conditions, development patterns, and social attitudes (Porse, 2014). Simultaneously, probable alternatives are constrained by past decisions and prevailing infrastructure. Urban water systems are envisaged to face many challenges for instance, more stringent pollution regulations, water scarcity, increasing flood risks in coastal cities, and growing maintenance needs. Planners must design cost-effective systems that combine aging infrastructure with newly built components (Porse, 2014).

2.2.1.1 A problem of urban water infrastructure

Urban water infrastructure is considered sticky in the sense that the current system tends to persist and influence future development. Further, urban infrastructure requires large investments in capital and expertise thus creating an operational inertia that makes reformulating network structures difficult. Consequently, today's available choices are constrained by the past decisions (Porse, 2014). Porse (2014) further states that a central problem of urban water infrastructure is the tension between tendency towards long-term stasis and the need for advancements to respond to evolving challenges. This is exemplified by the fact that while the built infrastructure is relatively static, elements that influence economics and operation and output of urban infrastructure are very dynamic. For example, population changes can affect spatial or geographic demand for a particular service, e.g. water supply and technological advancements can also swiftly change infrastructure decisions. Customarily, in industrialised cities, systems were managed in different sectors, departments or even different agencies. However, with the new paradigm shift in water and other infrastructure management that seeks integration in planning and management, cities and other government agencies are rethinking the compartmentalisation of duties. This implies integrating duties which caveat is changing institutions that are path dependent.

2.2.2 Centralised versus decentralised water supply systems

Means of supplying water can be characterised along two axes. The one axis looks at infrastructure that can be either centralised or decentralised. The other axis deals with the water which is used: either freshwater only, for a single use; or alternative sources of water (OECD, 2009). Provision of centralised water, wastewater and stormwater services for urban areas has been common practise for over 100 years (Sapkota et al., 2015). The trend of centralisation in design and operation of urban infrastructure hastened through the industrial era during the sanitary reforms of the 19th and 20th century, driven by economies of scale and adherence to rational planning. Industrialised countries invested large amounts of financial resources in centralised water and wastewater infrastructure over an extremely long period of time making it macro-economically possible (Holler, n.d.). Conventional municipal water supply systems are characterised by the acquisition of fresh water from protected catchments, purification of raw water and safe distribution in sufficient quantities (Cook et al., 2009). Cook et al. (2009), further state that in centralised systems, only a small fraction of high-quality water supplied is used for drinking and cooking. A large quantity of water is utilised in flushing toilets and transporting the waste through sewers to the wastewater treatment plants. Currently, centralised drinking water systems serve millions of households globally. Centralised water supply is often considered the optimal water supply system due to its convenience of service. However, according a UNICEF WHO report, by 2008, only 57% of the global population accessed drinking water from a large-scale piped network. In the developing countries, only 49% of the population accessed drinking water through a large piped network with a big disparity between the urban and rural communities at 73% and 31% having access respectively (UNICEF WHO, 2011). It should be noted that the failure of centralised systems to provide clean, sufficient potable water is dependent on several factors that are either technical, economic or legal.

Centralised systems have provided considerable benefits to the modern society especially through the provision of safe and reliable potable water, improved public health through the removal and treatment of wastewater and flood mitigation. However, there is a growing realisation that there is a need for a change of tact in the provision of safe drinking water to a bigger majority of the population especially in the wake of aging centralised infrastructure, demographic changes, socio-economic factors, climate change, biodiversity, energy use, water supply and consumption (Sapkota et al., 2013; Hering et al., 2013; Sapkota et al., 2015). Most planners now recognise that the large-scale centralised systems may no longer be viable, due to high maintenance costs and resource needs. This is true for both water supply and wastewater infrastructure. Currently, the management of sustainable infrastructure is one of the most demanding global issues as urban centres continue to sprawl. However, conventional centralised infrastructure for water supply and wastewater treatment does not follow the demands of sustainable sanitation because it depends on an extended pipeline system (Hoffer, na). A growing emphasis on sustainability goals, along with concerns over scarce water resources, is driving municipal water managers to promote self-sufficiency, coordination, and flexibility through “portfolios” of water supply options (Porse, 2014).

Some identified disadvantages of using centralised systems

1. Due to the size of the distribution system, the conventional system requires high investment costs
2. The large networks incur high operational and maintenance cost
3. The magnitude of water losses is high due to the size of the network

4. The large amount of infrastructure needed for instance; treatment plants, pipes, pumps, etc. in many instances it becomes impossible to connect the entire population to the centralised system. The most likely to miss out are:
    a. The people in the rural areas where the settlement is dispersed and scattered over a large area; and
    b. The people living in informal settlements where connection to the central network is technically and economically infeasible
5. The central systems are often poorly maintained thus compromising on the quality and quantity (hydraulic and quality reliability of the system) of the water supplied.

In technological terms, as indicated in Ashley and Cashman (2006), the mode of delivery of water services must shift from the conventional hard engineering (large new assets) approach to a balanced soft-hard and environmental (or ecological) engineering approach that better considers the viability of local, regional and global regimes and accounts properly for whole-life perspectives. For long term sustainability it will be important to transform the management mode of water systems from "technical fixes" to appropriate systems that include community management and encompass a diverse range of delivery options (Ashley and Cashman, 2006).

Water, wastewater, and stormwater service requirements can be disaggregated into many quality, quantity, and reliability attributes. Different end-uses, customer classes, and locations do have varying sets and subsets of needs that current one-size-fit-all infrastructure does not always meet effectively or efficiently (Ashley and Cashman, 2006). One size does not fit all the different functions of urban water services for instance supplying potable water, non-potable water uses, rainwater management, sanitation, etc. Most appropriate scales for each function have to be combined and articulated (OECD, 2009). Unilateral centralised systems thus restrict opportunities to harness the potential of technical alternatives that are in demand and available in the market to support the utilisation of water on a fit-for-purpose basis.

Quoted verbatim, decentralised systems according to Cook et al., 2009, "*involve the collection, treatment and use of rainwater, stormwater, groundwater or wastewater at different spatial scales, from individual homes, clusters of homes, urban communities, industries, or built facilities, as well as from portions of existing communities either independent from or as part of a larger system*". Based on water sensitive urban design (WSUD) principles as well as the principles of integrated urban water management (IUWM) decentralised systems are being planned and implemented for urban development either as separate facilities or in combination with a centralised system (Cook et al., 2009).

2.2.2.1 Features of decentralised systems

As depicted in Cook et al. (2009), features that generally characterise decentralised systems can be identified as follows:

Rainwater tanks: Installed at individual dwellings and can also be used as communal tanks in a small community. Rainwater can be harvested and treated locally and used in various ways. Rainwater can be used in the kitchen and can also be used for hot water supply, toilet flushing, laundry and garden irrigation, which can contribute to significant reticulated water savings.

Stormwater Systems: Surface runoff generated from rain is known as stormwater. Subjected to appropriate treatment, stormwater can be used as an alternative water resource at sub-divisional scales. Stormwater can be stored and recovered for reuse by methods such as the Aquifer Storage and Recovery (ASR). Stormwater systems such as on-site detention tanks, buffers, swales, bio-retention devices and ponds are operated mainly for environmental protection and enhancement.

Greywater Recycling Systems: Greywater is used water sourced from the bathroom and laundry, and to a lesser extent, from the kitchen since kitchen wastewater contains higher concentration of gross contaminants as well as fats, oils and greases. Greywater is basically non-industrial wastewater generated from domestic processes. Reuse of treated greywater can significantly substitute reticulated water for non-potable use. It can be reused for irrigation, flushing toilets and other purposes. Greywater can be used immediately or treated and stored. An additional significant benefit from greywater recycling is the reduction of flow discharged to sewers.

Wastewater Recycling Systems: Wastewater is the used water from exiting living units, including greywater and blackwater carrying toilet waste. Only intended to be used for non-potable purposes. Treated effluent can be used in non-potable applications including garden irrigation, and can also be used for toilet flushing after disinfection and potentially for household supply. The end-use applications are influenced by the wastewater characteristics and treatment methods used.

Demand Management Strategies: Considered a “new tap” based on the WSUD principles, demand management strategies are an important component of achieving water supply/demand balance for an area. Demand management strategies reduce the total amount of water required to service a population

2.2.2.2 Classification of decentralised water supply systems

Based on the water supply, decentralised supply systems are classified based on the quantity of water they can supply (http://www.sswm.info/). Three main categories of decentralised supply systems can thus be discerned as follows:

1. Point-of-use (POU) supply: this treats approximately 25 L/day for one household;
2. Point of entry (POE) supply: this treats all water entering into a household, usually as an additional purification of water from a centralised supply; and
3. Smal-scale systems (SSS): this provides water to communities in quantities of 1000-10 000 L/day. They are often employed as emergency camp water supply systems

2.2.2.3 Pros and cons of flexibility through “portfolios” of water supply options

A study conducted for the OECD governments on the alternative ways of providing water: emerging options and their policy implications (OECD, 2009) identified some pros and cons of a variety of ways of providing water. Table 2.6 is a typical excerpt of the findings.

Table 2.6 Some pros and cons of a variety of ways of providing water

	Freshwater only	**Alternative sources of water**
Centralised infrastructure	**Pros** • Scale effects • Provides consistent services • Financial solidarity at municipal level **Cons** • A number of negative externalities (environmental, financial) • Capital intensive and fails to attract private capital	**Pros** • Positive environmental externalities (resource, wastewater discharge) • Financial solidarity at municipal level **Cons** • Costly (several networks) • Energy intensive
Decentralised infrastructure	**Pros** • Less water leakage in mains and less energy used to transport water • Reduced energy use • Flexible and resilient • Deferred and reduced investment costs **Cons** • Additional connections are needed for reliable sourcing • Unequal service provision in the municipality • Inadequate monitoring systems	**Pros** • Positive environmental externalities (resource, wastewater discharge) • Reduced energy use • Flexible and resilient • Deferred and reduced investment costs • May harness new sources of finance **Cons** • Health issues related to potable reuse • Questions about relevance when central infrastructure is in place • Scale effect • Unequal service provision in the municipality • Inadequate monitoring and regulatory systems

2.2.2.4 Benefits and drawbacks from alternative water supply systems

The primary drivers for shifting to decentralised water, wastewater, and stormwater systems are mainly the escalating infrastructure costs of the centralised systems, the ecological impact and the scarcity threat on water availability (Sapkota et al., 2015). Some of the identified benefits and drawbacks of alternative water systems are summarised as follows:

Potential benefits from alternative water systems

Generally, the semi-centralised approach offers a wide range of flexibility in implementation, energy self-sufficient operation, enormous saving potentials in water demands through intra-urban water reuse and further more advantages in comparison to centralised sectored solutions as practised today. Other benefits include:

- Reduced demand for fresh water resources resulting from diversified water sources and enhanced reliability of access to resource;
- Reduced volume of wastewater discharged into the environment;

- Reduced energy to transport water from the point of production to the point of use as a result there is also the added benefit of reduced greenhouse gas emissions (due to energy savings);
- Less infrastructure and deferred and reduced costs for the construction of networks;
- Relieving public finance from part of the investment burden, as new players are incited to invest their own money in the (decentralised) infrastructure; and
- Flexibility and adaptation to changes in population and consumption, land use, and technology

Though a lot of uncertainty still exist due to the limited experiences in using a combination of alternative water systems, there are some potential drawbacks that have identified through case studies (OECD, 2009) that are listed below:

- They can generate additional costs, in particular when not initially integrated in the plan for service provision and building construction;
- Integrated semi-centralised supply and treatment systems face the challenge of growing amounts of wastewater and solid waste combined with rising needs of water for private households and industrial use;
- The daily water demand reduction due to hybrid water system may have a negative effect on the travel time in the centralised water supply system, creating water age and potable water quality issues due to stagnation in the pipe network;
- They may have implications on the operational performance of the downstream infrastructure and existing treatment processes. For example, reuse of greywater reduces the wastewater flow, however there will be more concentrated contaminants flows going to the sewage system;
- They generate a number of risks, associated with the economy of water services at the municipal level. From a social and economic perspective, decentralised systems forbid cross subsidies and financial solidarity between rich and poor;
- It is not sure how decentralised water systems will contribute to a sustainable network. In particular, the combination of decentralised systems with existing, central infrastructures has to be reflected. Experience in this area is scarce, however some case studies have been conducted for instance Australia, Paris, and Calcutta (where wastewater treated locally can either be reused by the inhabitants or discharged into the municipal sewer) provide some references;
- From a revenue side, the financial attractiveness of alternative water systems is limited by the fact that revenues come from water tariffs and other charges and do not reflect the positive externalities for the society at large.

Points generating from the arguments for and against centralised and decentralised systems show that both systems should not be considered in isolation. Studies also show that centralised and decentralised systems do not need to be exclusive. Firstly, it is considered appropriate to speak of degrees of de/centralisation and secondly the communities can combine both approaches (OECD, 2009). A combination of centrally-provided and alternative water systems (decentralised) is progressively gaining consideration as the most practical in many cases. However, there is limited experience on the best way to combine both approaches and to actualise these approaches, more work needs to be done on the technical, regulatory, economic and financial aspects of this matter (OECD, 2009).

2.2.3 A paradigm shift in urban water management

In the face of uncertain access to resources, cities are increasingly recognising resource scarcity and climatic variability as global threats. The policy makers, managers, and technical experts are forming new types of knowledge themes, created in the essence of fraught cooperation and healthy competition, to develop policies of Secure Urbanism and Resilient Infrastructure (SURI). The strategies in SURI are at de-coupling cities from increasingly uncertain regional and national resource networks, in favour of advanced and sophisticated localised resource exploitation (Porse, 2014)

Studies show that present development of the world population is characterised by two major trends that is: absolute population growth and rapid urbanisation. Conventional centralised infrastructure of supply, treatment and disposal of water is not able to cope with the new challenges ascending from these trends which in history and incomparably developing at a high rate. In response, and for ecological, sociocultural and economic reasons, new approaches to infrastructure supply and treatment systems are required (Bieker et al., 2010). With the global growth of cities and increasing emphasis on environmentally-friendly urban development, a new paradigm of urban water resources is needed. Today, many cities are rethinking industrial-era approaches to building and maintaining infrastructure within the context of sustainability goals (Porse, 2014). Such sentiments are echoed for instance in Novotny et al. (2010) and Daigger (2011) who state that the new era underscores integrated water management and equal objectives for environmental quality, economic prosperity, and social development. Bieker et al. (2010), for instance refer to a semi-centralised approach that focuses on an integrated water supply and treatment structures for wastewater and waste on the neighbourhood level as a plausible solution to the challenges resulting from the rapid urbanisation and growing resource needs. They argue that shifting from centralised to semi-centralised supply and treatment systems will minimise the severe divergence between the rapid urban growth and the provision of supply and treatment infrastructure.

The new paradigm narrative of water infrastructure integrates water reuse, landscape-based contaminant removal through infiltration and green infrastructure, as well as conservation with the purpose of meeting the potentially competing goals of “sustainable” urban development. Apart from the technical integration, policies and institutional reform that integrates disparate functions and includes citizen involvement is also an important component of sustainable water management (Porse, 2014). Porse (2014) also reiterates the need for improved understanding of ecological processes as well as improved coordination between engineers, urban planners, architects, and city administrators to improve stormwater system design. Other measures identified in Porse (2014) as elements required in the success of the new paradigm include the following: codifying standards into city codes for new construction to minimise regulatory costs; local retention, storage, and water reuse for irrigation and drinking to potentially reduce long-term infrastructure and pumping costs. As stated in Brown et al. (2008), and Porse (2014), despite the fact traditional utility planning practices accentuated imported supplies and wastewater conveyance, the new era advocating for *water-sensitive cities* seeks to reduce per capita consumption by emphasizing more localised supply and reuse, environmental design, and citizen participation to create more *water-sensitive cities*.

The drivers metabolising the paradigm shift in urban water infrastructure and management can be summarised in five major themes as identified in Porse (2014) as follows:

1. The threat of climate variability and resource scarcity is driving many cities to revise their policies to accentuate energy and water self-sufficiency. Priority is also being given in developing resilient urban infrastructure
2. Silos or sectorial utilisation and management of resources is seen to be expensive hence the call for a cross-disciplinary planning processes
3. As the key service providers, cities have invested in innovation hubs for products that suit their purposes and reduced dependency on government funding
4. New tools for system analysis are being developed (e.g. SCADA) with computing power and big data analysis being the drivers of research to understand how systems can increase efficiency, reliability and performance
5. The shift towards greener cities drive new approaches for urban sustainability that link urban lifestyles with a more aesthetically-pleasing urban environment.

These emerging themes are influencing urban water management in several ways as summarised in Table 2.7.

Table 2.7 Emerging Paradigms in Urban Water Infrastructure Development (adapted from Porse, 2014)

Concept	Driving Factor
Integration: Longer-term planning across water, wastewater, and stormwater sectors	• Rise of integrated resources management approaches • Resource scarcity and climatic variability • Increasing management costs and need to identify multiple benefits for new projects • Recognised drawbacks of centralisation and compartmentalisation • Regulatory policies • Cost efficiencies in planning and delivery
Hybridisation: Combining centralised and distributed approaches in design (infrastructure measures) and management (expert institutions & community involvement) to meet environmental regulations and reduce costs.	• Large debt-burdens from capital-intensive infrastructure, forcing a reconsideration of past approaches • Opportunity to externalise costs for stormwater management and conservation to private sector through building codes
Resilience: Self-sufficiency (energy and water), portfolio approaches (set of options are prescribed), and risk-based planning for uncertain events, both chronic (e.g. long-term drought) and acute (e.g. hurricanes and floods), that can affect urban water systems.	• Long-term droughts and short-term floods due to climatic variability • Maintenance and outages • Catastrophic events that can cause large economic damages • Insecurity of existing resources and reduced availability of new water sources to support economic growth • Rise in crisis-related narratives
Cities as Innovators: Cities will continue to lead innovation in urban water management approaches, similar to nineteenth and early twentieth century. Cities have often provided the majority of funding, but were not always drivers of innovation.	• Reduced government funding and environmental regulatory involvement • Growth of cities as metropolitan regions and economic engines • Greater flexibility in city governments to solve problems • Political paralysis at the national level regarding long-term climate issues • Resident calls for greater sustainability • Ability to use local building codes to externalise government spending on treatment and conservation
Complex Systems: Understanding water infrastructure as complex networks with social, technical, and environmental components, which can yield emergent properties and have cascading effects.	• Rise of complex systems science and network-based analysis • Recognised opportunity to use management of network for increased flexibility • Rise of big data, with better visualisation and analysis tools • Opportunities for real-time management

Concept	Driving Factor
	• Predominant tendency to look to latest technology and innovation for solving environmental problems

Analysis of the emerging themes thus indicate that integration in planning for the management of the urban water cycle, hybridisation in water supply systems as well as resilience are key factors to consider in actualisation of the *water sensitive cities* concept. The quagmire though is that even as cities consider new strategies, they are constrained by past choices, a condition referred to by David (1985) and Liebowitz and Margolis (1995) as the *Path dependence*, or the tendency for past investments and actions to shape future strategies, that is strong in urban infrastructure.

In the *Path dependence* scenario, cities create and then retain bureaucratic and physical infrastructures to manage centralised systems, and prior investments influence the economics of operations. Yet, cities must examine strategies that update current systems to decrease energy and water consumption, improve environmental restoration, and promote amenities such as urban greening (Schott, 2004; Porse, 2014). Despite the strong path dependence in development agendas, cities are exploring many approaches to meet these challenges, including developing ***hybrid systems*** with centralised and distributed measures, incorporating climatic and resource uncertainty into planning, and shifting from expert-based management to include more citizen involvement.

Ashley and Cashman (2006), indicate the belief that the general populace will be best served if water authorities migrate towards a hybrid model which incorporates greater decentralisation and autonomous management of water supply, greater participation of additional service providers and smarter management of the water grid.

2.2.4 Trends in hybrid water supply systems

Water is an essential natural resource for the survival and well-being of human kind. Water demand has been increasing and continues to grow globally, as the world population grows and countries become wealthier and consume more (Wada et al., 2016). Water is needed for irrigation to meet increasing demands for food for growing population, it is also required for aquatic life, recreation and for industrial use. Population growth, improving standards of living, coupled with increased urbanisation and climate change are placing increased pressures on available water resources. Safe, affordable, easily accessible water and reliable water supply is vital for individual welfare and for the community development. According to Howard and Bartram (2003) it is estimated that 50 litres per person per day is needed for consumption and hygiene which includes personal and food hygiene, bathing and laundry needs. It is estimated that the growing food demands and increasing standards of living raised global water use approximately 8 folds from 500 to 4000 km^3 per year (Wada et al., 2016). As water demands approach the total renewable freshwater availability, each drop of freshwater gets increasingly valuable hence the need for efficiency and intensity in its management. Given that demand will but continue to increase, there is therefore, a need for innovative supply and demand management to achieve economic, environmental and social sustainability. Coleman et al. (2007), in assessing the challenges facing water resources management in South Africa evaluated the constraints and opportunities that set the background for a proposed framework for future resources analysis in the country. Several years on, and the framework of the water resource analysis is beginning to be put in place albeit with some adjustments. However, it is agreed that the challenges that the water resources planners faced then and now are not new. Coleman et al. (2007), reiterate that the core questions to be answered still follow: How much utilisable water is available? How are the water resources to be conserved and developed to meet the projected water requirements with water of a suitable quality? How can the sustained utilisation of the water resource be balanced with the protection of aquatic ecosystem through an appropriate implementation of the ecological reserve?

The one source, one system, and one discharge approach assume that all water should be treated to the drinking water standard regardless of the purpose for which it will be used (human consumption, industrial use, or garden and park watering). This is an inefficient use of money, energy, and water (Jacobsen, 2013). Matching water quality to its intended function is the future in many cities, and the present in some. For instance, the concept of water that is fit to a purpose has been implemented in the city of Durban, South Africa, to respond to a conflict between water demand for domestic use and economic development under conditions of water scarcity. The eThekwini Water Services developed a strategy to recycle wastewater as an additional water source for industrial use. At operational capacity, the reclamation plant meets 7 percent of Durban's water demand and reduces the wastewater discharge by 10 percent. As a co-benefit, industrial customers reduce their costs by purchasing reclaimed water rather than high-quality, potable water. Further to the fit for purpose water use, a diversity of solutions also is seen to provide flexibility. If water is scarce, then stormwater, greywater, and even wastewater are potentially economically attractive sources. Figure 2.6 presents the Durban scenario.

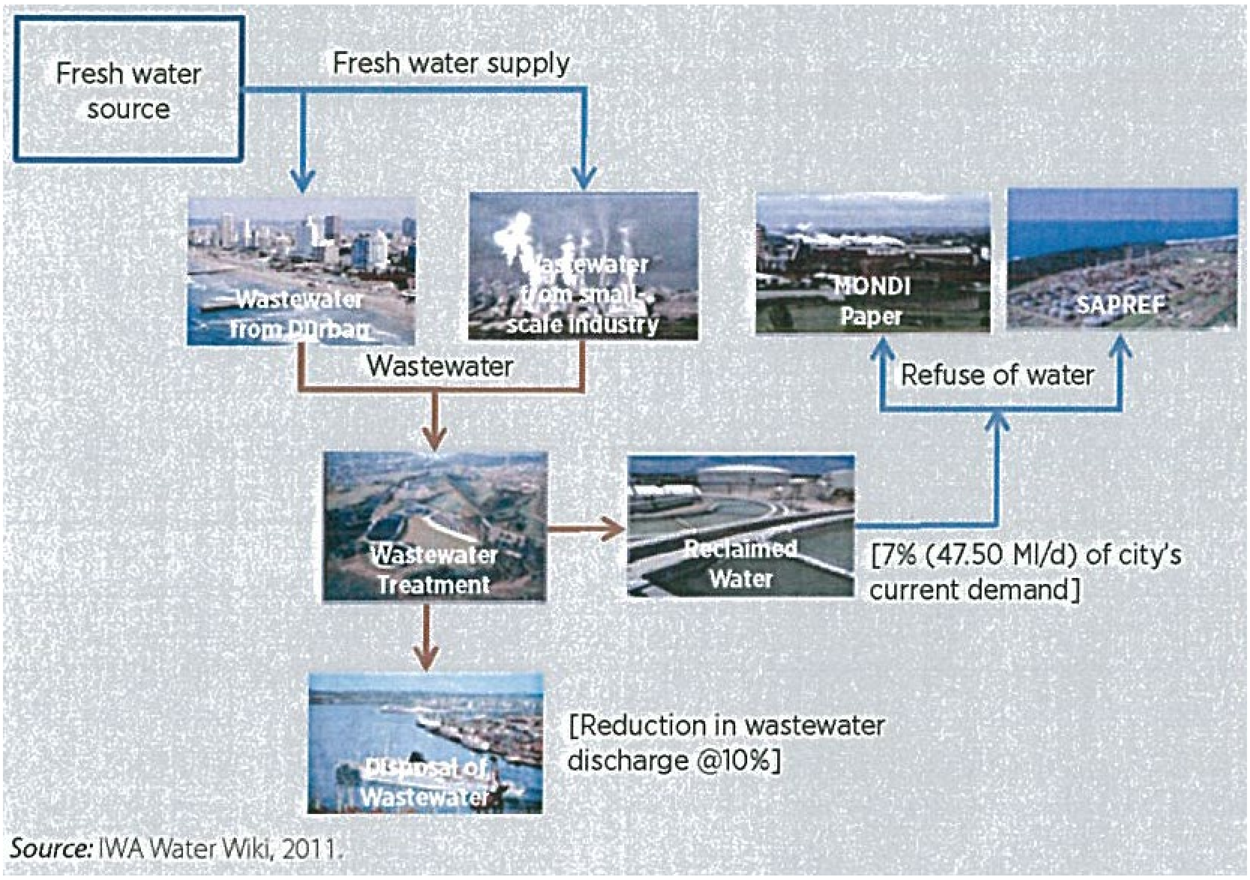
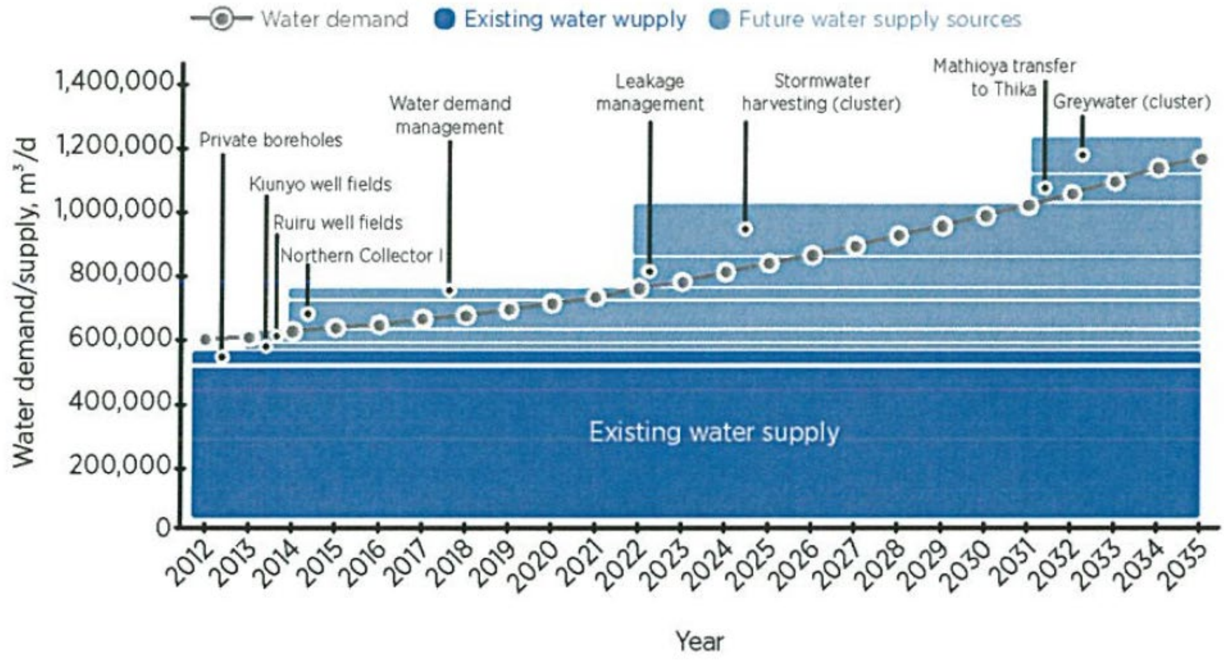


Figure 2.6 Dual benefits of water fit-for-purpose: reduced consumption of fresh water and reduced wastewater discharge (Adapted from Jacobsen et al., 2013)

It is a noted fact that large cities will continue to need massive infrastructure. However, an overreliance on major infrastructure makes cities vulnerable. By relying on a limited number of surface-water sources to supply centralised systems, cities put themselves at risk of increased competition for water, climate variability, and political wrangling. In preparations for future development, a case study for Nairobi shows a proposed cascaded approach to development of alternative sources of water as depicted in Figure 2.7.



Source: World Bank.

Figure 2.7 Proposed staged development of alternative water sources in Nairobi, Kenya, 2010 to 2035 (Adapted from Jacobsen et al., 2013)

A high priority is given to the study of alternative water supply which includes the use of centralised water supply system and decentralised water supply system, hybrid water supply systems. Water reclamation and reuse is a well know practice for creating additional water supplies and, thereby, increase the security of supply of urban water supply system. Factors affecting the selection of the optimum approach include local hydrology, available water supplies, water demands, local energy and nutrient-management situations, existing infrastructure, and utility governance structure. It is reported that integrating centralised and decentralised water supply and wastewater management, along with water reclamation and reuse, distributed water treatment, and rainwater harvesting, can offer the potential for increased urban water system security and sustainability. Implementation of these new approaches to urban water and resource management can lead to sustainable solutions, financial stability, using local sustainable water supplies, energy-neutral, responsible nutrients management, and access to clean water and sanitation (Sapkota et al., 2015).

Sekhukhune District Municipality (SDM) is an agricultural district hence a lot of emphasis is also put on irrigated agriculture. Good quality surface and groundwater resources are limited in the district. They are also diminishing due to urbanisation, contamination, and impacts of climate change. On this premise, proper allocation and management of these resources is a critical challenge for satisfying the rising water demands of the SDM agricultural sector. Previous studies in SDM have suggested the conjunctive use of groundwater and surface water resources as an alternative management option in efficient allocation and utilisation of the available water resources in the district. Conjunctive use refers to a coordinated and planned use of surface and groundwater. Literature suggests that it is now recognised that reclaimed wastewater is a water resource developed right at the doorstep of the urban environment. This implies that in a typical contemporary watershed, there are three recognised water resources for water supply meaning: surface water; groundwater; and reclaimed wastewater (Funamizu and Magara, 2016). Hence in a collective manner, conjunctive use could be referred to as a coordinated and integrated management and wise use of these water resources.

This study aimed to develop a framework for hybrid water supply systems for Sekhukhune District Municipality based on the ethos of the Water Sensitive Urban Design (WSUD) framework for South Africa. It is further envisaged that a model for conjunctive use of water in the SDM will be developed.

As earlier stated, a combination of centrally-provided and alternative water systems (decentralised) is progressively gaining consideration as the most practical in many cases. However, there is limited experience on the best way to combine both approaches and to actualise these approaches, more work needs to be done on the technical, regulatory, economic and financial aspects of this matter (OECD, 2009). As a beginning step, characterising and understanding the components that would make up the various combinations in the hybrid set up is paramount.

2.3 MANAGEMENT OF DECENTRALISED AND ONSITE WATER SYSTEMS

The operation and maintenance of decentralised systems is mostly left to homeowners resulting in many cases of system failure due to improper maintenance. Most of the home-owned decentralised wastewater treatment systems do not provide a treatment level that is needed to protect public health and the environment. It is imperative to develop policies, programs, guidelines, and institutions to ensure proper design, construction, operation and maintenance of the system. There is also a need for more integrated management of both onsite and cluster wastewater treatment systems. An integrated management will insure effective management that include economic, social, technical and environmental dimensions are taken into consideration. It is imperative to note that the needs and conditions of wastewater management vary within the same country and properly managed system will help protect public health and local water sources. These management systems should address the major problems related to wastewater treatment approaches primarily in a particular region (Massoud et al., 2009).

A good analysis and understanding of the urban water cycle provide a platform for the development of a working framework for the implementation of a decentralised water supply system. In the urban water cycle, the two main subsystems or components are: Stormwater and rainwater management. This includes the collection, treatment, distribution, use and disposal (or reuse) of harvested rainwater and stormwater as well as Wastewater management that includes the collection, treatment, and discharge or reuse of wastewater.

2.3.1 Rainwater harvesting system

Many urban areas suffer water scarcity but ironically, a local source of water such as rainwater is mostly considered as a risk rather than a valuable resource (Damenech and Sauri, 2011). However, recent developments show that rainwater harvesting is increasingly becoming an integral part of the sustainable water management toolkit (Ward et al., 2012). Rainwater harvesting (RWH) is the directly accessible water supply source and it provides water at the point of use. It may play a central role in widening water security and reducing impacts on the environment. RWH presents many benefits for urban sustainability and it is emerging as a key strategy in order to cope with water scarcity in cities (Ferreny et al., 2011). As stated in Mwenge-Kahinda and Taigbenu (2011), RWH as an innovative water technology has the potential to improve rural water supply and contribute to the provision of the first 6 kL of water consumed monthly. Operation and maintenance problems are reduced because families have full control of their own systems. Rainwater harvesting system is considered as a sound strategy of alternative water sources and it has become one of the economical and practical measures for providing supplementary water supplies with its easy installation system. The system has become a means of supplying water for growing and urbanising populations in Africa, Asia and South America (Vohland and Barry, 2009; Basinger et al., 2010; Domènech and Sauri, 2011). In Tanzania for instance, 50% of the area, people rely completely on rainwater. In urbanised areas, rainwater can be a supplementary water source for miscellaneous household uses such as toilet flushing, lawn watering, landscape and ecological pools and cooling for air conditioning (Peter-Varbanets et al., 2009; Su et al., 2009). Recent studies shows that potential potable water savings from rainwater harvesting could be significant; for example, in Brazil RWH practices could reduce residential sector potable water demand by 48-100%, in Jordan it is estimated that potable water saving from RWH implemented in residential sectors ranged from 0.27% to

19.7%, in Germany, where residential RWH practices emerged in the early 1980s, estimate that the average household could reduce potable water demand by 30-60% (Su et al, 2009).

There are three major forms of rainwater harvesting (Helmreich and Horn, 2010): in situ RWH, collecting the rainfall on the surface where it falls and storing in the soil; external water harvesting, collecting runoff originating from rainfall over a surface elsewhere and stored offside; domestic RWH (DRWH), where water is collected from roofs and street and courtyard runoffs. Generally, the challenges of rainwater harvesting are the seasonal variability in supply, the uncertainty of rainfall and unreliable water quality due to infection and regrowth during storage (Peter-Varbanets et al., 2009).

In a South African context, Mwenge-Kahinda and Taigbenu (2011) give a comprehensive analysis of the rainwater harvesting in South Africa: Challenges and Opportunities where further reading on the same could be sought. In their presentation, they give a history of RWH in South Africa including the various techniques used. Some of the challenges highlighted include the following:

The definition and classification of RWH: The key issue here is in the distinction between water harvesting (WH) and rainwater harvesting (RWH) whereby often the two terminologies are used interchangeably;
Financial Challenges: The challenge identified here is that some of the techniques are either too labour intensive hence create a challenge to poor communities to afford the needed labour and capital to put up security features for the sustainability of the system;
Challenges in Water Legislations: Identified here is the lack of a proper legal framework for the adoption of RWH; and
Institutional arrangements: lack of a national umbrella body that coordinates RWH is seen to not only hamper the expansion of RWH but also makes documentation of the practice difficult.

The opportunities identified include the following:
Government programmes: These include the Government initiated RWH programme that provided financial assistance for the implementation of storage tanks. A notable output of this programme is the developed set of guidelines that not only assist with the construction of underground tanks but also with the use and maintenance of the system;
Non-Governmental Organisations: A few NGOs promote RWH for domestic and agricultural purposes; and
Water Research Commission funded projects: Examples include the development of the micro-basin tillage technique in the municipal area of Thaba Nchu and the development of the Rainwater Harvesting Decision Support System (RHADESS) that analyses RWH from an integrated systems approach.

2.3.2 Rainwater harvesting as an alternative source of supply: rainwater quality challenge

2.3.2.1 Microbial and chemical quality of rainwater

Domestic rainwater harvesting (DRWH) involves the collection and retention of water in storage tanks. Microbial and chemical contaminants in DRWH tanks can originate from the polluted air that traverses with the raindrops, catchment areas and storage tanks (de Kwaadsteiniet et al., 2013). This necessitates that the entire system be monitored so that all possible points are monitored. Various factors affect the quality of harvested rainwater (RW) namely roof geometry, material, location and maintenance history of the roof; rainfall events; concentration of substances in the air and other meteorological factors (Abbasi and Abbasi, 2011). Thirty-seven West African cities were monitored to evaluate the suitability of DRWH. A holistic approach was introduced to determine the impact of structural design, environmental processes and public health knowledge to the risks of water and sanitary exposure. The intervention was designed to predict the potential health impact considering variables such as roof size, location of storage tank and storage capacity (Asano and Cotruvo, 2004).

The presence of microbial contaminants poses immediate health risks unlike chemical contaminants. Hence substantial research has been driven to microbial contaminants. Chemical contamination has adverse effects after prolonged exposure at low dose exposure. Even at low doses, it may pose cumulative toxic properties particularly heavy metals that have carcinogenic properties. This requires the need for policy makers to implement guidelines and constant monitoring that will allow users to trust unconventional water sources. The need for water security requires co-operation and partnerships from all stake holders in order to maximise efficient use of total water resources (de Wrachien and Fasso, 2007).

In the majority of the few studies that have been conducted, raised levels of lead have been detected. Lead levels above the recommended guideline pose neurological disorders among young children. Fluoride levels in rainwater are also below the recommended guidelines which necessitates supplementation in order to prevent dental decay (de Kwaadsteiniet et al., 2013).

Areas with intensive agricultural and industrial activities can result in collected RW with high chemical contaminants as RW traverses through the polluted air. A study conducted in Brisbane established that in 21% of the incidents recorded, concentrations of lead in the harvested rainwater exceeded the Australian drinking water guidelines. The primary sources were anthropogenic, attributed to traffic exhaust fumes and discharge and industrial discharges. This led to the community being discouraged to harvest RW for domestic use. Certain herbicides were also detected although levels were below the detectable levels (de Kwaadsteiniet et al., 2013).

Drainage pipes and roof top are significant sources of contamination. Depending on the type of material used in construction and its' maintenance, it can lead to contaminated run-offs. Acrylic and lead based paints also contribute to pollution as they leach to RW. An investigation conducted in Zambia observed higher zinc concentrations from roofs constructed from galvanized iron sheets. Although Korean studies have found suitability of four types of roofing materials, with galvanised steel being the most suitable. This necessitates further analysis and suitability to find suitable material to enable integration to future building ventures (de Kwaadsteiniet et al., 2013).

The significant presence of pesticides and polycyclic hydrocarbons (PAHs) in semi-urban and rural areas due to agricultural activities can contaminate RW. The presence of such chemicals was significantly noted during and immediately after application of fertilizers. The leaching of pesticides used as construction seals of flat gravel roofs posed a greater source of chemical pollution. PAHs are known carcinogens that originate from incomplete combustion of fossil fuels that can be deposited in dry and wet conditions. Household heating also produces PAH as observed in Belgium (Sanchez et al., 2015).

Whether RW is harvested in underground or above surface storage tanks, it is important that the material used for the storage tanks does not negatively influence the chemical characteristics of RW. An increase in pH was observed when RW was stored in concrete tanks when compared to non-concrete tanks (Zhu et al., 2004). The studies conducted in New Zealand and Canada found that the increase in pH was attributed to the leaching of calcium carbonate from concrete walls.

A relationship has been established between magnitude of rainfall in the region and quality of RW. In Jordan, higher concentrations of heavy metals were attributed to lower rainfall levels. It also found that during lower dry seasons, more contaminants are deposited into RW (de Kwaadsteiniet et al., 2013).

Organic contaminants that have been newly developed have also been detected in ground water. Such emerging organic contaminants (EOCs) also pose adverse human health. A broad survey conducted in 14 countries in Europe, Asia, Middle East and North America evaluated the occurrence and fate of EOCs in groundwater. Groundwater contamination by organic contaminants is strongly affected by physical and geological effects such as the degree of confinement of the aquifer. Arid environments have been shown to be particularly susceptible to ground water contamination by EOCs (Lapworth et al., 2012). Threats are also presented by severe sewer leakages that allow nitrate and ammonium concentration to rise. High rates of nitrate contamination can be reported in the high-density rural settlements in the Northern Cape, Northwest and Limpopo provinces in South Africa (Tredoux et al., 2009).

2.3.2.2 Rainwater contaminated due to atmospheric deposition in urban environments

The transfer of atmospheric pollutants to terrestrial and aquatic ecosystems can allow deposition of heavy metals, polycyclic aromatic hydrocarbons sulphates and nitrates. The sources of contamination are meteorological, particle characteristics and average interval between rain events. The source of nitrogen and phosphorus stems from natural sources such as roof runoffs containing bird faeces. Oceans are also significant sources of chlorides in rainwater and sulphates that originate from land soil and human activities. Coastal rainwater is strongly influenced by the sea-salt aerosols hence their presence (Sanchez et al., 2015). Atmospheric deposition of heavy metals builds up during dry seasons and are highly deposited during wet seasons due to high soluble fractions of heavy metals. Depending on the type of metal, some are suited to wet or dry depositions.

The significant presence of pesticides and polycyclic hydrocarbons (PAHs) in semi-urban and rural areas due to agricultural activities can contaminate RW. The presence of such chemicals was significantly noted during and immediately after application of fertilizers. The leaching of pesticides used as construction seals of flat gravel roofs posed a greater source of chemical pollution. PAHs are known carcinogens that originate from incomplete combustion of fossil fuels that can be deposited in dry and wet conditions. Household heating also produces PAH as observed in Belgium.

2.3.2.3 Microbial quality of water collected by DRWH

The quality of the harvested and stored rainwater depends on the characteristics of the considered area – such as topography, weather conditions, proximity of pollution sources, type of catchment area, material used for the construction of water tanks, handling and management of the tank (Kahinda et al., 2007; Zhu et al., 2004).

A number of researchers have conducted investigations on the microbial quality of harvested rain water. Contamination has been attributed to faecal deposits of birds and squirrels that are deposited on rooftops. Subsequent rainfall then enables the animal faecal droppings to be deposited into tanks via gutters. Hence E. coli biochemical phenotypes were detected. Further studies by Sazakli et al. (2007) found that highest microbial counts were detected during the autumn season.

It remains technically and economically impractical to assess the safety of water by conducting analysis of all known pathogens. Hence indicator organisms are monitored to determine the sanitary quality of the water. Heterotrophic plate counts also provide an indication of the general microbial quality of the water. Hetero trophic plate counts exceeding 500-1000 CFU/mL are indicative of poor microbial quality of water.

The presence of total coliforms and E. coli are also commonly used to assess the sanitary quality of drinking water because it would be technically impossible to test for all known pathogens. Although some researches have tested for coliforms as indicators of environmental contamination and E. coli indicative of faecal pollution (Abbott et al., 2012). The heterotrophic plate count (HPC) serves as an indication of the general microbial quality of water (Allen et al., 2004). However, it can detect opportunistic pathogens such as Aeromonas, Klebsiella and Pseudomonas hence it has been suggested that HPC be considered as a health-based drinking water parameter (Allen et al., 2004).

A five-year study conducted in rural New Zealand to monitor the microbiological content of roof-collected rainwater, found that more than 50% of the samples exceeded the minimum acceptable standards. The source of contamination was faecal from frogs, birds' rodents and possums. The source of faecal matter is deposited in the gutters and roof tops (Abbott et al., 2012). This phenomenon is however not limited to New Zealand as it has been reported in other countries (Zhu et al., 2004; Kahinda et al., 2007; Kwaadsteniet et al., 2013). The presence of total coliforms and E. coli is therefore expected under such circumstances which renders the water unsafe for human consumption. Abott et al. (2012), further classified the level of contamination, minimal to heavy based on the number of organisms present per 100 mL. This level of quantification poses health risks and would be misleading as they regarded less than 60 organisms per 100 mL acceptable of either total coliforms or E. coli. In a country such as South Africa facing the HIV/AIDS pandemic and other diseases it would be detrimental to subject people to contaminated rainwater. Water is considered potable if it has no faecal or total coliforms present (Kahinda et al., 2007).

The maintenance of the DRWH mainly consists of constant cleaning in the catchment area and interior of the storage tank at regular intervals as well as diversion of the first millimetres of rain. It is not feasible to clean the roof in order to prevent contamination from the roof top. Hence diversion of the first millimetres of rains is an option in order to exclude contaminants (Kahinda et al., 2007).

2.3.3 Water reclamation and reuse

Wastewater reclamation and reuse is an element of water resource development and management that provides an innovative and alternative option for agriculture, municipality and industries. It can significantly reduce the peak demand on potable water supply infrastructure. Reclaimed water can be used for groundwater injection to prevent seawater intrusion into potable water aquifers and for groundwater recharge to replenish exhausted aquafers (Daigger and Crawford, 2007; Sapkota et al., 2015). Water reclamation and reuse at local level has been limited by the availability of treatment technologies. Reclaimed water has mostly been used for non-potable uses such as toilet flushing, fire flow and air conditioning. The end-use applications of recycled wastewater are influenced by the wastewater characteristics and treatment methods used (Cook et al., 2009). There are several technologies available for wastewater treatment depending on the local conditions, intended use of the water and water quality standards. However, costs may vary, making the choice of the most appropriate technologies a sensitive decision (Sapkota et al., 2015). Currently, safe use of recycled wastewater still faces a greater challenge compared to greywater due to the need for more advanced treatment for the high levels of faecal microorganisms and the potential presence of pathogens, persistent organic pollutant and pharmaceuticals as well as the fear of the new emerging pollutants (Cook et al., 2009).

Groundwater recharge has been achieved with reclaimed municipal wastewater and found to be more desirable economically, environmentally and poses no burden on infrastructure. Soil-aquifer storage also renders the water free from pollution, evaporation and algal contamination. There are various ways of groundwater recharge namely surface spreading or percolation and direct aquifer injection. However, the utilisation of reclaimed municipal wastewater can pose serious concerns that may require pre-treatment. The microbiological content, total dissolved solids, heavy metals and harmful organic substances can render the water unacceptable and unsuitable for utilisation (Asano and Cotruvo, 2004). It is therefore necessary to design multiple-barrier systems to assure production of safe water in order to minimize risks and establish standards and guidelines for end user protection. Aesthetic considerations must also be taken into consideration if meant for potable consumption as it strongly affects consumer confidence. The lack of governing policies and guidelines on reclaimed municipal wastewater utilisation for groundwater recharge severely hampers adoption for large scale utilisation.

2.3.4 Stormwater harvesting system

Stormwater harvesting has received the most attention as a water resource among other alternative water resource such as greywater and wastewater reuse and desalination (Imteaz et al., 2011). According to Imteaz et al. (2011) in Australia, federal, state and local government authorities have been promoting stormwater harvesting through campaigns and offering financial incentives and grants to promote water saving ideas and innovations. The flora and fauna of receiving waters can be adversely affected by the increased runoff and discharge of polluted stormwater. Rainwater tanks are considered as a potent component of stormwater mitigation because it can protect urban streams by reducing stormwater runoff volume and the pollutants reaching downstream waterways (Sapkota et al., 2015). The use of stormwater as an alternative water supply is generally hampered by factors such as the area required for storage. However, this obstacle could be circumvented albeit temporarily by the application of alternative methods such as stormwater Aquifer Storage and Recovery (ASR) that offer opportunity to store stormwater and recover it for reuse. Stormwater systems such as on-site detention tanks, buffers, swales, bio-retention devices and ponds are operated mainly for environmental protection and enhancement (Cook et al., 2009).

2.3.5 The urban water cycle

The urban water cycle's main components, pathways, and alternative supply options in the urban water system are shown on Figure 2.8. There are three separate water systems within the urban water cycle. These systems are potable water supply system, supply-wastewater system and the rainfall-stormwater discharge system (Wong, 2007; Ashley et al., 2013; Sapkota et al., 2015).

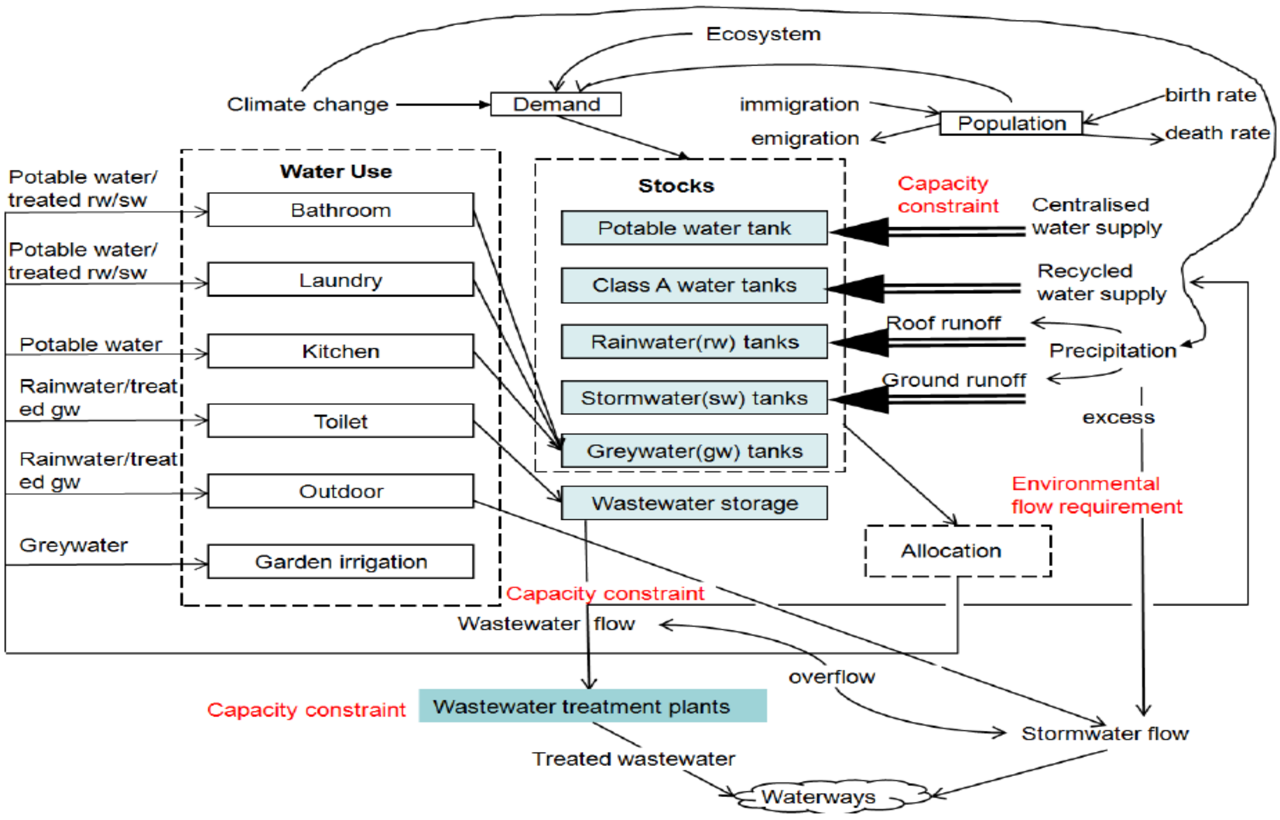


Figure 2.8 Urban water cycle's main components and pathways and novel technologies (adopted from Sapkota et al., 2013)

Water is supplied on a fit-for-purpose basis from various alternate sources (greywater, wastewater, stormwater and rainwater) along with centralised supply to meet daily demands. These systems are inter-dependent, interacting depending on the location, season and utilisation of wastewater and stormwater. To highlight the interconnectedness in this model, water supply, wastewater and stormwater have been considered in a single framework (Sapkota et al., 2013). Changes in one component of the water cycle can have impacts on the other components, thus addition of a different alternative water service infrastructure can bring changes to the overall urban water system.

2.3.6 Case studies on hybrid water supply systems

Several studies that focus on hybrid water supply systems have been conducted for various perspectives. A case study carried out in Qingdao, China has shown that the integrated semi-centralised approach offers flexible solution to cope with the new demands where certain thresholds of population density are exceeded. Studies focusing on large urban areas have demonstrated the capabilities of reducing potable water use and energy consumption. Cases from Australia, Europe and United State of America have illustrated the benefits of distributed water system. These cases were assessed based on their ability to reduce cost and resource use; improve service security and reduce risk of failure; strengthen local economies; strengthen community well-being, regenerate and protect the natural environment; and redefine traditional systems (Daigger and Crawford, 2007; Sapkota et al., 2013). Table 2.8 shows an example of large urban areas with hybrid urban water management systems.

Table 2.8 Example of large urban areas with hybrid urban water management systems (adopted from Sapkota et al., 2013)

Urban area	Urban area Hybrid system elements
New York City, USA	Decentralized wastewater collection and treatment incorporating 14 wastewater treatment plants.
Orlando, Florida, USA	Groundwater supply with reclamation of wastewater at several wastewater treatment plants and recharge to groundwater
Hampton Roads, Virginia, USA	Several water supply, treatment, and distribution systems. Interconnected wastewater collection system serving nine wastewater treatment plants. Local reclamation and reuse.
Metropolitan Area, Washington DC, USA	Multiple water supply systems. Multiple interconnected wastewater collection and treatment systems. In-direct potable reclamation and reuse practiced.
Southern California, USA	Imported surface water and local groundwater supplies, with groundwater recharge. Many wastewater collection and treatment systems incorporating multiple forms of water reclamation and reuse
Denver, Colorado, USA	Imported surface water and local groundwater supplies with several water suppliers. Several wastewater collection and treatment systems with multiple forms of water reclamation and reuse.
Sydney, Australia	Principally surface water supply. Several wastewater collection and treatment systems with water reclamation and reuse.
Republic of Singapore	Water supply based on “Four National Taps”: (1) Local water resources, (2) Imported water, (3) Desalination, and (4) Distributed water reclamation and reuse.
Bangkok, Thailand	Predominantly groundwater supply. Distributed wastewater collection and treatment using several systems at various scales.

Sapkota et al. (2016), conducted a study that assessed the interactions between existing centralised system and decentralised system. Figure 2.9 shows the generalised framework that was adopted. The study adopted a framework that considered the varying nature of urban developments and forms. Several analytical tools including water balancing modelling, contaminant balance modelling, multi-criteria decision analysis and future change analysis supported the framework. Impact of hybrid water supply systems on potable water, wastewater and stormwater flows was analysed. The framework was divided into two parts: the analysis of the physical system and the ranking method. Under physical systems analysis the framework explored the local conditions such as climate, geology, development pattern, future population projection and water demand, water resource availability, environmental flow requirement and wastewater and stormwater disposal limits, and system capacity quantities such as capacity of the water supply, sewage and stormwater drainage networks; water, stormwater and wastewater treatment plants. Specific objectives were set to meet water supply and demand, quantity and quality of wastewater and stormwater discharge and system capacity. The following criteria were set for the evaluation of the performance of hybrid water supply system: Reductions in potable water demand from centralised water supply systems; reduction in wastewater discharges, both flow rate and volumes; reduction in contaminant loads of wastewater flow; reduction in stormwater flows, both intensity and volumes; reduction of contaminant loads form stormwater to receiving water; improvement of supply reliability of fit for purpose water. Various hybrid water supply scenarios were developed in consultation with the water utilities that involved combinations of recycled water, treated greywater, rainwater tanks and stormwater tanks. Under proposed ranking method water and contaminant balance outcomes were evaluated against the specific objectives set out for water demand and system capacity. Empirical and analytical approaches which included cost benefit analysis, life cycle analysis, community cost incorporating life cycle and environmental cost, and various multi-criteria assessment methods were employed to provide an integrated assessment of hybrid water supply systems performance.

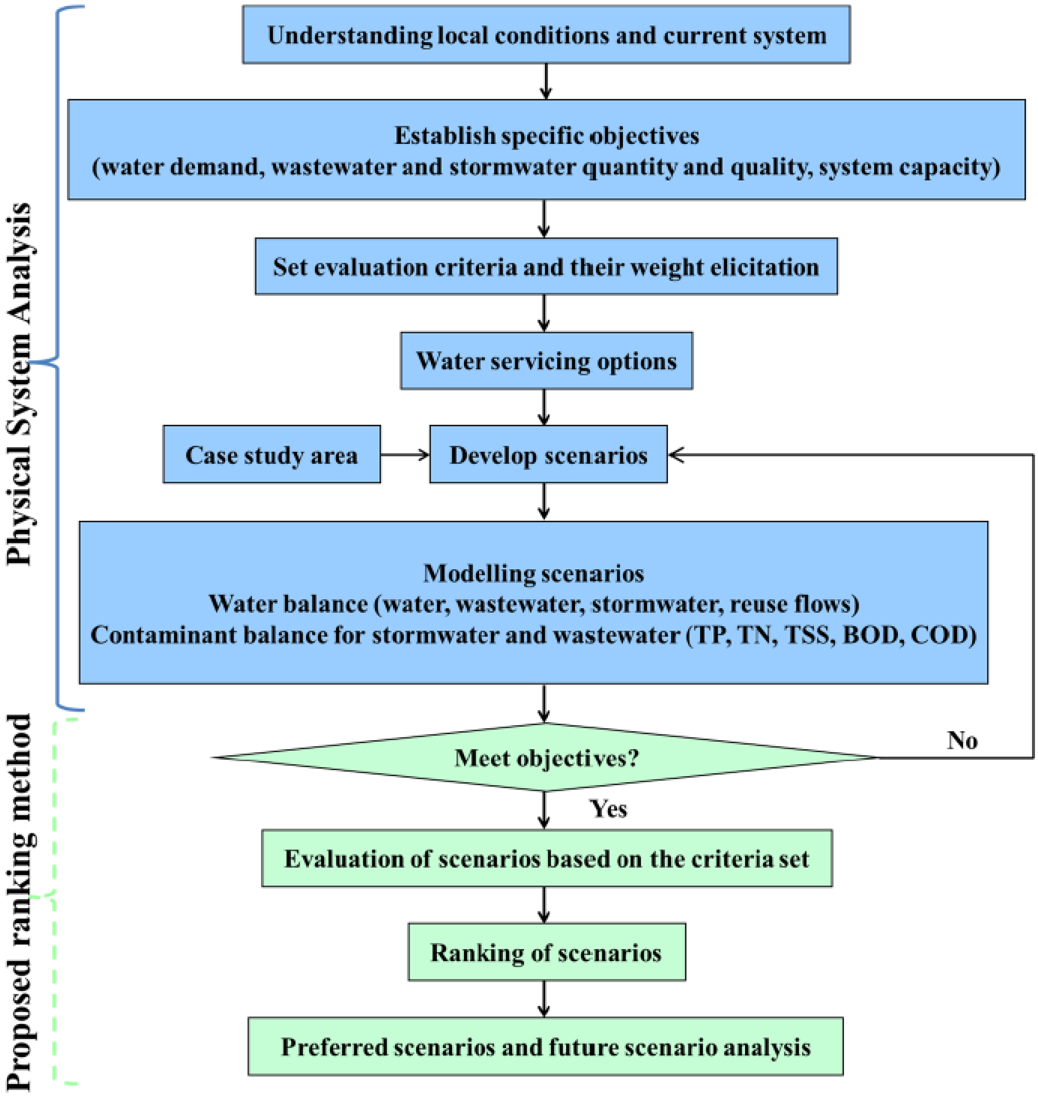


Figure 2.9 Framework to evaluate hybrid water supply systems (Sapkota et al., 2016)

Two scenarios were compared to illustrate the application for the framework. Scenario 1 considered only a centralised water supply system where the water demand was met by potable water. Figure 2.10 shows the schematic diagram of scenario 1.

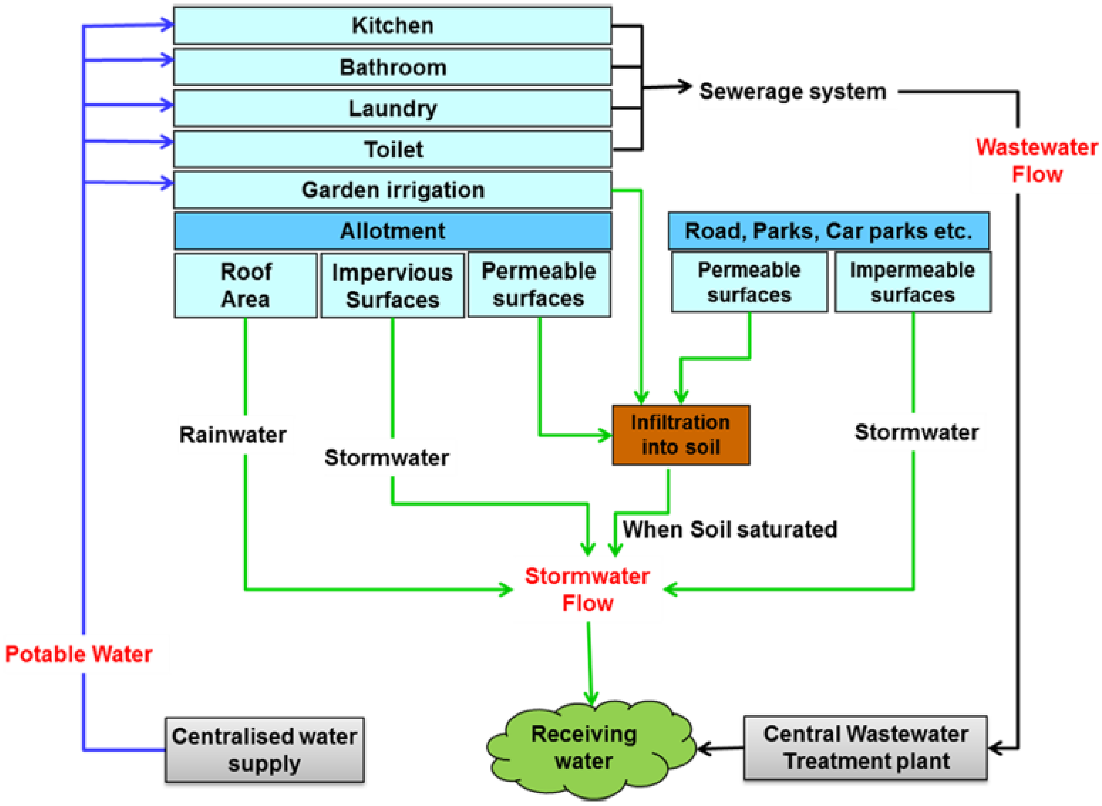


Figure 2.10 Schematic diagram of Scenario 1 (Sapkota et al., 2016)

Scenario 2 considered the combination of centralised system with treated recycled water. The scenario illustrated the effects of a decentralised water supply system on the centralised water infrastructure. Wastewater, in this scenario, was collected at development level and distributed through a dual reticulation system for toilet flushing and garden irrigation after treatment, the remaining water demand was met from potable water supply. Figure 2.11 shows the schematic diagram of scenario 2. Results showed that the use of alternative water supply combined with centralised water supply system can significantly reduce potable water demand and change wastewater flow and contaminant concentration. Hybrid water supply scenario uses 16.97% less potable water and generates 24.64% less wastewater flow as compared to centralised scenario.

A further analysis of scenario 2 showed that wastewater concentration was increased by 32%. Hybrid water supply scenario reduced the variability in potable water use (1.16-5.05 mL/day) compared to centralised scenario (1.4-6.11 mL/day). Changes in demographics and population was evaluated and results showed population changes having more significant effect on potable water use compared to climate change. For Scenario 1, potable water supply volume and peak was changed by 13.31% and 14.90% for increased population condition, potable water supply volume was increased by 3.81% for climate change condition. For climate change, wastewater flow volume was increased by 5.84% and increased by 4.76% for demographic conditions. Hybrid scenario was found to provide extra water needed for the area with relatively less change in daily average peak potable water supply under changed condition. The results from this case study helped to demonstrate that the framework is suitable to assess hybrid water supply and contributed in the understanding and implementation of hybrid water supply system in the development of sustainable and resilient urban infrastructure system.

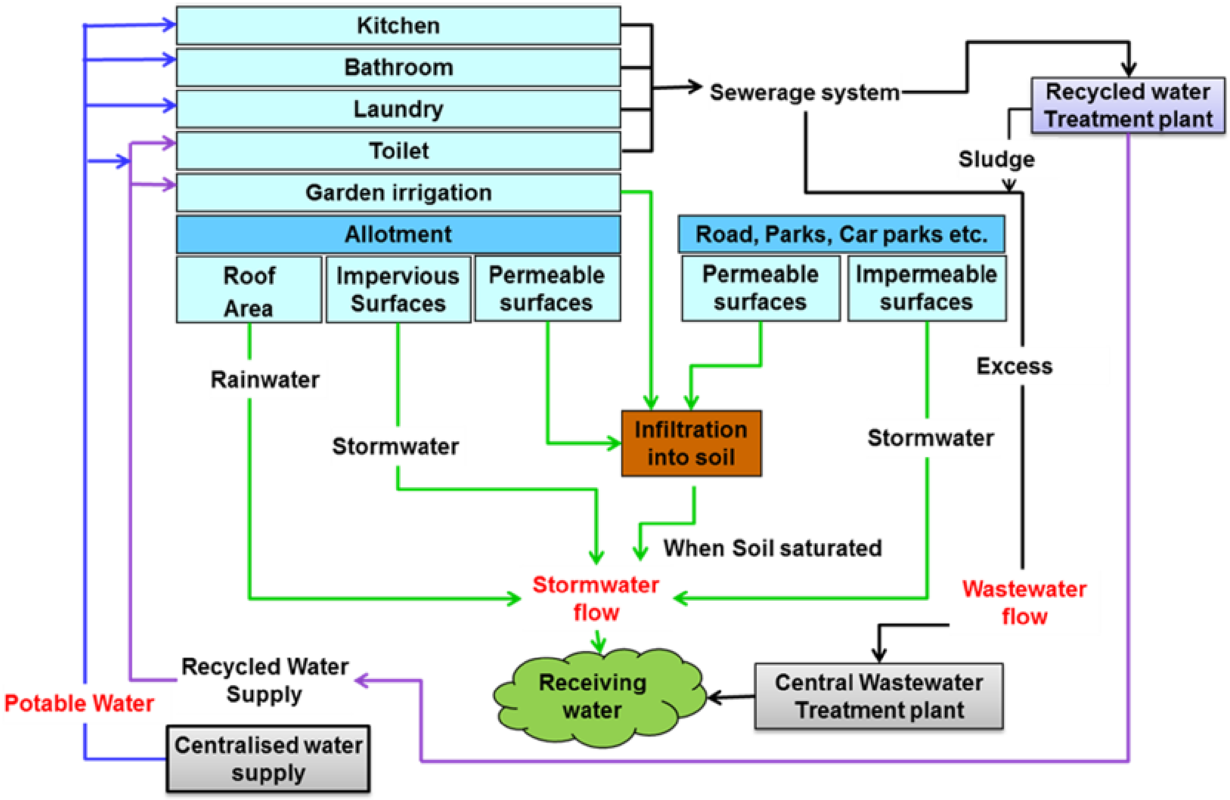


Figure 2.11 Schematic diagram of Scenario 2 (Sapkota et al., 2016)

2.3.7 Challenges in the assessment of hybrid water supply systems

As previously stated, there is limited experience on the best way to combine both centralised and decentralised (alternative supply) approaches and to actualise these approaches, more work needs to be done on the technical, regulatory, economic and financial aspects of this matter (OECD, 2009). Likewise, a dearth of information exists on systems set in place to assess the performance of hybrid water supply systems. Currently there is limited literature that present the assessment framework and empirically based evidence leading to an assessment of hybrid water supply systems. There are no methodologies that evaluate the impacts of hybrid systems on the interaction between centralised and decentralised infrastructures and the work by Sapkota et al. (2015), sets the tone for further work to be done in this field. Some framework has evaluated the environmental impacts of hybrid systems, but did not evaluate the impacts of hybrid systems implementation on the quantity and quality of wastewater, stormwater on centralised systems.

2.4 CONJUNCTIVE USE OF SURFACE WATER AND GROUNDWATER RESOURCES

2.4.1 Introduction

Water is arguably the primary medium through which climate change impacts will be felt by people, ecosystems and economies. Second to water, food security will be of major concern too. As one of the ways to address the impacts of climate change on water resources, South Africa, will, among other actions develop and implement an household rainwater harvesting incentive programme as well as implement integrated water resources management including protecting and restoring natural systems, increasing conjunctive use of surface and groundwater and learning through adaptive management experiments (http://www.climateresponse.co.za) . Water stress is one of the key manifestations of climate variability and change in Sekhukhune District. Further, water scarcity is considered to be the result of a combination of insufficient and highly variable rainfall conditions, issues of equitable water resource management, and the absence of drinking water, bulk water and irrigation infrastructure that would enable the distribution of water to all rural villages and hospitals (Ziervogel et al., 2006). There is an urgent need for the development of adaptive strategies not only at the local district level but at the Provincial and National level. One such strategy as stated above is the implementation of the IWRM including increasing conjunctive use of surface and groundwater resources.

Conjunctive or integrated water is recognised as an effective strategy for development and management of water resources. Conjunctive use systems are designed to increase the total available and usable water supply in a watershed. Given the connectivity of the surface and groundwater regimes in a hydrological cycle, the initial application referred to a coordinated and planned usage of surface water and groundwater. In that paradigm, the systems were developed either of the following reasons:

(a) In cases where water resources of either surface water or groundwater could not meet the demand; or
(b) In cases where the quality of groundwater was poor and mixing of groundwater with surface water was required to improve the water quality (blending).

However, in its contemporary application, the terminology has a broader concept now that incorporated the concept of deriving beneficial uses from treated municipal and industrial wastewater through reclamation, recycling and reuse as integral components of water resources management that may also include artificial recharge of groundwater. The purposes of artificial recharge of groundwater include the following:

(a) To mitigate the decline of groundwater levels due to excess groundwater withdrawals;
(b) To protect coastal aquifers against saltwater intrusion; and
(c) To store surface water including flood or surplus water and reclaimed wastewater

In the case of reclaimed municipal wastewater and recycled industrial wastewater, caution must be taken to protect the public from contamination and exposure to pathogenic microorganisms and toxic substances. These could be achieved through: (a) reducing concentrations of pathogenic bacteria, parasites, and enteric viruses in the reclaimed water; (b) controlling chemical constituents in the reclaimed water; and (c) limiting public exposure to the reclaimed water.

To many, conjunctive use is narrowly defined as a combination of surface water supplies through canals and use of groundwater through pumping. Forester et al. (2010), reiterates that adopting this rather ‘narrow definition’ excludes consideration of: the artificial recharge of aquifers with surface runoff or by rainwater harvesting (without direct supply from the surface water source); the use of groundwater pumping to support river base flows (without direct supply from water wells); and without direct augmentation of surface water with recycled/reclaimed water. With reference to conjunctive use in agriculture, it can potentially access four different water sources, i.e. groundwater, rainfall, canal water, and drainage water. Conjunctive use can cover any combination of two, three or perhaps all the four sources. It thus follows that in a simplistic and systemic form, the input-output relationship in basic conjunctive use model would be of the following order as shown in Figure 3.1:

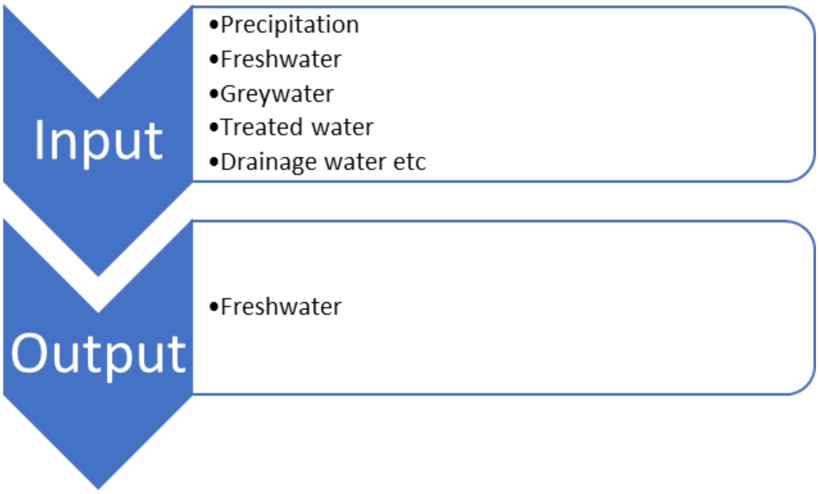


Figure 2.12 Input-output relationship in a basic conjunctive use model

2.4.2 Basic design principles

In designing a conjunctive water use system, one needs to strike a functional balance between the two main usage phases, i.e. the *Recovery Phase* and the *Recharge Phase*

- *Recovery Phase:* Occurs during the dry season when water is drawn from groundwater resources
- *Recharge Phase:* Occurs in the period when the water table is high and the use of the surface water is to be maximised. During this phase, the recharge of groundwater may be enhanced artificially by either surface or subsurface water recharge or both.

Balancing the recovery and recharge phase is fundamental to prevent against overexploitation of one source especially the groundwater. The degree of balancing impacts on the degree of modification of the hydrological system. For instance, in the water supply conjunctive use of groundwater and surface water resources, a typical hydrological modification resulting from a successful conjunctive use of groundwater and surface water resources is given in Figure 2.13. As reported in Foster et al. (2010), the form and shape of Figure 2.13 is a consequence of the successful operational strategy based on the following set criteria:

- Abstract preferentially from the river whilst its flow-level is above the minimum required for 'downstream' wastewater assimilation and dilution and/or ecological interests (except where river water is periodically not treatable because of high suspended solids and/or pollution)
- Use water-wells at other times, especially during extended drought when surface-water availability is limited – whenever possible ensuring that the impact of water-well abstraction is mainly delayed until higher river flow periods. One source may, however, not always be capable of completely substituting the other for capacity reasons, and it is the balance between the uses of the two sources that is varied.

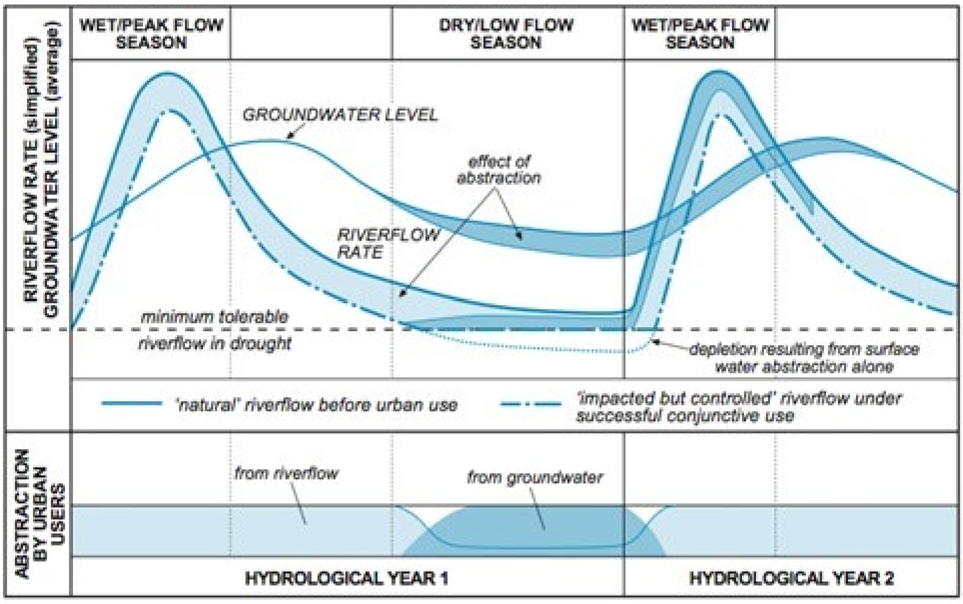


Figure 2.13 Typical hydrological modifications caused by successful conjunctive use of groundwater and surface-water resources for urban water-supply (adapted from Foster et al., 2010

2.4.3 Urban water supplies conjunctive use versus agricultural irrigation conjunctive use

Considering the simplistic definition of conjunctive water use as the combined use of surface and groundwater only, a distinction of the various uses can be made for the urban water supply and agricultural irrigation uses as either spontaneous or planned. Figure 2.14 presents the various use categories and their attributes.

Some benefits of conjunctive use of groundwater and surface water sources

Foster et al. (2010), identifies that in some form or other and with varying degrees of effectiveness, the conjunctive use of groundwater and surface water sources is capable of achieving the following:

- Much greater water-supply security. This is achieved by taking advantage of natural groundwater storage in aquifers
- Larger net water-supply yield than would generally be possible using only one source alone
- Better timing of irrigation-water delivery since groundwater can be rapidly deployed to compensate for any shortfall in canal-water availability at critical times in the crop-growth cycle; and
- Reduced environmental impact by counteracting land waterlogging and salinization, and excessive river flow depletion or aquifer overexploitation

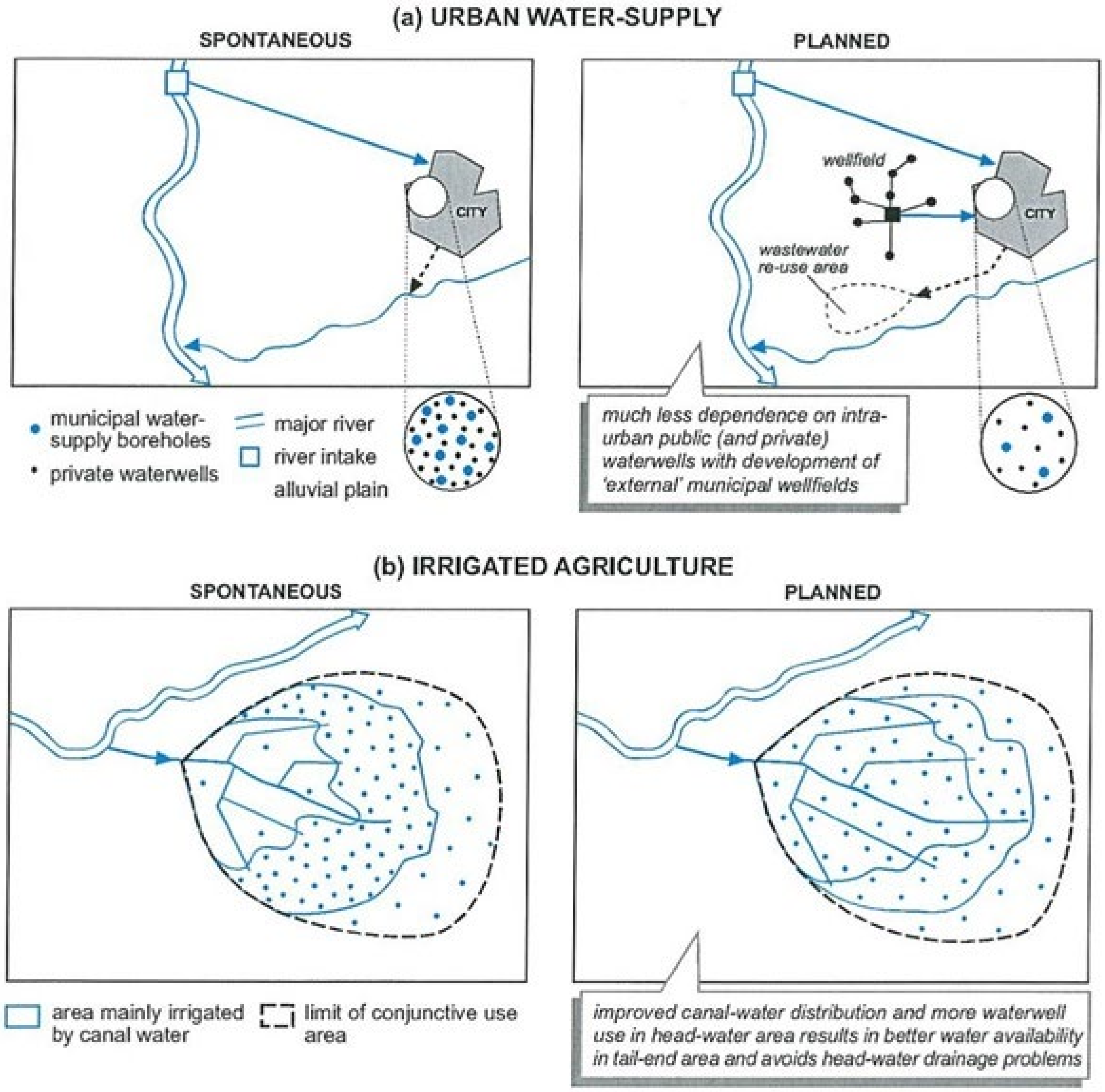


Figure 2.14 Typical schemes of conjunctive use of groundwater and surface-water resources for (a) urban water-supply and (b) irrigated agriculture with evolution from unplanned or spontaneous occurrence to planned development (adapted from Foster et al., 2010)

2.4.4 Threats emanating from uncontrolled conjunctive water use

Uncoordinated management of water resources may lead to sub-optimal use of scarce resources or to threats to the stability of land and water resources. The dynamics of conjunctive use in agricultural irrigation is varied depending on the hydrogeological regime including such factors as average rainfall and the geomorphological spatial location. Table 2.9 presents some of the identified threats arising from uncontrolled conjunctive use of surface and groundwater resources.

Table 2.9 Threats arising from uncontrolled conjunctive use of surface and groundwater resources

Threat	Main causes
Groundwater depletion	Unregulated growth of shallow tube-wells in areas of fresh groundwater
Soil salinization	• Excessive recycling of shallow groundwater leading to salt accumulation in upper layers of soil • Pumping of poor-quality groundwater to compensate for deficits in surface water supplies
Deterioration in groundwater quality	• Leaching of salt accumulation into groundwater • Depletion of shallow freshwater overlying saline groundwater • Lateral intrusion from saline groundwater
Inequity of access to water resources	• Tail-end water users forced to pump excessive amounts due to excessive use of surface water resources by head-end farmers

Figure 2.15 presents some of the salinization mechanisms that can threaten sustainability of conjunctive use of groundwater and surface. This is for the case of alluvial plains.

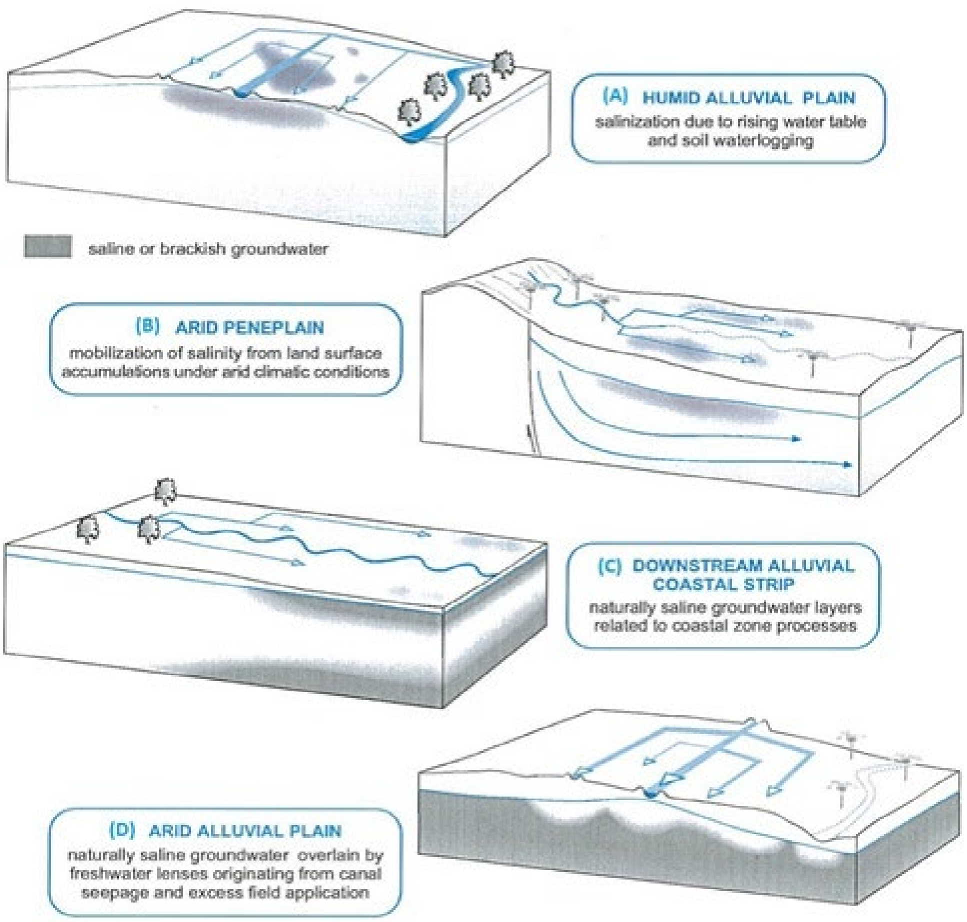


Figure 2.15 Groundwater salinisation mechanisms that can threaten sustainability of the conjunctive use of groundwater and surface water (adapted from Foster et al., 2010)

2.4.5 Conjunctive use in Greater Sekhukhune District Municipality

In an effort to destigmatise the perception that groundwater may not be a useable water resource in South Africa, du Toit et al. (2012) carried out an analysis of datasets in the newly established groundwater data repository, the Limpopo Groundwater Resource Information Project (GRIP). The findings demonstrated that large quantities of groundwater can be obtained and used for bulk supply if the drilling sites are scientifically selected thus pitching groundwater as a strategic water resource in rural Limpopo Province. Groundwater resources in the Province accounts for almost 70% of rural domestic water supply. The resource is available throughout the Province in varying quantities and qualities depending on the hydrogeological properties of the underlying aquifer (du Toit et al., 2012). As indicated in du Toit et al. (2012), groundwater resources can have a competitive advantage, especially within the short-to-medium term solution space, vis-à-vis the following:

- As a conjunctive resource: It can be utilised as an alternative (primary or secondary) water resource together with surface water to meet water demands;
- For rapid development: In instances where high-yielding aquifers are quite common like in South Africa, such can be developed at or close to the user within a short space of time; and
- In phased development: When developing a multiple of sources (alternative supply) that need to be considered for use within the next 20 to 30 years of planning at different intervals.

In a study conducted by du Toit et al. (2012), key findings were that in Limpopo province, the value of conjunctive use cannot be underestimated and therefore short-to-medium term solutions provided by groundwater need to be combined with surface water solutions to provide the optimum solution, where groundwater resources can be developed first, followed by a surface water resource. Despite viability of conjunctive use solution however, the study also found that chemical and bacteriological data show all boreholes to be Class 2, 3 or 4 and raw water is not suitable for domestic supply. This would thus imply that the costs to treat the water to potable standards may still have to be added to the development costs. Probable solutions would also include blending for instance with rainwater harvesting and conventionally treated potable water in order to meet specified fit-for-purpose standards.

2.4.6 Techniques for modelling conjunctive use of groundwater and surface water

A critical challenge that mankind has to face and cope with is how to manage the intensifying completion for water among the growing urban centres, agricultural sectors and instream water uses. These compounded by the adverse effects of climate change. Basin-wide strategies including integrated utilisation of surface and groundwater resources are plausible but need proper and judicious planning and decision-making tools. Conjunctive use modelling of surface and groundwater resources has a wide range of applications in the fields of water resources management, ecology, eco-hydrology and agricultural water management (Ramesh and Mahesha, 2012). Conjunctive use models are developed based on the purpose and objective as well as the technique used. Conjunctive use models may be classified as follows:

- *Simulation and prediction models*: They provide a framework for conceptualising, analysing and evaluating stream-aquifer systems. To simplify their solutions, various numerical models using finite difference or finite element methods have been used for their solutions. Simulation and decision support tools have shown to be valuable in planning and management of regional water (Ramesh and Mahesha, 2012)
- *Dynamic programming models*: They elucidate the endogenous structure of the system under study, to observe how the different elements of the system actually relate to one another and to experiment with changing relations within the system when different decisions are included. They have the advantage of modelling sequential decision-making processes, and applicability to nonlinear systems, ability to observe stochasticity of hydrological processes and obtain global optimality even for complex policies. Biggest drawback is dimensionality.

- *Linear programming models*: Most widely used in conjunctive use optimisation models. problems of nonlinearity may arise depending on the set up
- *Hierarchical optimisation*: The constraint region is implicitly determined by a series of optimisation problems which must be evaluated and solved in a predetermined sequence
- *Nonlinear programming models and others*: For Conjunctive use, the solutions with nonlinear constraints are nonlinear

Ramesh and Mahesha (2012) indicate that despite the many complex optimization models and techniques cited in literature, most conjunctive use optimisation work reported in literature deal with hypothetical problems, simple cases or steady state problems.

Some developed conjunctive use models:

- A simple groundwater balance model
- A GIS linked conjunctive use groundwater-surface water flow model (MODFLOW)
- Interaction of surface water and groundwater modelling
- Integrated Groundwater and Surface water Model (IGSM)
- Conjunctive use optimisation model
- Linear optimisation model
- Non-linear optimisation model
- Multi objective conjunctive use model

CHAPTER 3: DOMESTIC RAINWATER HARVESTING POTENTIAL AND RAINWATER HARVESTING SYSTEMS SELECTION FRAMEWORK

3.1 INTRODUCTION

3.1.1 A brief on service delivery in SDM: Access to water

Sekhukhune District Municipality is a mainly rural district with 117 administrative wards and a total of 764 villages. The District is made-up of four Local Municipalities, namely; Elias Motsoaledi, Ephraim Mogale, Makhuduthamaga and Fetakgomo Tubatse. The main towns in the district being: Burgersfort, Steelpoort, Groblersdal, Marble Hall, Apel, June Furse, Mohlaletsi, Driekop, Penge Mine, Prakiseer, Motetema and Mosterloos. 46% of the total area of the SDM is State-owned land (46% of SDM is designated as Municipality Area). 48% is designated as Traditional Authority Area (Department of Rural Affairs and Land Reforms – DRDLR, RSA, 2019). The Traditional Authority Area is made up of villages that are scattered throughout the area. Therefore, providing centralised service delivery is quite a challenge to the municipality. The implication therefore is that service delivery systems are distributed. By extension, development of stormwater and on-site domestic rainwater harvesting systems is also distributed.

As noted in the SDM Development Plan 2021, 10.26% of the households in the district have piped water inside the dwelling; 38.82% of the households in the district have piped water inside the yard; 17.88% of the households in the district have access to communal piped water at RDP-level of service that is less than 200 m from their dwelling; 16.40% of the households in the district have access to below RDP-level of service of communal piped water located more than 200 m from their dwelling; and 16.64% of the households have no formal piped water. These statistics translate to approximately 33% of households in the district living in below RDP-level service to no service at all that require alternative sources of potable water. This scenario presents an opportunity for the district to explore the on-site domestic rainwater harvesting and stormwater harvesting systems as alternative water supply sources for domestic use.

3.1.2 Rainwater harvesting and stormwater harvesting

Rainwater harvesting and stormwater harvesting are terminologies that are often used interchangeably in literature. However, the distinction is made between the two as follows: Rainwater harvesting is the direct capture of rainwater mainly from rooftops. It is thus the process of collection, treatment, storage and distribution of rainwater for supplementary on-site uses such as toilet flushing, clothes washing, and irrigation and if treated to potable standards may be used for drinking and cooking, it may also be used as an emergency water supply or a complete off-the grid system. It can be stored in water tanks or reservoirs. Rainwater harvesting can either be active or passive. As an active process, the harvested rainwater is stored in tanks for later use while as a passive process, the harvested water is stored directly in the ground. Stormwater harvesting is the collection, treatment, storage and use of stormwater runoff from pervious or impervious surfaces (Viljoen, 2014).

3.1.3 Passive rainwater harvesting systems

Passive rainwater harvesting systems utilise land contouring and other methods to collect, direct, and infiltrate rainwater directly into the soil for useful purposes. These systems help in managing stormwater and aid floral growth. By retaining water on-site, the systems reduce the off-site runoff that could contribute to flooding and pollution. A typical passive system consists of the following components (City of Bellingham, 2012):

- Catchment surface: this is considered as the pervious or impervious area that water flows off of. For example, the roof top, driveway or the sloped part of the compound;
- Infiltration area: consists of the depressed, mulched, and vegetated surfaces where water is captured and infiltrated into the soil. Types of infiltration areas include bio-retention swales, rain gardens, micro-basins among others; and
- Overflow structure: this is a structure that allows excess rainwater to flow out of the infiltration area to a desired location. Figure 3.1 presents examples of passive rainwater harvesting systems.

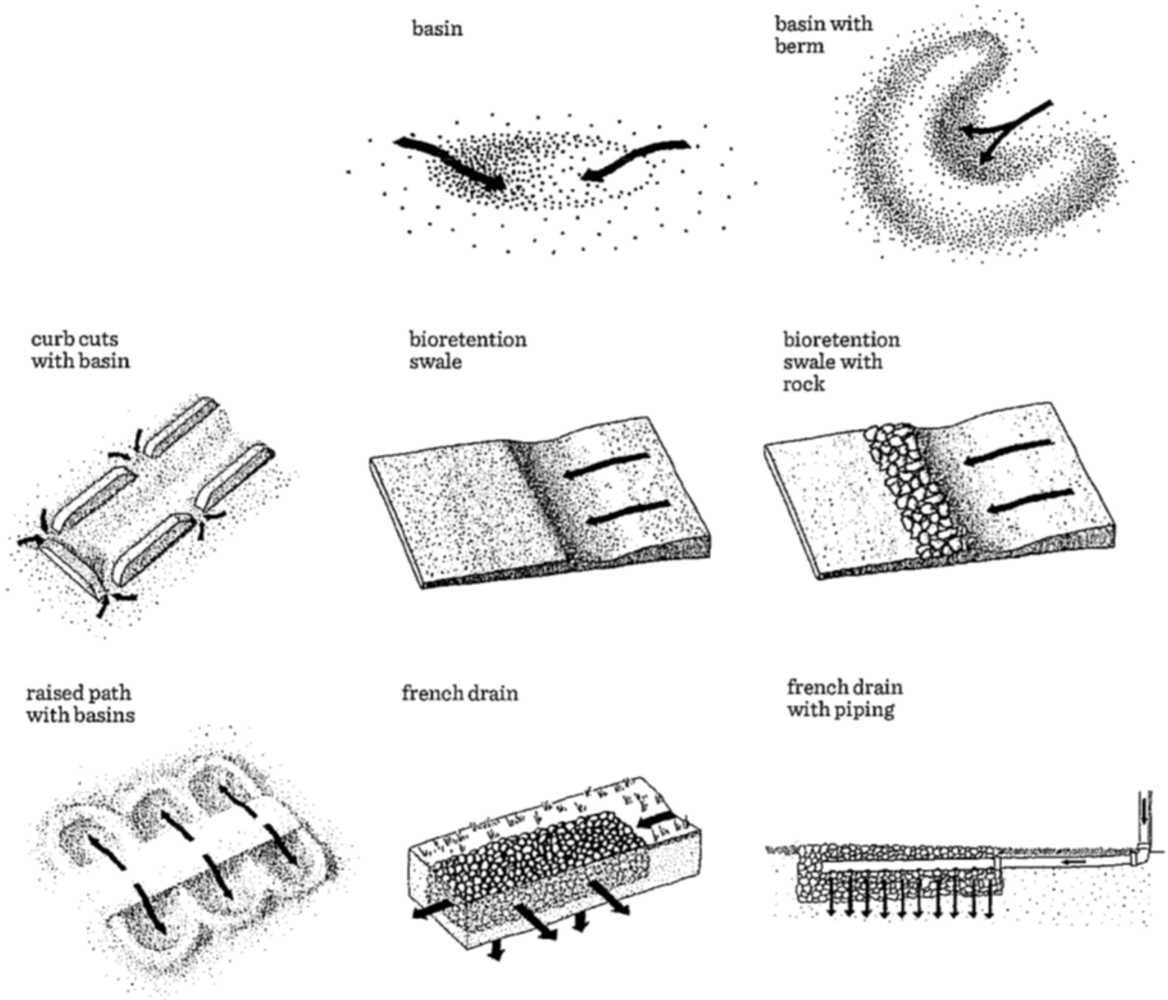


Figure 3.1 Examples of passive rainwater harvesting systems (Adapted from City of Bellingham, 2012)

3.1.4 Active rainwater harvesting systems

Contrary to the passive systems, active systems utilise kits designed for collection, filtration, storage, and delivery of harvested rainwater. The storage component extends the usage time for both indoors and outdoors purposes. Collection systems do vary in size. If storage is above ground then the water is mostly delivered through gravity. However, for below ground storage, water is delivered via a pump. A typical active rainwater harvesting system would include the following components:

- Collection surface: this is the impervious surface where the water flows for instance a surface of a roof;
- Conveyance system: this is a system consisting of the gutters and downpipes that transit the water from the collection surface to a storage container;

- Pre-tank diverts and filters: these are components that obstruct the leaves and other foreign particles before the water enters the storage container;
- Storage container: this is a watertight tank for storage of harvested rainwater;
- Water treatment system: additional water treatment may be required depending on the intended use of the harvested rainwater for instance drinking or irrigation. For drinking purposes, the water must meet the set drinking water standards. Typical treatment may include filtration and/or disinfection. Figure 3.2 presents examples of active rainwater harvesting systems with above ground and below ground storage tanks.

For the purposes of this study, the active rainwater harvesting system is considered. More so reference is made to the active rainwater harvesting systems as either Domestic Rainwater Harvesting System (DRWHS) or Rainwater Harvesting System (RWHS).

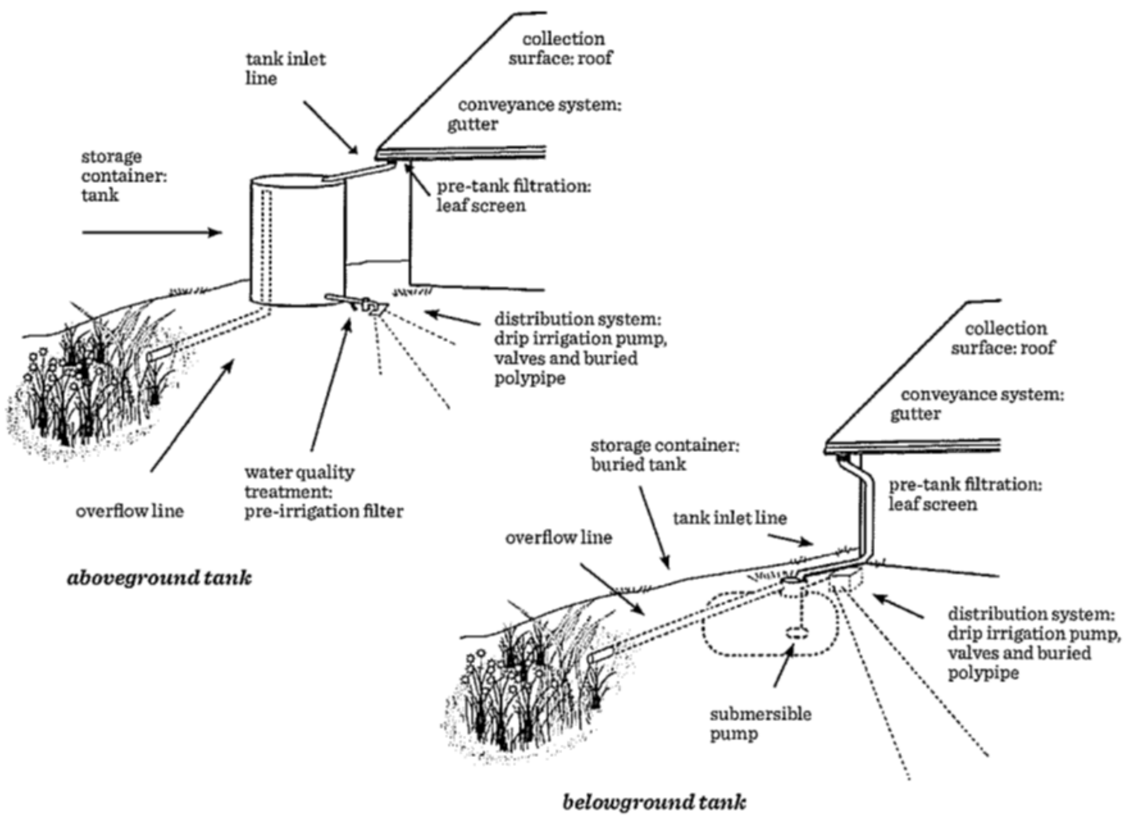


Figure 3.2 Examples of active rainwater harvesting systems (Adapted from City of Bellingham, 2012)

3.2 RAINWATER HARVESTING SYSTEMS IN PRACTICE: A REVIEW OF GLOBAL CASE STUDIES

3.2.1 Introduction

Due to the global water crisis, there is evident paradigm shift in developing alternative water sources to the conventional ones in order to avert this crisis. As indicated in Zhang et al. (2009), rainwater is still considered as a traditional yet greatly undervalued and underexploited source of water which in the current space has seen a revival in demand due to its potential in bridging the deficit in available water supply. With water being a global crisis, the interest in the promotion of the use of decentralised alternative water sources such as rainwater has grown tremendously over the years. More particularly in the regions that are vulnerable and often under water scarcity such as the arid and semi-arid areas. Notable growth in promotion of decentralised alternative water sources has been in the Mediterranean climate areas that constitute the Mediterranean Sea basin, California, South Africa (Cape Province), Central Chile and Southern Australia (Farreny et al., 2011).

Active rainwater harvesting, also referred to as Domestic Rainwater Harvesting (DRWH) is recognised as one of the potential “new taps” that would provide alternatives in water supply and in safeguarding the future of our environment (City of Bellingham, 2012). Rainwater could be used as both a main or supplementary source of water and, the scale and level of use depends on the region where rainwater harvesting is practised. For instance, Silva et al. (2015), indicate that in developing nations such as Botswana, India, China, Bangladesh, Kenya, Thailand, Mali, and Malawi, harvested rainwater is used significantly as a resilience to withstand persistent water shortages for both potable and non-potable use. However, in most developed nations (e.g. United States of America, France, Germany, New Zealand, Belgium, and Singapore), with exception of Australia, rainwater harvesting is promoted as a complementary system to the conventional water distribution system for non-potable use. Identified common non-potable uses include: laundry, toilet flushing, and irrigation. In Australia, however, rainwater harvesting is extensively promoted for potable uses as well.

3.2.2 The role of rainwater harvesting in sustainable water management and the need for studies

Water is a key at-risk resource and therefore improved management of the resource is vital. Quantitatively, two major alternatives in water resource management can be classified as: (a) improvement in water use efficiency; and (b) exploring alternative water sources (Silva et al., 2015). One of the principles of WSUD is environmental sustainability. A means of attaining environmental sustainability with respect to meeting the water demand through increase of supply is to utilise alternative supply sources such as Rainwater Harvesting (RWH). Rainwater Harvesting is largely perceived to be comparatively cheaper; simpler to install, operate and maintain; and environmentally friendlier than many other water resource alternatives (Ndiritu et al., 2018). RWH and Stormwater Harvesting (SWH) are also considered as one of the “New taps” / New water resources alongside water demand management and conservation, treated effluent, groundwater, and desalinated water (Armitage et al., 2014).

Rainwater harvesting has been identified as an increasingly viable alternative water source. This is because it can be easily collected and utilised without significant treatment for non-potable purposes (Silva et al., 2015). Sustainability in the use of water is key to the achievement of the global sustainable development goals. This therefore prescribes to the utilisation of water in and for activities that support the capacity of the utility populace to endure and flourish into the unforeseen future without compromising the integrity of the hydrological cycle or the ecological systems that depend on it (City of Bellingham, 2012). As a means of securing a sustainable and reliable water supply in the future, it is increasingly being accepted that harnessing rainwater at the point of use could be a reliable “new tap” either as the primary source or secondary source of water. Incorporating rainwater harvesting as part of the integrated resource planning elements with regards to sustainable water management approaches is and will continue gaining prominence in the water resources management realm. This is because, incorporating rainwater harvesting is considered as one of the strategies that would ensure a safe, cost-effective, and reliable drinking water supply now and in the future (City of Bellingham, 2012). Water footprint analyses also show that introducing RWH systems relieve stress on water resources where RWH system exists. However, the drinking water system does not relieve the water stress (Vialle et al., 2015). Farreny et al. (2011), and Barthwal et al. (2014), sum up some of the benefits of presenting rainwater harvesting as a sustainable strategy that needs to be integrated in the management of the urban water cycle as follows: (a) that it may minimise a city’s water dependency ratio in terms of the available water resources, (b) that it may provide relief against water stress, (c) that it may contribute to the reduction in non-point source pollutant loads, (d) that it may reduce the volume of treatable urban stormwater, (e) that it may prevent flooding and consequently aid in alleviating some of the negative impacts of climate change, (f) that it aid in recharging

aquifers and consequently acting as a drought mitigation tool, and (g) that as part of the water sensitive urban design strategy, may be part of a cooling system of cities suffering the “urban heat island effect”.
Rainwater Harvesting (RWH) is progressively becoming a central part of the sustainable water management toolkit and as such, global studies have been undertaken in order to build a credible body of knowledge that could be used in optimising the application of rainwater harvesting systems. Amos et al. (2016) note that in the contemporary days, with the ever-growing concerns about water security, rainwater harvesting system, which exhibits great potential for saving water has become a pivotal field of research with regard to water resources management. This has led to a significant contribution to the body of knowledge on rainwater harvesting in recent years.

3.2.3 Rainwater harvesting studies

An analysis of the various studies on rainwater harvesting systems implies that most of the case studies could be categorised as either dealing with the feasibility of rainwater harvesting in a given region with regards to the following key topical issues: Feasibility (Yield potential, Economic, Technical, Social and Environmental), Design and Reliability or Modelling of the Rainwater Harvesting Systems (RWHS) as well as the Quality of the harvested rainwater. The following sections give a review of the various studies in the identified categories globally. In these case studies, the outcomes give pointers as to the rainwater harvesting potential, critical parameters to be considered in design and operation of rainwater harvesting systems, the factors that determine the sustainability and economic potential of a RWHS as well as the environmental impacts wherein, the key indicators are the Energy Use Potential (EUP, kWh/m^3) and the Global Warming Potential (GWP, kg CO_2 eq.). Such studies are carried out by way of life cycle assessment (LCA) and dynamic simulation (Morales-Pinzón et al., 2015). The results presented are also representative of different climatic zones, various scales (i.e. local, medium, large and regional) and scenarios. Given the mix of study parameters and conditions, the results presented thus provide valuable information for the advancement of sound guidelines that are required in mainstreaming RWHS as per the required need.

3.2.4 Feasibility analysis studies

Feasibility studies focus on the following key items: Physical feasibility (yield potential or the hydrological opportunities), economic feasibility (profitability of implementing a rainwater harvesting system), Technical feasibility, Social feasibility (Socio-economic acceptance of a preferred rainwater harvesting system), Environmental analysis (negative environmental impacts / energy intensity of implementing a favourable rainwater harvesting system) and Harvested Rainwater Quality.

3.2.4.1 Physical feasibility (yield potential)

Physical feasibility entails the hydrological opportunities (Kumar, 2004) or the yield potential. It deals primarily with environmental parameters that determine the potential of the rainwater harvesting in a given region. Apart from the environmental parameters, physical feasibility also implies physical feasibility of installing a rainwater harvesting system which then plays the scalability issue (Kumar, 2004). Basically, the feasibility of rainwater harvesting depends upon the rainfall amount, the type of storm received in an area, the length of the dry periods as well as the availability of alternative water resources in the target area. Rainfall or precipitation in general is considered the variable of interest for a RWHS. This is because the losses that are quantified as evaporation, spillage, leaks, surface wetting, etcetera are accounted for by the choice of the runoff coefficient (Silva et al., 2015).

In his evaluation of the potential of RWH as an alternative domestic water supply source, Thomas (1998), analysed three different techniques of domestic rainwater harvesting (DRWH) namely:

(a) Wet-day DRWH, which is a DRWH style operated with a storage not exceeding a day’s consumption;

(b) Wet-season DRWH, which is a DRWH style operated with a storage sufficient for a 3 to 10 day's consumption; and
(c) All-year DRWH, which is a DRWH style operated with a storage equalling a 60 to 300 day's consumption.

These styles were evaluated via three case studies of China (northern parts of China), Rural East Africa, and Singapore. The use of the wet-day and wet-season DRWH technique options imply in principle that there exists a supplementary source of water for usage in dry seasons. The outcomes of this study suggested the following:
(a) That for regions like the northern parts of China where the aquifer quality is deteriorating or the water table levels have significantly dropped then DRWH is favourable compared to long distant water transfer schemes;
(b) DRWH is most appropriate as a primary/main source of water supply "where the product of precipitation and roof area per capita exceeds the per capita consumption";
(c) DRWH can be used as a secondary source/partial supply where condition in (b) is not met (i.e. the wet-day and wet-season options are practiced); and
(d) RWH systems work best where it has been designed into the structure rather than retro-fitted.

Salinity in both surface and groundwater, Arsenic pollution of groundwater as well as the high cost of drilling wells and boreholes in the Sylhet area of Bangladesh has necessitated the search for alternative water sources as a practical solution to the identified problems. Rainwater harvesting has been suggested as a probable solution in the Sylhet region due to its abundance especially in the rainy season that begins in March to October every year. Alam et al. (2012), carried a study to investigate the possibilities of implementing a rainwater harvesting system in Sylhet, Bangladesh. In this study, they analysed a 44-year rainfall record. The study also determined the rainwater yield and the domestic water demand. Water quality of the harvested stored rainwater (stored in Ferro-cement tanks) was also monitored for a period of three (3) months at a 15 days' interval. The parameters monitored were: suspended solids, dissolved solids, turbidity, hardness, pH and Lead. They also did a cost comparison between the private water supply system, conventional water supply system and the rainwater harvesting system. Some of the key pointers from this study, also corroborated in Silva et al. (2015), are: that local conditions and systems configurations influence the level of pollution of harvested rainwater; that water quality research highlight the need for specific monitoring campaigns for each local and installation since generalisation may be prone to errors; studies confirm the viability of harvested rainwater for non-potable use and its potential for potable use without extensive treatment requirements in many regions; that the harvested rainwater is contaminated by a variety of pollutants and pathogenic organisms depending on: the type of roof; location; and the antecedent dry weather conditions among others. Kus et al. (2010), found that diverting the first 2 mm of rainfall assures compliance with the Australian Drinking Water Guidelines (ADWG) standards except for lead and turbidity, which required bypassing approximately the first 5 mm of rainfall. A first flush system improves the physical-chemical quality of collected rainwater but it cannot avoid the microbial contamination of stored rainwater.

Jordan, an arid to semi-arid (ASAL) country, is a water scarce country whereby as of the year 2009, the water use was already outstripping the available renewable supply (Abdulla and Al-Shareef, 2009). Among the many available options to alleviate the water scarcity situation in Jordan, rainwater harvesting has been suggested; a system that as of 2009 had not received notable attention in Jordan. Abdulla and Al-Shareef (2009), conducted a study in Jordan with the main objective of evaluating the potential for potable water-savings through the use of rainwater harvesting in residential sectors of the twelve (12) governorates of Jordan. In their findings, Abdulla and Al-Shareef, (2009) identified the following:
(a) That there is a variation in the potential for rainwater harvesting among the 12 governorates. This is expected given the variability in average rainfall depths in the various governorates with the highest annual rainfall being in Ajlun at 582.2 mm and the lowest being in Aqaba at 31.8 mm. This would thus imply a possibility of differentiated rainwater harvesting systems implementation;
(b) The potential for water-savings also varied among the governorates ranging from 0.27% to 19.7% in Aqaba and Ajlun respectively;

(c) That the quality of harvested rainwater depends on the following:
   i. Location as the rainwater may be exposed to air and/or automobile emissions,
   ii. Rainfall intensity and the number of antecedent dry days preceding a rainfall event,
   iii. Time of collection (after the first rain),
   iv. Storage, and
   v. Use.

(d) The social prejudice hindered the application of treatment systems such as filtration since it is popular belief in Jordan that rainwater is too pure to warrant any treatment before use. This perception resulted in only 30% of the households applying some form of treatment to the rainwater before use. Further on prejudice, Abdulla and Al-Shareef (2009), also noted that consumption of harvested rainwater is related to the perception of quality and that since rainwater does not carry any taste (due to its mineralogical composition), it is not well widely accepted; and

(e) Incentives and government support are necessary mechanisms to encourage widespread adoption of rainwater harvesting.

The Malaysian government began to promote the use of rainwater harvesting systems in 1999 (Le et al., 2016), which currently has begun to achieve its practicality. Malaysia has a dynamic climate and the country is currently experiencing a rise in water shortages that is prompting water rationing schedules by the authorities. With rainwater harvesting having been identified as an alternative source of water supply, Lee et al. (2016), conducted a case study to investigate the potential, policies, and development in rainwater harvesting as an alternative source of water in Malaysia. Due to the dynamic nature of the climate, Lee et al. (2016), argue that there is a consequent expected variation in average annual precipitation as a result of climate change. Therefore, the potential of rainwater harvesting has to be studied by considering precipitation projections and impacts of climate change on precipitation before the deployment of any favourable rainwater harvesting system. They also pointed out that clear-cut policies and guidelines are required in an effort to mainstream rainwater harvesting as an alternative water source in Malaysia. In their study, Lee et al. (2016) also identified and categorised the challenges in mainstreaming rainwater harvesting systems (RWHS) in Malaysia as either *environmental, economic, policy, social, and technical* in nature. These challenges are not unique to Malaysia and could be experienced globally. A brief illustration of these challenges is given below.

Environmental challenges:
The predictions of climate change effects are not certain but need to be factored in the analysis of the feasibility of a favourable RWHS. Such variations would include uneven distribution of precipitation, decrease or increase in annual average precipitation, erratic occurrences of dry spells and floods, etcetera. All these challenges need to be factored in the design of a RWHS.

Economic challenges:
The issue of the correct tariff structure as well as the incentives and rebates need to be properly articulated so as to reflect the value of implementing a RWHS. A rational cost-benefit trade-off is necessary to determine a rational payback period. This is normally a big challenge. Amos et al. (2016), corroborate this notion as they indicate the paradox in economic assessment studies of RWHS. Domènech and Saurí (2011), also note that the major drawback of rainwater harvesting systems is the long pay-back period.

Policy challenges:
Many governments, especially in the developing nations have not put in place policies, guidelines and regulations that would authoritatively and in an organised manner, mainstream RWH as an alternative source of water for both potable and non-potable use. In countries where such initiatives have been put in place, the policies are not robust enough to promote the installation of RWH as the case might be in Malaysia (Lee et al., 2016). Kahinda and Taigbenu (2011) also illustrate this challenge with respect to South Africa in which they highlight the lack of clear legal framework for the mainstreaming of RWH, a condition that basically renders RWH illegal if the water related regulations were to be strictly applied. Incoherent and uncoordinated policy documents beget duplication of roles and mandates of various government departments. This calls for the

need for inter-ministerial and multi-stakeholder cooperation in the strategic policy development and alignment so as to effectively and authoritatively mainstream rainwater harvesting as an alternative source of water. There is also the need to mainstream RWH into the education curriculum. This is also currently lacking in many countries.

Social challenges:
Apart from promoting public popularity and acceptance, other social challenges as identified by Abdulla & Al-Shareef (2009), Helmereich & Horn (2009), Lee et al. (2016) and other authors include:

(a) The "*paradox of plenty*" whereby the public have a misconception of having water in abundance when there are frequent rainfall events. In this case, RWHS are seen as a luxury addition to one's needs, a "nice to have" facility within a building.
(b) In certain cases, rainwater is seen as a lower-grade supply source meant only for the "poor" and the demand is always for the first-class citizenry service delivery where everyone demands to be serviced from the centralised supply system.
(c) Perception on rainwater quality prejudices the consumption rate and willingness to adopt RWHS.
(d) The inability of various government departments and ministries to conduct civic education and awareness campaigns to popularise RWHS.

Technical challenges:
The scaling and optimisation of the RWHS design is a key consideration in the feasibility analysis of a RWHS. Through optimisation of the design, the supply and demand needs are met at optimal reliability. The technical parameters to consider in the optimal design of a RWHS include:

(a) The rainfall characteristics – challenge lies in the stochasticity, effect of climate change and reliability of the recorded data among others;
(b) The catchment area – in the case of DRWH, the roof area. The challenge here is in the determination of the ideal size, the different types of roofing materials and configurations, etcetera among others;
(c) The tank storage size – the challenge is in optimising the size for the optimal scale of application (for instance, diffuse or compact settlement model);
(d) The rainwater demand as well as the general water use pattern – the challenge is in the characterisation of the various users and meeting the expected end use water quality and quantity reliably over the demand period; and
(e) Estimated losses in the catchment and collection system for instance the first flush volume, evaporation, splashing, etc. these are greatly affected by the elements of weather such as wind direction and speed, temperature among others.

As in most ASAL areas, Namibia lacks access to potable water hence rainwater harvesting plays a pivotal role in providing alternative source of water for both potable and non-potable uses. Sturm et al. (2009), in Namibia, through the CuveWaters project undertook a study aimed at examining the technical and economic feasibility of rainwater harvesting techniques as well as the affordability of the RWHS for future users. The study was conducted in Central Northern Namibia. The basic building blocks of this study were the hydrological, technical, and socio-cultural conditions required to develop optimal solutions for RWH in Namibia. As technical variables, Sturm et al. (2009), considered two small-scale RWHS options: one being the roof catchment system (corrugated iron roofs) targeted for domestic consumption whereas the second being "treated" ground surface system (concrete-lined as part of the treatment) targeted for livestock consumption, small-scale irrigation and part domestic consumption. Three alternatives above ground tanks (AGT) were used in this study, these being the Ferro-cement tanks, the Polyethylene Plastic tanks and the Block tanks. The economic viability was done through the dynamic cost analysis based on the calculation of the Net Present Value (NPV) to assess the different technical options that were then compared in terms of amortisation times and water prices as the prime costs. The local and regional water prices of the following modalities of water supply were considered: the communal water points, the private water taps, as well as the private water vendors. For the systems tested, the findings of this study indicated that in terms of vulnerability and dependency, it is reasonable, sustainable and viable to apply decentralised systems of RWH in the study area of Epyeshona in Namibia.

Chittagong city, south Agrabad in Bangladesh experiences both water scarcity and urban flooding in the same year (Akter and Ahmed, 2015). Akter and Ahmed (2015), evaluated the potential of RWHS of Chittagong through a modelling approach whereby they applied the Analytical Hierarchy Process (AHP), a multi-criteria decision analysis procedure. They based their criteria on the size of the roof area, slope, drainage density and the runoff coefficient. To simulate the rainfall-runoff process, the HEC-HMS algorithm was used. The model results showed that the City's water supply could be supplemented annually by up to 20 litres per capita per day. The use of AHP also aided in the identification of potential rainwater harvesting zones through the development of rainwater harvesting potential indices.

Regarding the availability of alternative water supply as a determinant of physical feasibility, An et al. (2015), evaluated the potential of multi-purpose usage of harvested rainwater for both water resource recovery and cooling effect for Hong Kong City. The harvested rainwater was mainly intended for toilet flushing and areal climate control. The water resource recovery was based on the availability of seawater for toilet flushing and an index; **A**rea **P**recipitation per **D**emand **R**atio (APDR), being the quotient of rainwater harvested and building water demand was used as a determinant for water supplies. The results of this study indicated that districts that had freshwater toilet flushing had higher potential for rainwater harvesting and utilisation (i.e. had a higher APDR) in comparison to the districts with seawater toilet flushing. It therefore implies that rainwater harvesting can be subjected to a multiple of uses apart from the main use; providing alternative source of water.

In general, while determining the physical feasibility, studies show a variety of parameters to consider. However, regardless of the choice of the RWHS, the key parameters required are as follows:

(a) A long reliable record of rainfall data (> 30 years);
(b) Information on the population characteristics with regards to the water demand;
(c) The catchment characteristics vis-à-vis the catchment area and the runoff coefficient;
(d) Technical specifications such as optimal storage capacities and ground catchment size. Under this parameter, Sturm et al. (2009), indicate that several techniques are available as depicted in DTU (1999), and Gould and Nissen-Peterson (2003). Such techniques include graphical, statistical, as well as computer-based techniques. They also indicate that in most instances, graphical techniques are found to be sufficient;
(e) Quality of the harvested rainwater. This needs to be monitored over time and in most cases is spatial and season specific
(f) Cost analysis information and tools

Sturm et al. (2009), further indicate that run-off coefficients of concrete-lined ground catchments are usually considered higher than those of otherwise treated or natural surfaces. The quoted range of the runoff coefficient for the concrete-lined ground catchments is 0.73-0.76. They also indicate the following:

(a) That for areas with low rainfall such as most ASALs, treated ground catchments are preferred to the roof catchments. This is because roof catchments' productivity/yield is limited by roof size whereas the ground catchments allow for collection from a larger area;
(b) That tank design that is appropriate to the local conditions is critical as it has a significant cost implication of the RWHS. The design should be considered appropriate by accounting for local conditions such as the technical skills and tank material;
(c) That the harvested rainwater tank storage capacity is a function of: annual rainfall patterns, local water demand, size of the catchment surface, and the runoff coefficient of the catchment surface; and
(d) That physical and social conditions aid in identifying the technical specifications requisite to the assessment of economic and physical potential of any proposed RWHS.

3.2.4.2 Economic feasibility

In a broader perspective, financial or economic feasibility is adjudged through an economic analysis. The BusinessDictionary (n.d.), defines Economic Analysis as “A systematic approach to determining the optimum use of scarce resources, involving comparison of two or more alternatives in achieving a specific objective under the given assumptions and constraints. It considers the opportunity costs of resources employed and attempts to measure in monetary terms the private and social costs and benefits of a project to the community or economy”.

Economic feasibility analysis of a RWH system is critical. Farreny et al. (2011), point out that according to previous studies done on the basic criteria for the dissemination of RWH system (RWHS), most authors for instance Ghisi and Ferreira (2007); Rahman et al. (2010); and Roebuck et al. (2010), single out financial costs and benefits above other factors such as rainwater quality and public acceptability as a key criterion in the decision-making of whether a utility entity would install a RWHS.

Silva et al. (2015), indicate that direct economic viability of RWHS is dependent upon the following factors: (a) the balance between the investment on the RWHS, operation and maintenance costs of the RWHS and (b) the cost savings obtained from the public water supply. In their observation, the defined balance exhibits a non-linear function of the potential amount of rainwater available, the actual quantity of rainwater utilised for different purposes and the cost of the alternative sources of water provision. One of the reasons for the conflicting results in many of the cited economic analyses is that they have ignored the full benefits that a RWHS can offer. The analyses should consider both the extrinsic and intrinsic attributes of the costs and benefits accrued from implementing a RWHS. Such intrinsic elements would include; options for saving water, the cost of alternative water supply (opportunity costs), environmental benefits, operation and maintenance costs, and capacity building and development costs. Such studies can be carried out by way of life cycle assessment (LCA) and dynamic simulation (Morales-Pinzón et al., 2015).

Life Cycle Assessment or Analysis (LCA) is a tool to assess the environmental impacts and resources used throughout a product's life cycle. It considers all the stages of a product’s life from raw material acquisition, through production and use phases (including repair and maintenance), to waste management (recycling or disposal). The methodological development in LCA has been strong, and LCA is broadly applied in practice. It is strongly suggested that before implementing rainwater harvesting systems, studies incorporating a life cycle assessment methodology should be undertaken to look into issues related to sub-processes with high environmental impacts for instance, pumping and infrastructure (Vialle et al., 2015).

Studies, according to Farreny et al. (2011), show that rainwater harvesting presents many potent benefits as a viable resilience measure against water scarcity in both urban and peri-urban settings. However, there is still a dearth of knowledge representing the optimal scale financially, that the rainwater harvesting infrastructure should be set up. This is more pronounced in serving the densely settled areas. In an attempt to address the challenge of the lack of sufficient knowledge addressing the financial scale of infrastructure setup, Farreny et al. (2011), conducted a case study in Spain via a Life Cycle Costing (LCC) approach. In their study, they did an analysis of the cost-efficiency of several rainwater harvesting strategies in urban environments that are densely populated under a Mediterranean climate. In the Mediterranean climate, the average rainfall oscillates between 600 mm and 750 mm per annum. The Mediterranean climate is distributed worldwide and is majorly a characteristic of five regions namely: the Mediterranean basin, California, Central Chile, Cape Province in South Africa, and the South-Southwest of Australia (Di Castri and Mooney, 1973 cited in Angrill et al., 2011). Four strategies were considered based on the spatial scale as well as temporal scale. The temporal scale was defined by the moment of rainwater harvesting infrastructure set up, i.e. retrofit action versus the new construction and the spatial scale was defined by the building and its neighbourhood. Two scenarios were used in analysing the various strategies. The scenarios were based on the current water prices and the projected increased future water prices. Their analysis showed that rainwater harvesting strategies in dense urban dwellings under Mediterranean conditions are only economically advantageous when setup at the appropriate scale that permits economies of scale as well as considering the expected growth in water prices. A core finding from this study is that a rigorous choice process of the appropriate scale for rainwater harvesting infrastructure should be in place as a key determinant of economic feasibility of the favourable RWH system being put in place.

Life Cycle Costing is commonly applied in the energy and water sector in order to provide informed economic decisions regarding infrastructure installation. LCC involves a comparison of flow of costs and benefits accruing from an investment. The flows are discounted to net present equivalent values (Amos et al., 2016). The many financial indicators used to express the results of an LCC are as follows: Net Present Value (NPV), Benefit-cost-ratio (BCR), Return on Investment (ROI), Payback Period (PP), Internal Rate of Return (IRR), and Levelised Cost (LC). Tables 3.1 and 3.2 present a summary of some selected rainwater harvesting systems economics resulting from previous studies (adapted from Amos et al., 2016).

Table 3.1 Rainwater harvesting system economics (Adapted from Amos et al., 2016)

Location	Water price*1 AU$/m³	Water Price Annual % Increase	Inflation (%)	Interest (i) %	Life Cycle (Years)	PP* (Years)	NPV* AU$ over project life	LC* AU$/m³	BCR*	Reference
Sydney, Australia	1.48	3	1	5-15	60	None	-	-	0.5-1.01	[1]
Perth, Australia	2.76-5.22	-	-	5,7,9	15	None*1	-	-	-	[2]
Melbourne, Australia	1.5-2.7	6	-	-	20	1-12, 12-47 *2	191760-980566	0.09-0.71	-	[3]
Brisbane, Australia	-	-	-	3, 6, 9	25, 50	-	-	7.62-11.17	-	[4]
Nairobi, Kenya	0.3-0.8, 6.3	-	-	-	25	25 *3	139, 236	-	-	[5]
Spain	1.3-4.2	-	3	-	50	5.5-204 *4	-	-6.9 to 2.4	>1 *4	[6]
Yorkshire, UK	5.1	-	-	3.5-15	50	None	-	-	-	[7]

Key:

PP* = payback period; NPV = net present value; LC = levelised cost; BCR = benefit-cost ratio; *1 = unless the real estate value is included; *2 = Government funding 1-12 years and the household owner from 12-47 years; *3 = The PP was set to the lifespan of a tank, and the water prices that gave that lifespan were calculate; *4 = Apartment scale only

Table 3.2 Rainwater harvesting system installation scenarios corresponding to Table 3.1 (Adapted from Amos et al., 2016).

Location	Annual Rainfall (mm)	Roof Area (m^2)	Tank size (m^3)	Usages *1	Water use (m^3pcd) *2	Reliability (%)	Water savings (m^3/hh/yr) *2	Costs *3	Reference
Sydney, Australia	-	4000	75	O, L, T	-	70, 99	45	C, M, I	[1]
Perth, Australia	826	125, 250	2, 5	O	-	-	-	C, M	[2]
Melbourne, Australia	550-900	-	0.6-5+	O, T, L	0.26	-	105	-	[3]
Brisbane, Australia	-	98-117	4.4-6.7	O, L, T	0.11-0.16	68-80	43	--	[4]
Nairobi, Kenya	938	15	48.8	All	0.03-0.05	30-65	-	C, M	[5]
Spain	284-1794	80-4580	3-125	L	-	8-96	1-12	-	[6]
West Yorkshire, UK	-	76	1.2, 2.4	-	-	58-65	-	C, M	[7]
Jordan	42-582	100-500+	20	All	0.07-0.4	0.27-19.7	0.3%-20% *4	C	[8]

Key:
O = Outdoor; T = Toilet; L = Laundry; C = Construction; M = Maintenance; I = Infrastructure savings; *1 = Usage; *2 = pcd means per capita per day and hh/yr means household per year; *3 = Costs included in the economic analysis; *4 = Percentage of total domestic water use.

[1] Mitchell, C., and Rahman, A., (2006); [2] Zhang et al., (2015); [3] Gato-Trinidad, S., and Gan, K., (2014); [4] Maheepala et al. (2013); [5] Essendi, (2014); [6] Morales-Pinzón et al. (2014); [7] Roebuck et al. (2012); [8] Abdulla, and Al-Shareef., (2009).

The economic aspects of rainwater harvesting systems play a vital role in determining its viability in both the short- and long-term period of implementation. Amos et al. (2016), in their review of the global situation of the rainwater harvesting systems identify the fact that due to the pivotal role that rainwater harvesting plays in increasing water security for both individual households and the local, regional or national government, there is a demand for tools to aid the technical and economic analysis of rainwater harvesting systems. This has consequently led to increased research in this field. However, Amos et al. (2016), also depict a contrast or paradox in the studies of economic analysis of rainwater harvesting systems (RWHS) in that economic analysis of RWHS plays a key role in evaluating cost-effective solutions to sustainable water provision worldwide. However, economic analysis of RWHS has restricted prominence in scientific literature. Despite this, the limited literature available presents varying and conflicting results. The probable reasons for the conflict are varied ranging from financial assumptions to the modelling parameters. These may be discerned as follows: (a) Price of Water; (b) Interest rate; (c) level of Inflation and the period used for analysis; (d) costs; and (e) economic benefits.

Price of Water:

Studies on economic analysis of rainwater harvesting systems indicate that the price of water is a fundamental parameter in the economic analysis of RWH systems. This is because water savings are considered to be the primary benefit of the RWH system (Morales-Pinzón et al., 2015). The price of water has been used to represent financial viability in the following forms (Amos et al., 2016):

(a) Water price required to make the installation of a rainwater tank able to recover the investment costs; and
(b) Calculation of the payback periods

Interest Rates:

Many authors contend that generally, the price of water is in most instances expected to have a higher rate increase as compared to the general interest rate with variations from country to country. For instance, as depicted in Table 3.2.

Inflation and Period of Analysis

The economic analysis of a RWH system is dependent on a country's state of economy and its dynamics. Khastagir & Jayasuriya (2011) indicate that as a function of the interest rate, a shorter payback period is realised in conditions where a country's economy encounters low inflation coupled with higher discount rates.

Costs:

Costs of RWH systems are dependent on many factors for instance (a) level of innovation, (b) financial responsibility of the owner, (c) improper consideration of the operation and maintenance costs, and non-consideration of energy use as an operational cost.

(a) *Level of innovation* has the capacity to minimise both the cost and the environmental impacts. Studies show that the component of a rainwater harvesting system that contributes to the highest capital cost is plumbing. This can render the intended system to be economically nonviable. Options such as outdoor use only require less plumbing hence may render themselves optimal economically in most instances.
(b) *Financial responsibility of the owner* also contributes to the financial viability of a rainwater harvesting system project. For instance, if the owner's financial responsibilities are restricted to only operational and maintenance costs, void of capital costs then chances of the proposed system to benefit the owner financially are better. Other innovative schemes that could cover the capital costs and as a result encourage uptake of rainwater harvesting systems include: incentive rebates by government as well as regulations and subsidies.
(c) *Improper consideration of operation and maintenance:* In their review, Amos et al. (2016) identify improper consideration of operation and maintenance costs as another costing factor that cause conflict in economic analysis of rainwater harvesting systems. This is so because maintenance expenses are often recurring hence seem like cumulatively adding costs that outweigh the accrued

benefits. Other authors also mention that the greatest effect on cost effectiveness of a RWH system is due to the varied yield, use of pumps and the tank life (Silva et al., 2015).

(d) *Non-consideration of energy use as an operational cost* also contributes to conflict in economic analysis of RWH systems

Economic benefits

Economic benefits realised from using a RWH system is derived from the volume of water that is saved and the price one would have otherwise paid for it. Other intrinsic measurable benefits may include:

(a) Quality of rainwater: - the quality of rainwater determines the power usage in heating and treatment when used in laundry and hot water systems. The benefit is quantified by calculating power savings, saved washing powder, and carbon savings (environmental benefit);
(b) Infrastructure savings: - implementing a RWH system implies delaying the water mains supply headworks; and
(c) Improved food security: - by using RWH systems for irrigation of small-scale home gardens. The benefits in this case are quantifiable through cash flow from improved crop yields.

Non-quantifiable benefits could include: free use of rainwater without restrictions as compared to restrictions subjected to the use of water from the mains and increase in real estate value where a RWH system is implemented. Silva et al. (2015), also corroborate that indirect benefits of RWHS may result from using onsite solutions, that tend to be more flexible and are adjusted uniquely to specific users. They also determined that up to a given point, the potential water savings are more dependent on the daily rainfall distribution than on the annual precipitation.

Morales-Pinzón et al. (2012), in their study carried out on the financial feasibility and environmental analysis of potential rainwater harvesting systems in Spain, argue out that in as much as literature posts evidence of financial feasibility studies and other studies on the potential environmental impacts of Rainwater Harvesting (RWH) systems, there is lack of integration between these studies to provide for a platform that permits for prompt assessment tools for such RWH systems as useful planning and decision making tools. The outcomes of this study suggested that, regarding the financial feasibility analysis, modelling of both conventional financial indicators; the NPV and Internal rate of Return (IRR) and the indicators of potential environmental impact; GWP and EUP is feasible by applying linear systems and an appropriate sizing scale for most of the rainwater harvesting systems. Notable results from this study also show that scaling is the defining factor in the design of RWH systems. The results also show that the neighbourhood scale is the most favourable alternative while the material used for storage tanks is one of the least determinant factors.

Further, in support of findings of Angrill et al. (2011), and Morales-Pinzón et al. (2015), Rahman, Keane & Imteaz (2012) conducted a study in Greater Sydney Australia. The study investigated the water savings potential of rainwater tanks fitted in detached houses. The study was conducted in ten (10) different locations in Greater Sydney Australia. Three different tank sizes at 2 kL, 3 kL, and 5 kL were used in the study in which the water savings, reliability and financial viability analysis was done for each tank size based on a developed daily time scale water balance simulation model. The results of this study suggested a very strong correlation between the average annual water savings from the rainwater tanks and the average annual rainfall. The study also considered various sources of funding and incentives for the adoption of rainwater harvesting and utilisation. In this regard, the results of this study showed that without government rebate, then the BCR for the rainwater tanks are less than 1.00. Further, Rahman et al. (2012), determined that in terms of reliability, the larger tank (5 kL) met the demand for toilet flushing, laundry and irrigation water use for over 70% of the days in a year as compared to the smaller tanks (2 kL and 3 kL) which met the demand for less than 70% of the days in a year. Hence the larger tank (5 kL) was preferred to the smaller tanks (2 kL and 3 kL). The same trend was also shown for water savings and the life cycle cost analysis. The study also showed that in order to optimise or maximise on the financial outcomes, the home owners should not subject the RWH systems to single use only but to multiple uses such as connections to toilet, laundry and outdoor irrigation.

Studies on economic viability with a focus on water savings potential have been conducted in many countries. Table 3.3 presents a summary of the results of some of such studies conducted by various authors. The results presented are adapted from Silva et al. (2015) with the cited authors/references also quoted for ease of cross-referencing and further consultation of the same. Silva et al. (2015) also demonstrate the importance of the water tariffs on the economic viability of RWHS as well as the need to optimise rainwater tank capacity/volume to mitigate the effects of variability in precipitation.

Table 3.3 Examples of some evaluation studies on specific technical and economic viability of rainwater harvesting systems (Adapted from Silva et al., 2015).

Location	Scope	Tank size (m^3)	Water savings potential (%)	Cost efficient	Reference
UK	Flushing/measurement		57		[1]
Brazil (Florianópolis)	Non-potable / measurement	10	39.2-42.7	Yes	[2]
Brazil (Palhoça)	Flushing & Laundry / measurement	3	33.6	Yes	[3]
		5	35.5	Yes	
Brazil (Chapecó, Criciúma, Florianópolis, Joinville & Lages)	Non-potable / estimate	Variable 0-20	Variable 0-50	Yes	[4]
Nigeria (Abeokuta)	Flushing & laundry / estimate	5	90 (flushing), 50 (flushing + laundry)		[5]
USA (Toledo)	Toilet flushing / estimate	771	<100	No[a]	[6]
		384	100	Yes[b]	
Sweden (Norrköping)	Toilet flushing & irrigation / estimate	20-40	45-73 (flushing)	Yes	[7]
		20-120	8-75 (irrigation)		
Italy (Genoa, Florence, Catania)	Non-potable / estimate	2.5-400	40-100		[8]
Europe (46 cities)	Non-potable / estimate	0.4-150	20-100		[9]
South Korea (Seoul)	Toilet flushing / measured	200	58		[10]
USA (23 cities)	Potable, non-potable & irrigation / estimate	0.19-15.14	20-100		[11]

Key: [a] Rainwater harvesting and standard toilets; [b] Rainwater harvesting and low flush toilets

[1] Fewkes (1999); [2] Ghisi and Ferreira (2007); [3] Ghisi and Oliveira (2007); [4] Ghisi and Schondermark; [5] Aladenola and Adeboye (2010); [6] Anand and Apul (2011); [7] Villarreala and Dixon (2005); [8] Palla et al. (2011); [9] Palla et al. (2012); [10] Mun and Han (2012); [11] Steffen et al. (2013)

3.2.4.3 Social feasibility

Feasibility of mainstreaming rainwater harvesting systems does not stop at the economic, environmental, physical and hydrological condition analysis. It should also encompass the perceptions, attitude and ease of acceptability by the target end users. Despite the known benefits of rainwater harvesting, in many countries especially the developed nations, the uptake of rainwater harvesting as an alternative source of water has been treated with a lot of scepticism, particularly in low rainfall areas (Domènech and Sauri, 2011). Domènech and Sauri, (2011) also highlight the paradox in many urban areas that suffer water scarcity yet they treat a readily available local source of water such as rainwater as a risk rather than a valuable resource. Domènech and Sauri (2011) carried out a study in Spain's Metropolitan Area of Barcelona whereby they analysed the use of harvested rainwater at two scales: the single-family buildings and the multiple-family buildings. The study parameters were: the users' practices and perceptions, the savings accrued for drinking water while using harvested rainwater and the economic costs in implementing the rainwater harvesting systems. Two outstanding observations from the study were that regulations and subsidies were found to be good measures in promoting the uptake of rainwater harvesting systems in residential areas. Further, it was observed that a major weakness of rainwater harvesting is the long time required to experience an appreciable return on investment.

Rainwater harvesting systems are designed with the aim of improving the wellbeing of the end users and therefore involves a lot of human interphase and interaction. The successful implementation of such systems thus depends on the level of engagement and the buy-in from the end user side. Barthwal et al. (2014), conducted such a study in India whereby they conducted a case study in three different locations of varied hydraulic reliability with respect to the mains water supply so as to determine the occupants' perspective of rooftop RWH. The pivotal attribute from results of this study was that favourable RWH systems are unique for a given set up given the uniqueness and variations in household income level, the level of awareness with regards to the benefits or perceived inconvenience of establishing a rainwater harvesting system in the household, as well as the differentiated government policies in line with the subsidies and/or incentives at different levels of the community. It therefore implies that the community participation must be engaged from the onset of the project to its decommissioning phase, i.e. the complete life cycle of the project. Other authors for instance Adenike and Titus (2009), Domènech and Sauri (2011), Amos et al. (2016) and the references therein also corroborate this fact.

3.2.4.4 Environmental Analysis

In the mainstreaming of rainwater harvesting systems, many an urban planners and designers have largely neglected to incorporate, as part of the design and planning, the benefits of rainwater harvesting in the context of a sustainable management of the harvested rainwater as a vital resource (Angrill et al., 2011). Studies show that environmental impacts of exclusive use of potable water and that of rainwater harvesting (RWH) are very similar even though the RWH system has slightly higher impacts than the conventional potable water (Vialle et al., 2015). In their study, Vialle et al. (2015), indicate that for the RWH, the consumption of electricity for pumping produces the strongest impact even though in considering disinfection and infrastructure results in slightly higher environmental impact in all impact categories that were considered such as Global Warming Potential (GWP, kg CO_2 eq.) and Energy Use Potential (EUP, kWh/m^3). These are environmental indicators associated with life cycle assessment (LCA). Other impacts for instance the construction of the High-Density Polyethylene (HDPE) tanks that are used in storage in the rainwater harvesting system immensely contribute to environmental risks such as the release of carcinogens and respiratory organics.

Morales-Pinzón et al. (2015), in their study, modelled the economic cost and environmental analysis of RWH systems considering two key aspects: tank size and scale of analysis (i.e. single-house scale and apartment-building scale). Three scenarios were considered: optimistic (more favourable), pessimistic (less favourable) and average (using all rainfall data). In their analysis with respect to environmental performance it is reported that on the single-house scale under optimistic scenario, the GWP shows that a storage volume above 5 m^3 is undesirable since it would exceed the potential environmental impacts resulting from the main water system. For the same scale and in an average scenario, the tank volume should not exceed 2 m^3, and for pessimistic scenario, the tank volume should not exceed 1 m^3. On the apartment-building scale, the GWP shows the desirable storage tank volumes for optimistic, average and pessimistic scenarios should be below 33 m^3, 20 m^3 and 10 m^3 respectively. Regarding the EUP, the values obtained are lower on a single-apartment scale as compare to those evaluated for the distribution of a conventional network. This implies that at the single-house scale, a Rain Water Harvesting system can be a good alternative. The results show a contrary effect with the apartment-building scale. However, in order to make rain water harvesting systems feasible at the apartment-building scale probable options include having a tank distributed over a roof or placing a tank below a roof to keep the energy consumption low. From this analysis, it can be observed that the use of economic and environmental indicators, e.g. estimated costs and Global Warming Potential (GWP) can help avoid oversizing rainwater tanks, consequently leading to savings and other benefits due to reduced negative environmental impacts.

In their review of the energy intensity of rainwater harvesting systems, Vieira et al. (2014), indicate that the median energy intensity of both empirical and theoretical rainwater harvesting systems studies stands at 1.40 and 0.20 kWh/m^3 respectively. They also conclude that observed studies show that currently executed RWH systems frequently have operational energy intensities that are much higher than the centralised urban water supply systems and are comparable to recycled water supply systems. Conversely, from theoretical studies, upcoming formations and combinations for RWH systems that generate most of their flows through gravity, with the application of header tanks, have the ability to provide fit-for-purpose supply at energy intensity levels that are competitive to the conventional urban water supply systems. It is further reiterated that a prudently planned RWH system is vital to guarantee reduced environmental impacts when using rainwater in buildings. They also argue that the main factors that determine the level of acceptable economic and environmental performances of a rainwater harvesting system are: the local characteristics (i.e. the rainwater demand, the settling model – single or storey buildings in a diffuse or compact density), the design of the rainwater harvesting sub-systems, the design of the potable water plumbing network as well as the town or urban water energy intensity.

From a climate change perspective, Silver et al. (2015) and Trenberth et al. (2007) cited in Angrill et al. (2011), also show in their findings that RWH can indirectly and significantly so contribute positively to the environment in a climate change perspective. They indicate that, if implemented in a large scale in a densely urbanised area, RWH may contribute to the reduction of the peak discharges in the storm drainage system. This consequently results in reduced urban floods frequency. The process in seen as an adaptive strategy to climate change against the reduction of water availability (Trenberth et al., 2007 cited in Angrill et al., 2011).

Vialle et al. (2015), further suggest that before implementing rainwater harvesting systems, studies incorporating a life cycle assessment methodology should be undertaken to look into issues related to sub-processes with high environmental impacts for instance, pumping and infrastructure. Table 3.4 presents some of the positive and negative aspects of rainwater harvesting sub-system.

Table 3.4 Positive and negative aspects of rainwater harvesting sub-systems (Adapted from Vieira et al., 2014)

Sub-system	Common practices	Type /applicability	Positive aspects	Negative aspects	Energy consumption
Collection	Roof catchment	All types	Higher quality of raw rainwater as compared to rainfall yields from other surface areas for example stormwater	Could present lower rainwater yields as a result of area constraints. May encourage the contamination of rainwater with heavy metals, organic matter and/or pathogens depending on the roof type, surroundings and maintenance frequency	No direct energy implications. Depending on the location and design of roofs, there may be opportunities to install rainwater gravity distribution systems without pumping requirements
Treatment	First flush diversion	All types	Effective minimisation of pollutant loads from harvested raw rainwater	In relatively low rainfall regions, the diversion of the first flush may significantly reduce the quantity of rainwater collected	No direct energy implications. Its inclusion may reduce energy use by eliminating head losses of pressurised distribution systems with in-line filters placed after pumps
	Gross filtration	All types	Removal of gross pollutants that may deteriorate the water quality in storage tanks	May require constant maintenance as per the design	No direct energy implication
	Fine filtration	All types	Removal of fine particles that may harbour or be associated with pathogens. Improvement of rainwater's aesthetics.	May appreciably increase the energy use of the RWH system when subsequent to pumps. This is because of the accumulation of particles in the filter medium. The accumulation is dependent on the quality of the rainwater as well as the maintenance frequency.	No direct energy implications. Indirect energy implications depend on filter design and location. Filter placed after pumping rarely require energy. Self-cleaning filters are preferred as they prevent excessive particles and pressure losses.
	UV disinfection	Potable water supply	Use of rainwater for all water end uses. The UV disinfection is more potent in inactivating	High energy requirement. The energy requirement depends on the design. Due to lack of residual disinfectant there is regrowth of pathogens.	May have high energy consumption. Optimisation of design may assist in better management with regards to energy consumed.

Sub-system	Common practices	Type /applicability	Positive aspects	Negative aspects	Energy consumption
			pathogens than chemical disinfection		
	Chemical disinfection	Potable water supply	Use of rainwater for all water end uses	May need constant manual operation. By-products in the water may cause odour nuisance and intoxication	If designed for automated dosing may require energy.
Storage	Large tanks	All types	Improvement of rainwater supply reliability. Have other indirect benefits such as probable reduction in floods in urban areas. This depends of the size of tank and the density of the tanks in a given region	There could be a challenge of space for both above ground and underground tanks. For above ground tanks, the issue of aesthetics could be problematic. Cost of large tanks could also pose a challenge of feasibility.	Static pressure head will determine the energy requirement. Gravity flow is preferable. The location of the tanks also influences the lengths of the pipe and the corresponding frictional losses which have an impact on the energy consumption.
	Slim line tanks	All types	Improvement of rainwater supply reliability in space constrained sites.	Economic constraints	Similar issues as stated above
Distribution	Direct external supply	Fixed speed pump	Low installation cost	May need variable amounts of energy as per the end use flow rates	Commercially available fixed speed pumps operate efficiently at high flow rates of > 15 L/min and are suitable to supply external uses.
	Direct internal and external supply	Fixed speed pumps	Same as raised above	For some end uses, it may require high energy consumption as a result of inefficient pump operation.	Existing fixed speed pumps will fail to meet both high and low flow rate water demand at optimal energy performance. Most likely to utilise excessive energy at low flow rates since the

Sub-system	Common practices	Type /applicability	Positive aspects	Negative aspects	Energy consumption
					selection of fixed speed pumps is based on the pump meeting the largest flowrate requirement
		Variable speed pump	Enhancement of the energy performance of pressurised water supply with variable flow rate	Economic constraints and specialised installer required to adjust pumping system to the most used flow rates	Energy benefits may accrue since variable speed pumps can achieve optimal energy efficiencies at both low and high flow rates. Careful selection is needed so as to meet site-specific conditions and intended outcomes.
		Pressure vessel	Enhancement of the energy performance of pressurised water supply with variable flow rate	Economic constraints and specialised installer required to adjust pumping system to the most used volumes per consumption event	Lets the reduction of pump start-ups by accumulation pressure into a vessel that boosts rainwater to consumption points. The energy performance is a function of its capacity to supply multiple rainwater consumption events without constant pumping.
	Header tank	Indirect supply	Very low energy consumption. Pump operation at the best efficiency point. Rainwater supply during power outages	Limited compliance with some pressure requirements. Installation may be limited by space or structural constraints depending on the size of the header tank.	Indirect supply systems with header tanks will generally enable the reduction of pump start-ups and operation of pumps at the best efficiency point. To promote minimal head losses and high energy efficiency, the diameter of the pipe between the ground level tanks and the header tank should be optimised.

Sub-system	Common practices	Type /applicability	Positive aspects	Negative aspects	Energy consumption
		Direct supply	No energy consumption	Reduced rainwater supply capacity, and limited compliance with some pressure requirements	Rainwater supply can be done entirely by gravity hence achieving energy neutrality in the RWH system.
Town water back-up	Trickle top-up.	All types	Simple installation in which town water is supplied into rainwater tanks when rainwater is not available.	May be misleading to the RWH system owners about the availability of the rainwater.	May increase the pumping operation in the RWH system with direct supply from storage tanks since town water may be pumped on-site along with rainwater. May have neutral energy implication in multi-storey buildings. This is so because town water is normally pumped on-site at all times in this building type depending on pressure requirements.
	Automatic switch	All types	Avoid pumping of town water in direct pumped systems	Require more components. Is less financially economical. May mislead RWH system owners about the availability of rainwater	Requires energy to power controllers and valves.
	Manual	All types	No energy consumption.	May be impractical. Potential unavailability of water due to operational lapses.	Neutrality in energy needs. In systems with high supply: demand ratio, the manual systems may require minimal operation thus promoting energy savings as standby energy consumption may be significant in RWH systems with low rainwater demand.

Angrill et al. (2011), corroborate some of the findings of Morales-Pinzón et al. (2015) regarding rainwater tank placement at the various scales that is the single-house scale and apartment-building scale. In their study, Morales-Pinzón et al. (2015) considered three scenarios of: optimistic (more favourable), pessimistic (less favourable) and average (using all rainfall data). In their study aimed at identifying the most environmentally friendly strategy for using rainwater in the Mediterranean Climate urban environments (Mediterranean climate regions are as previously specified), Angrill et al, (2011), however, selected eight (8) scenario for their analysis. The scenarios identified were classified as per the urban densities in terms of spread or “diffuse” (D) and “compact/concentrated” (C) newly constructed urban settlement areas models and the location of the rainwater harvesting infrastructure; the rainwater storage tank. The rainwater storage tank location scenarios were: (1) underground collection and storage tank; (2) below-roof rainwater collection and storage tank; distributed-over-roof rainwater collection and storage tank; and (4) a single block storage tank. The combination of the urban density variable and the location of the infrastructures added up to a total of the eight (8) scenarios used in the analysis. Again, as earlier suggested in other studies, the environmental impacts were quantified based on the LCA, since from literature, it is recognised that the application of environmental criteria to the study of rainwater harvesting usage is albeit underdeveloped. This justification is provided in Angrill et al. (2011), and the references cited therein duly support this argument. Angrill et al. (2015) used the Centre for Environmental Science (CML) 2001 Baseline method for the LCA application with the LCA methodology applied in each scenario as per the life cycle stages. The outcomes of this study suggested that for the contrasting urban density models analysed, regardless of the urban density, the environmentally optimal infrastructure is that in which the tanks are located on the roof, in an integrated design which is extended across the top of the building and evenly distributes the weight on the structure. In this study, the best scenario in both models was the distributed-over-the-roof tank (D3, C3). For the worst scenario, the spread or diffuse density model provided a reduction in impacts of up to 73% while the reduction in impacts obtained for the compact/concentrated urban design model was best at 92%. The cited advantages for this scenario were: reduced need for structural components (e.g. reinforcements for tanks, down pipes, gutter, supply pipe and pumps); the absence of catchment components (e.g. storage and distribution), the use of gravity flow for distribution of water supply, and the flexibility of the tank design in conformation to the shape of the roof. All the stated advantages also lead to energy savings. The results of the study also provided good environmental results in compact densities than in diffuse densities with respect to the GWP and higher water efficiencies. The following conclusion were drawn: that in the use of rainwater harvesting system:

(a) It is not a one-size-fit all application of RWH systems in drought-stress environments hence studies to enable the selection of a preferable system over another should not be seen as a waste of resources;
(b) Informed decisions in selecting the most favourable scenario in the development of newly constructed establishments presents a better strategy with huge savings in CO_2 emissions as compared to retrofit strategies which are currently prevalent; and
(c) While in the process of urban planning and design of rainwater harvesting structures, the stakeholders should consider an integrated approach that is all inclusive and incorporates the environmental criteria, economic, social, political, and technical factors. This should contribute tremendously in tailoring the design to the potential use that it is intended for.

As part of a Water Sensitive Settlement Design strategy, it would also be of use to carry out the energetics studies with a view to quantify the potential energy savings accrued by implementing the distributed-over-roof tank model in new urban establishments vis-à-vis a retrofit strategy of the same.

With regards to energetics studies, An et al. (2015), conducted a study in Hong Kong whereby they evaluated the potential multi-purpose utilisation of harvested rainwater for both water resource recovery and cooling effects. Part of the results of this study showed that the implementation of a rooftop rainwater harvesting garden had a significant cooling effect whereby a temperature drop of 1.3°C was observed as a result of the rainwater layer in the rooftop rain garden. The evaluation was done using ENVI-Met model. These results also further emphasise the usefulness of a multipronged approach in designing a rainwater harvesting system so as to fit the purpose for which it is intended to serve with additional intrinsic benefits.

3.2.5 Systems design studies

Water scarcity and water demand has led to an upward trend in the uptake in Rainwater Harvesting Systems (RWHS) globally. This has led to the rainwater harvesting systems to progressively become vital components of the sustainable domestic rainwater and stormwater management portfolio. Considerations of the environmental impacts and life cycle impacts of the RWH systems has occasioned the requisite for more precision in systems design (Ward et al., 2012). The need for precision calls for comprehensive guidelines for mainstreaming RWHS as part of the integrated water supply system strategy. However, in spite of the recorded upward trend and acceptability there is still limited comprehensive guidelines for integrating RWH systems as part of the integrated water supply systems strategy. Comprehensive guidelines such as hydraulic design and assessment guidelines, environmental impact assessment guidelines and standardised economic model guidelines are non-existent in many parts of the world (Ndiritu et al., 2018). The need for precision in systems design serves the following purposes: reduction in capital costs; lessen the quantity of materials used in developing the systems; and reduce the costs and resource requirements pegged on system installation and maintenance (Ward et al., 2012). Mun and Han (2012), further indicate that reliability and improved performance of a water supply is important for an efficiently operating water supply system and therefore appropriate design is necessary. Ndiritu et al. (2018) identifies storage size, catchment area, the rainfall, the rainfall yield, and the rainfall reliability as key factors to consider in developing a RWHS design and assessment guideline. Mun and Han (2012), further indicate that reliability and improved performance of a water supply is important for an efficiently operating water supply system and therefore appropriate design is necessary.

A typical RWHS contains three basic elements vis-à-vis (a) the collection surface/area, (b) the conveyance system, and (c) the storage and distribution system. The level of the system sophistication however differs between developed and developing (Silva et al., 2015). Despite the similarity in the basics, the RWHS vary with respect to their design and operation. Mun and Han (2012) developed a method to design and evaluate a RWHS. Their method is based on a water balance equation. In their method, Mun and Han (2012), identify the main design parameters of a rainwater harvesting system as rainfall, catchment area, collection efficiency of the catchment area (often referred to as the runoff coefficient), collection efficiency of rainwater from a filter (where applicable), the storage tank volume, and the water demand.

In developing guidelines for RWHS Design and Assessment for the City of Johannesburg (CoJ), Ndiritu et al. (2018) have used data based on the concept (premise) of hydraulic optimality to obtain relationships among the variables considered in determining the RWHS design parameters, *viz*. rainfall data, storage size, catchment area, rainfall yield, and rainfall reliability. To design a hydrologically optimal RWHS, the objective is to minimise storage size while maximizing the yield and reliability (Ndiritu et al., 2017, Ndiritu et al., 2018). The concepts espoused in Mun and Han, (2012) and Ndiritu et al. (2018) have been generalised to an idealised schematic relating the design components and associated design parameters of a typical RWHS. Figure 3.3 presents an idealised schematic of components of a typical RWHS with associated design parameters.

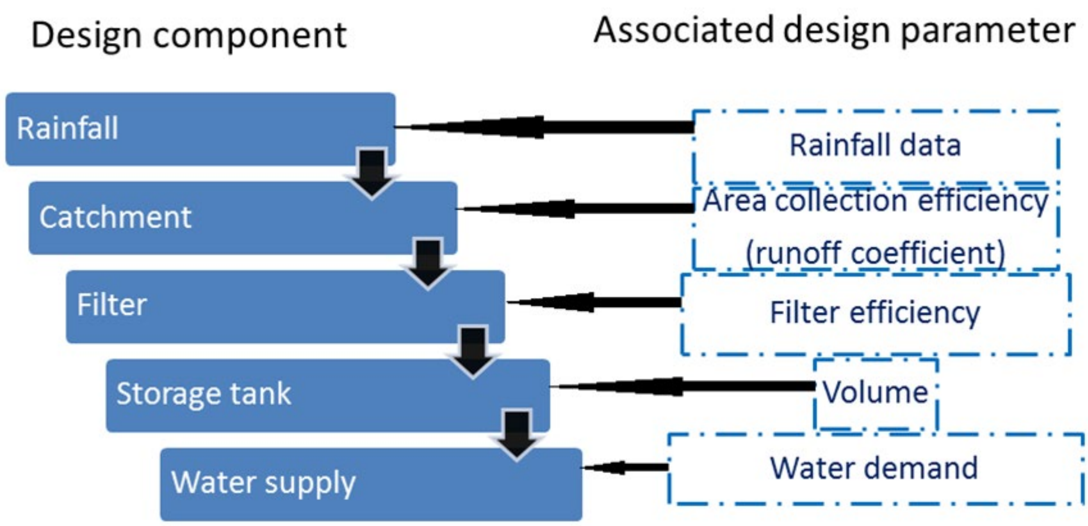


Figure 3.3 An idealised schematic of components of a typical RWHS with associated design parameters

From the operational side, in addition to the commonly used Water Saving Efficiency (WSE), Mun and Han (2012), identify the following additional key *operational parameters:* Rainwater Use Efficiency (RUE), and a parameter called the Cycle Number (CN). They define the operational parameter as follows:

$$\textit{Water Saving Efficiency (WSE)} = \frac{\textit{Annual Volume of Rainwater Harvested}}{\textit{Annual Water Demand}} \qquad [3.1]$$

This implies that WSE defines the proportion of total water demand that is satisfied by the harvested rainwater.

$$\textit{Rainwater Use Efficiency (RUE)} = \frac{\textit{Total Rainwater Supply}}{\textit{Volume of Rainwater collected / A / t}} \qquad [3.2]$$

Whereby A = Catchment area; and t = a given period. This implies that RUE is a function of the uses that the harvested rainwater is subjected to and therefore it is an indicator of the intensity as well as the multi-purpose nature of rainwater use in a given catchment area.

$$\textit{Cycle Number (CN)} = \frac{\textit{Total Rainwater Use}}{\textit{Rainwater Tank Volume}} \qquad [3.3]$$

The parameter CN as introduced by Mun and Han (2012), is basically an operational parameter that provides an indication of the quantity of rainwater being used per unit tank volume and hence could be applied as a design optimization parameter.

A design is not complete without a sensitivity analysis. Therefore, Mun and Han (2012), also define other parameters used in the sensitivity analysis. It is indicated that in most instances, the design and performance evaluation of RWHS seldom conduct a sensitivity analysis. Mun and Han (2012) therefore evaluated the effects of *design parameters* on the *operational parameters* based on the performance of the RWHS. In their study, Mun and Hans (2012), investigated the effects of tank volume and daily rainwater demand on the performance of RWHS. They defined the key *sensitivity analysis parameters* as:

$$\textit{Tank Volume to Catchment Area ratio} = \frac{V}{A} \qquad [3.4]$$

and

$$\textit{Rainwater Demand to Catchment Area ratio} = \frac{D}{A} \qquad [3.5]$$

The outcome of the study by Mun and Han (2012) indicate the following:

(a) That the water balance equation can be used to develop a design and evaluation method for a RWHS;
(b) That the design and evaluation method proposed by Mun and Han (2012) is a useful tool in the evaluation and comparative analyses of the performance of RWHS;
(c) That operational parameters RUE, WSE, and CN can be used to evaluate RWHS performance;
(d) That sensitivity analysis is a crucial procedure required in the optimisation of a RWHS design parameters and also to improve operation efficiency;
(e) That the ratios D/A and V/A can be effectively used as variables to analyse the sensitivity of design parameters to operational parameters with respect to the performance of a RWHS;
(f) That a design of a preferred RWHS based on the sensitivity analysis and judicious management of a RWHS should be accentuated to meet the objective operational parameters as well as increase operational efficiency.

Mun and Han (2012), propose and recommend an expanded rainwater use in areas with high and biased rainfall patterns for instance the Monsoon regions. This they opine is for improved Rainwater Use Efficiency in RWHS operations. However, the challenge is; based on their methodology and their suggested site-specific application, can the system work in an ASAL area?

Thomas et al. (2014), carried out a survey to determine the most common rainwater harvesting system setup, system materials and tank sizes as well as the real drive for rainwater harvesting in the United States of America. In addition, Thomas et al. (2014) also aimed to identify common treatment means and water quality practices for the respondents that harvested rainwater for potable uses. The outcome of their study showed that composite asphalt shingle and metal roofs are the most common roofing materials for RWH. Polyethylene, galvanised metal, and concrete were found to the most common tank materials. Regarding the size of the tanks, Thomas et al. (2014) remark that the respondents that use rainwater harvesting for potable use preferred larger tanks than those that harvest rainwater for non-potable uses. For the potable use category less than 13% of the respondents reported to testing the quality of their water on a quarterly basis. However, about 70% test the water quality yearly. The most common treatment method was found to be in-line Ultra Violet (UV) disinfection which was reported by approximately 70% of the respondents.

Other findings (Silva et al., 2015):

- The optimum tank capacity has a direct correspondence with the mean and median number of consecutive days without precipitation. This information can be used for pre-designing the RWHS

3.2.6 Systems performance studies

Palla, Gnecco, Lanza, and La Barbera (2012) conducted a DRWH system performance study in Europe. In their study, Palla et al. (2012) analysed the performance of DRWH systems under different climatic zones in Europe with the aim of optimising the design of DRWH systems under different rainfall regimes. For this study, 46 sites were selected within the European territory. The sites were equally distributed among five (5) main climate zones as per the Köppen-Geiger classification. To test the performance of the systems at each selected site, a behavioural model founded on a daily mass balance equation and historic rainfall observations as input variable was used. Scenario analysis was also conducted whereby the scenarios were assessed as a function of the environmental conditions (described by the hydrologic characteristics) and the operational conditions (described by the storage capacity). To rationalise the scenario analysis, the performance comparison was conducted as a function of two non-dimensional parameters, i.e. the storage and demand fractions. The output of the study was given in terms of the water quality and water quantity performance which was measured by detention time and an index referred to as the total water-saving efficiency index respectively. The following were deduced from the study:

- That the cold and humid temperate zones showed the highest quantitative performance in the entire spectrum of storage fractions that were characterised by frequent precipitation events and a modest inter-annual variability;
- That for low storage fractions, the water saving efficiency tends to decrease in response to a reduction in the frequency of precipitation events;
- Higher inter-annual variability in rainfall events also affects the system performance; and
- That limited rainwater availability results in the opposite behaviour vis-à-vis water quality performance.

3.2.7 Rainwater harvesting potential assessment framework

Few studies have evaluated rainwater harvesting potential at a city or regional scale for instance Ghisi et al. (2006), Proenca et al. (2011), Ishaku et al. (2012), and Belmeziti et al., (2013). The primary reason being that most of the domestic rainwater harvesting systems (DRWHS) are often implemented at a building scale. The studies by the cited authors show that key parameters and elements defining the DRWH at either local or regional scale remain similar. However, Liaw and Chiang (2014), present a more focused presentation and their study is herein discussed.

Following a multi-objective approach to develop a framework for assessing the rainwater harvesting potential in Taiwan, Liaw and Chiang (2014), identified three different categories of rainwater harvesting potential namely: The Theoretical potential; Available potential; and the Environmental bearable potential. The multi-objective approach considered a combination of the following factors of domestic rainwater harvesting:

- Climate;
- Building characteristics;
- Economy (Economic feasibility); as well as
- Ecological aspects (i.e. Environmental feasibility).

Most of the hitherto proposed rainwater harvesting potential methodologies have primarily concentrated on the quantity of the available rainwater. The flaw in this approach is in the focus on the rainfall element with little attention on other important elements of a rainwater harvesting system such as storage, the intensity of usage, economics (economic feasibility), as well as the environment (environmental impact of rainwater harvesting on the catchment hydrology) and socio-economic acceptability of the selected RWHS. In the Liaw and Chiang (2014), methodology, the area to be analysed is clustered into regions and rainfall zones (based on homogeneous rainfall intensities and duration). From their definitions, the following can be deduced:

3.2.7.1 Theoretical potential

Liaw and Chiang (2014), define the theoretical potential of domestic rainwater harvesting as the maximal amount of total collectable rainwater in a domestic rainwater harvesting system (DRWHS). In this definition climatic as well as the building characteristics, with the exclusion of the economic and environmental (ecological) factors are considered. The following expression is used to define the theoretical potential:

$$V_t = \sum_{i=1}^{n} \sum_{j=1}^{t} 0.001 \times \left[R_{ij} \times A_{ij} \times \bar{C}\right] \quad [3.6]$$

where

V_t = theoretical potential volume of domestic rainwater harvested in m^3

R_{ij} = average annual rainfall depth (mm) in the i^{th} region in zone j

A_{ij} = roof area (m^2) in the i^{th} region in zone j

$\bar{C}$ = average collection efficiency (runoff coefficient)

n and k = the total number of regions and zones respectively

3.2.7.2 Available potential

By factoring in the Rainwater Use Efficiency (RUE) (Mun and Han, 2012), the available potential of domestic rainwater harvesting value can be calculated from the following expression:

$$V_a = \sum_{i=1}^{n} . \sum_{j=1}^{k} 0.001 \times \left[R_{\text{ij}} \times A_{\text{ij}} \times \bar{C} \times \varphi_{\text{ij}}\right] \quad [3.7]$$

where

V_a = available potential volume of domestic rainwater harvesting in m^3

R_{ij} = average annual rainfall depth (mm) in the i^{th} region in zone j

A_{ij} = roof area (m^2) in the i^{th} region in zone j

$\bar{C}$ = average collection efficiency (runoff coefficient)

φ_{ij} = optimal rainwater use efficiency (RUE) = $\frac{\text{Total rainwater used}}{\text{Total rainwater harvested}}$ in region i and zone j

n and k = the total number of regions and zones respectively

RUE factor is due to the fact that due to limitations in harvested rainwater storage capacity, limitations in rainwater demand as well as the limitations in rainwater collection efficiency, total utilisation of all the harvested rainwater is impossible.

3.2.7.3 Environmental bearable potential

Liaw and Chiang (2014), and Mun and Han (2012), indicate that for large scale installations, DRWHS result in some environmental effects for instance reduction of downstream surface runoff (Sekar and Randhir, 2007). The reduction in downstream surface runoff may have some ecological impact on the downstream ecosystem. Liaw and Chiang (2014), utilise the total roof area percentage contributing to DRWH as an index to factor in the ecological aspect. The environmental bearable potential is then expressed as follows:

$$V_a = \sum_{i=1}^{n} . \sum_{j=1}^{k} 0.001 \times \left[R_{\text{ij}} \times A_{\text{ij}} \times \bar{C} \times \varphi_{\text{ij}}\right] \quad [3.8]$$

where

V_a = available potential volume of domestic rainwater harvesting in m^3

R_{ij} = average annual rainfall depth (mm) in the i^{th} region in zone j

A_{ij} = roof area (m^2) in the i^{th} region in zone j

$\bar{C}$ = average collection efficiency (runoff coefficient)

φ_{ij} = optimal rainwater use efficiency (RUE) = $\frac{\text{Total rainwater used}}{\text{Total rainwater harvested}}$ in region i and zone j

r_{ij} = roof utilisation efficiency = $\frac{\text{Total roof area used (in region i and zone j)}}{\text{Total available roof area (in region i and zone j)}}$

n and k = the total number of regions and zones respectively

A typical framework for estimating the domestic rainwater harvesting potential is as shown in Figure 3.4

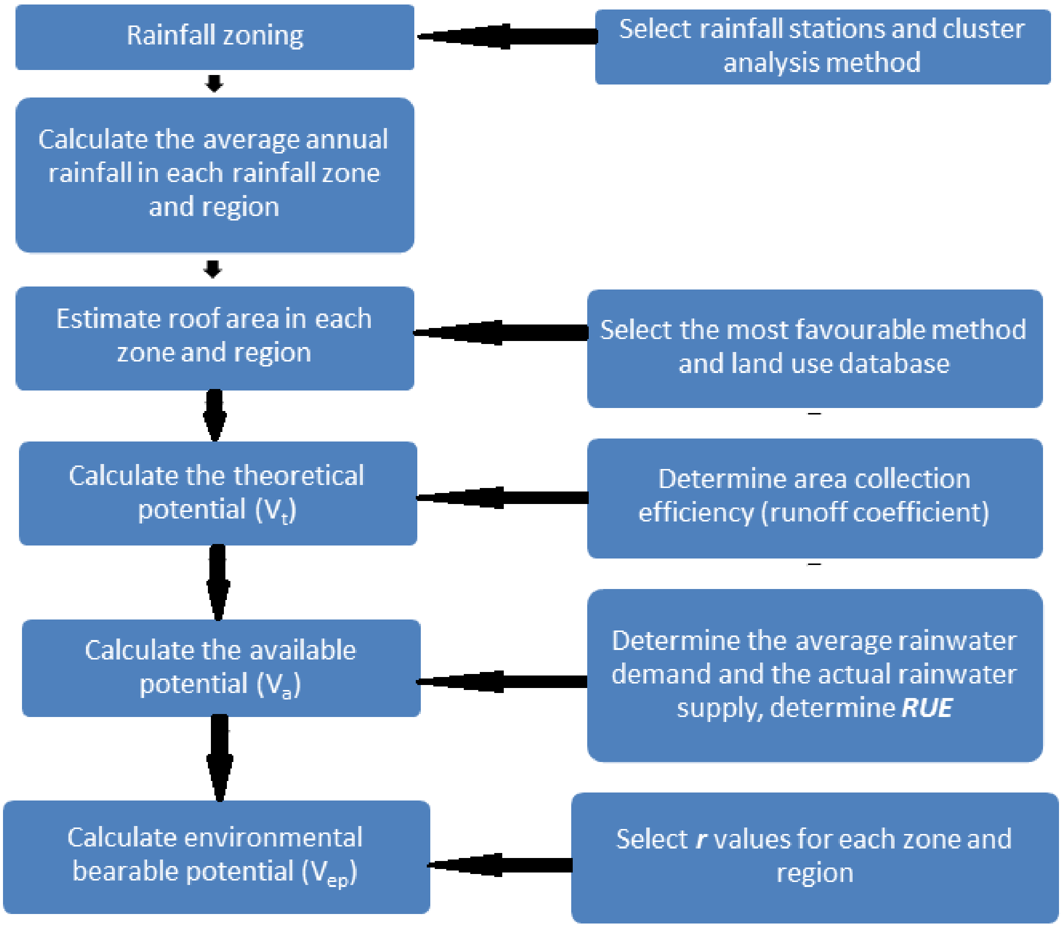


Figure 3.4 A framework for estimating DRWH potential (Adapted from Liaw and Chiang, 2014)

3.2.8 Revised rainwater harvesting potential assessment framework

The Sekhukhune District Municipally (SDM) study is considered a city or regional scale study hence the tenets applied would borrow a lot from proven works and experience by the cited authors in the preceding section. The proposed framework by Liaw and Chiang (2014) (Figure 3.4), forms a good basis for estimating DRWH potential in that it looks at the theoretical potential (physical availability), the available potential (practical quantity), and the environmental bearable potential (ecological impact of RWH). However, this framework could further be expanded by enlisting other determinants such as economic potential (through a life cycle analysis-LCA), social acceptance surveys and additional environmental indicators such as the energy use potential (EUP) and the Global Warming Potential (GWP) as illustrated by Morales-Pinzón (2012). The energy component is important since studies show that on average, 40% of the energy used in water networks is for production systems whereby the distribution accounts for 17% of the 40%. The implication thereof is that in saving potable water through RWH, one also saves energy. The impact of socio-economic variables on the viability of rainwater harvesting system is also considered vital in setting up the framework for the analysis (Morales-Pinzón, 2012). A revised framework should be more inclusive to incorporate the technical, economic, and environmental aspects of RWH. In this work, further suggestions to enhance the developed framework is through the inclusion of components accounting for:

1. Social feasibility (Socio-economic acceptance of a preferred rainwater harvesting system); and
2. Environmental analysis (negative environmental impacts as assessed through energy intensity of implementing a favourable rainwater harvesting system)

Literature suggests that in most feasibility studies of RWHS implementation projects, analyses of the socioeconomic acceptance of the preferred RWHS and the environmental impacts of implementing a preferred RWHS through a dedicated Life Cycle Assessment (LCA) is albeit underdeveloped (Angrill et al., 2011, 2015; Morales-Pinzón et al., 2015). Angrill et al. (2011, 2015), and Morales-Pinzón et al. (2015) also indicate, through the results of their studies, that environmental impact and socio-economic acceptance as criteria are key factors to consider within the framework of developing a holistic RWHS. These factors should be integral part of a multi-objective-multi-criterion decision-making feasibility analysis tool of RWH as a viable alternative water supply source for a targeted end-water-user. Environmental impacts are quantified based on the Life Cycle Assessment (LCA) of a suite of RWHS candidates. In this exercise, the possible negative environmental impacts such as Global Warming Potential (GWP, kg CO_2 eq.), Energy Use Potential (EUP, kWh/m^3), and Heath or Ecological Risks as measured through rationalised Environmental Risk Scores (ERS) are identified and recorded. A pool of decisions with scores and rankings can then be developed for selection of the optimal system from the suite.

Socio-economic acceptance of a preferred RWHS is measured as an index developed from a combination of data analyses, based on responses to the following pertinent leading questions: (a) Is rainwater source a necessary need or an option to be foregone? (b) Is rainwater a dignified source or of lower-grade in comparison to piped water? (c) Is there trust or confidence in the fidelity of the quality and value of rainwater, treated or otherwise? (d) Is there deliberate willingness to adopt RWHS? (e) Is there political will, a deliberate effort to disseminate information or conduct public awareness on the benefits of RWH as an alternative and dignified fit-for-purpose source of domestic water supply? (f) Are there set out guidelines, a deliberate move by authorities at all tiers of government (local, regional, and national) to mainstream RWHS as part of the whole with respect to water service delivery? For this study, a proposed revised framework is as presented in Figure 3.5.

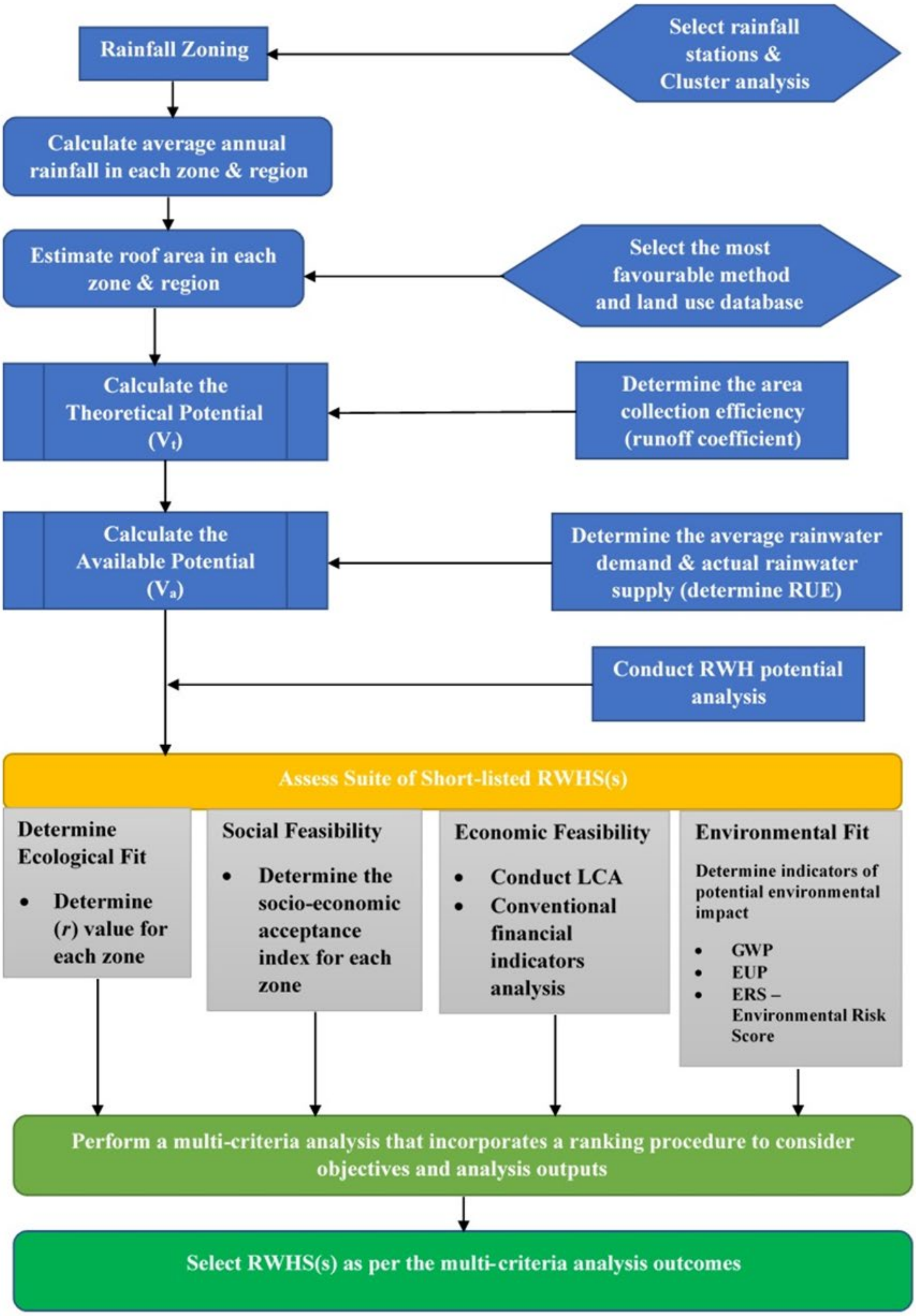


Figure 3.5 A proposed revised framework for estimating DRWH potential and selection of optimal RWHS(s)

3.2.9 Tasks to be completed to implement the revised rainwater harvesting potential assessment framework

The proposed revised framework (Figure 3.5) sets a basis for determining the actual quantities of the DRWH as well as the selection of an optimal RWHS from a proposed suite of RWH systems. It is a generalised framework envisaged to be applicable at either settlement or regional scale. A selected area of interest can thus be subjected to the steps in the framework to determine the desired DRWH quantities as well as a selection of an appropriate RWHS that suites the objectives of the resource managers in the subject area. Case studies with different scenarios can be applied to verify and/or modify the tenets of the framework.

3.2.9.1 Determining the optimum values of the parameters of the proposed revised framework

In order to draw informed conclusions on the feasibility of DRWH in a select area, a thorough assessment framework coupled with a comprehensive data base and analysis tools is necessary. The main challenge is the availability of reliable data to allow for among other activities, the development of scenarios that include climate change impacts for example. A brief of the set-out activities that are to complement the set framework are outlined in the section that follows.

3.2.9.2 Defining a workable functional unit

Key to the analysis is the definition of an appropriate functional unit (FU). Following the requirements of ISO 14044 (ISO, 2006), a functional unit is considered as a qualified performance of a product system for use as a reference unit. In the South African context, a more sensible functional unit would be the expected/allowable daily per capita supply of water for domestic use in the area of study since it is currently being used as a measure of service delivery by the various local and provincial governments as well as the national government.

3.2.9.3 Zoning

Key in determining the theoretical, available, and environmental bearable potential as depicted in equations 3.6, 3.7, and 3.8 and as also shown in the framework in Figure 3.5 is the accurate delineation of an appropriate zone in a given region. A selected functioning unit can only provide representative results if the zoning is also done effectively. The zoning/regionalisation/scaling in this study is defined by the settlement pattern as well as the administrative districts (local municipalities) and rainfall level characteristics. As described in the prelude to the development of the framework, the zones (rainfall zones) in a target region are classified based on homogeneous rainfall intensities and duration (Liam and Chiang, 2014). As for settlement types, the scaling is considered as being in either of the following categories: single house, neighbourhood or apartment building (diffuse or compact settlement density). This is informed mainly by the type of the present settlement patterns as well as the proposed schemes in the reference district. The clustering is also determined by the respective growth points in the district inter alia the population concentration point, district growth point, provincial growth point, municipal growth point and the local services point (AECOM, 2014).

3.2.9.4 Roof area calculations

The task of determining an aggregated roof area for a given zone is expected to be not only challenging but also time consuming. However, with the use of satellite information (GIS) a good estimate of the roof area is envisaged. For instance, in the South Africa case, the Department of Water and Sanitation (DWS formerly Department of Water Affairs-DWA) has implemented a DWA GIS system that was developed to capture all water services development in South Africa (AECOM, 2014) and this system is to be used to source for the necessary data to calculate the aggregated roof area. Based on the aggregated roof types, a consequent aggregated area collection efficiency (runoff coefficient) can be calculated.

3.2.9.5 Economic aspects

To determine the financial scale of a DRWH infrastructure set up, a Life Cycle Analysis (LCA) is to be conducted on existing and proposed systems. Though LCA is still a young field of study, it has been gaining prominence since its inception in the 1980s. The economic indicators to be used include among others the Net Present Value (NPV) as well as the other parameters previously described in the earlier sections in the discussions on Life Cycle Costing. LCA is extremely dependent on the concept of the Functioning Unit-FU (Cluzel et al., 2013) hence a representative FU is more likely to present a representative set of results.

3.2.9.6 Environmental aspects

The environmental aspects that are influential herein are; the Global Warming Potential (GWP), the Energy Use Potential (EUP), and Environmental Risk Scores (ERS). The framework and algorithms developed by Morales-Pinzón (2012) are so far the most comprehensive and adaptive in this field of study hence can form a great reference to be adapted in determining the GWP and the EUP parameters. However, as a contribution of this work, efforts have been made to develop enhanced frameworks for EUP and GWP. The Environmental Risk Scores (ERS) are derived through an analysis of the contribution of RWHS facilities or components such as HDPE tanks used for storage of harvested rainwater in the release of carcinogens and/or respiratory organics and Greenhouse gas emissions. The use of water treatment chemicals and the potential hazards posed by the treatment residues to the environment are, but other examples of environmental risks posed by the implementation of a RWHS. The Risk Score is a product of Likelihood of occurrence and Level of impact (ERS = Likelihood of occurrence x Level of impact). The ERS can then be ranked to prioritise the respective risks. The definition and selection of an appropriate FU is very key in this section as well.

3.2.10 Energy use potential framework

Energy consumption and GHG emissions resulting from setting up a rainwater harvesting systems requires that indicators of the extent of EUP and GWP be incorporated in the design. Regardless of the benefits of rainwater harvesting systems (RWHS) in mitigating water shortages or providing an alternative source of water, they also result in adverse impacts related to high consumption of energy (Vieira et al., 2014). UNICEF (2013), projects an increase in population with a more than 50% urban population share for most developing countries by 2050. Consequently, there is an expected increased pressure on the planet’s resources such as water and energy. This pitches water crisis as a present and future risk of human settlement. By 2035, the world's primary energy demands will grow by 40%, compared with that in 2010 (IEA, 2012). Saving water and energy resources becomes an important premise of sustainable development around the world.

Provision of water by designated water service providers entails planning and delivery of adequate water supplies for respective settlements (rural, peri-urban, and urban), commercial and industrial applications. The planning and delivery also involve the collection, treatment, and recycling of wastewater into the water cycle. Therefore, in the Water-Energy Nexus (WEN), a part of the story is that energy is required to supply water and the energy use in the water cycle is expended in the following systems shown in Figure 3.6.

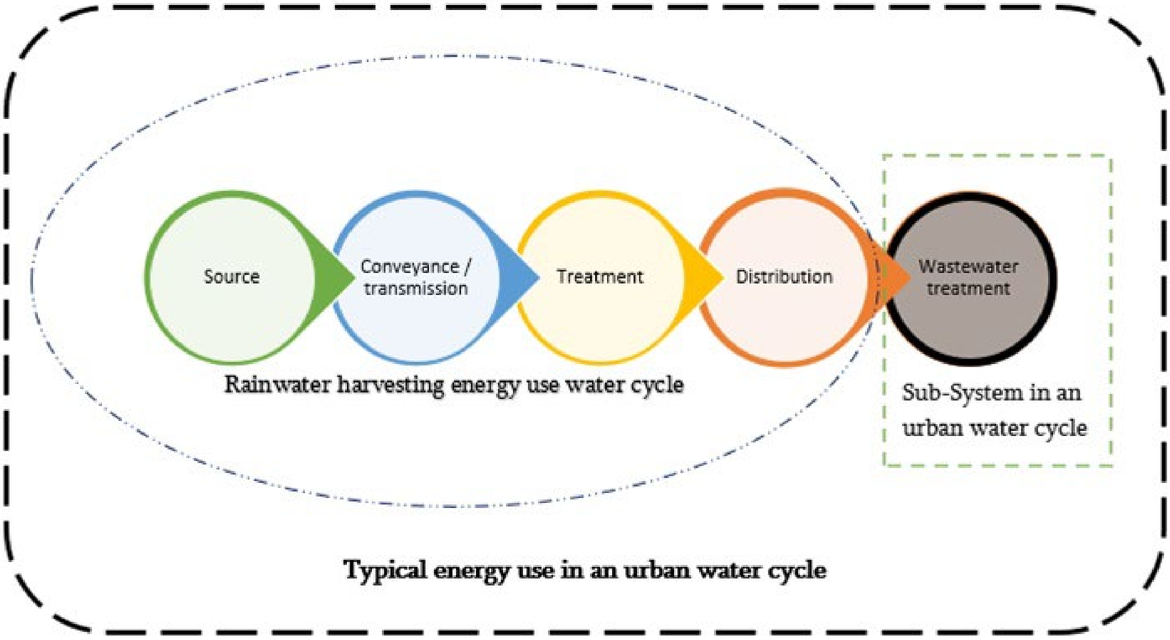


Figure 3.6 Typical energy use in a settlement water cycle

Energy intensity (EI), being the unit of energy per unit of water can be used as a key parameter for assessing the environmental feasibility of different RWHS

The energy use/requirement, also referred to as energy intensity (EI) or energy embeddedness (Kitessa et al., 2020) is calculated by computing the energy required per unit of water volume measured for each stage (kWh/m^3). Vieira et al. (2014) state that the energy intensity (EI), being the unit of energy per unit of water can be used as a key parameter for assessing the environmental feasibility of different rainwater harvesting systems (RWHS). The energy required in each stage (Figure 3.6) varies depending on the location (geographical attributes), quality, quantity, and distribution of the water source, as well as the type of technologies used in water supply system and the infrastructure in place (Wakeel et al., 2016; Kitessa et al., 2020). With reference to rainwater harvesting systems, Vieira et al. (2014) also point out that in determining the economic and environmental feasibility and/or acceptability of a designated RWHS, the local characteristics, including but not limited to rainwater demand, type of building (i.e. single-storey or multi-storey), RWHS sub-systems design, potable water plumbing system design, existing urban water energy intensity become key determinants in the performances analysis.

As depicted in Figure 3.6, water supply systems (water cycle) are one of the energy consumers in the service delivery cycle and yet, literature shows that for a long time, energy for water has received less attention in research with water supply systems and energy supply systems frequently being managed separately (Lundie et al., 2004; Kennedy and Wilkinson, 2011; Loubet et al., 2014). Vieira et al. (2014) highlight that the attention drawn to WEN has been prompted by the increasing significance of water security, energy efficiency, and economic feasibility of water supply systems. With reference to RWHS and any other water supply system, WEN is increasingly recognized as a principal factor for planning in the water resources utilisation and management. The complex interdependency between water and energy positions new challenges for resources managers and policy makers to strike a balance that attains a safe, secure, and sustainable supply of water and energy in the future (Kitessa et al., 2020).

The interdependence between water and energy use in the urban water cycle is strong. Water is used to generate energy (for instance hydropower, and solar thermal energy). Water is also used as an input to energy generation (for instance cooling water). Water treatment and transport requires energy, which contributes significantly to the environmental effects of water. It is estimated that pumping and treating urban water and wastewater consume two to three percent of worldwide energy use (ASE 2002). The International Energy Agency (IEA) (2016) estimated that 4% of total global electricity was consumed by the water sector in 2014 and it may rise by 80% by 2040.

3.2.11 Quantification of energy use of water

In recent years, energy assessment has been presented as one of the most important indicators of water utility performance evaluation. In equal measure, many methods that vary in scope and aim of the assessment/evaluation of energy transformation in water distribution systems have been presented in literature (Bylka and Mroz, 2019). Given that energy assessment of water supply systems is performed for different objectives, it is therefore not feasible to indicate a unitary universal method (Bylka and Mroz, 2019). Alegre et al. (2016) made a comprehensive revision of the IWA Performance Indicators (IWA PI) system for water supply services. The manual has a suite of indicators that have been tried and tested worldwide. However, in describing the energy metrics and performance indicators, two methods are extensively described in literature. The two types of methodologies are: the top-down and bottom-up approaches. The IWA Performance Indicator System for water services is now a standard worldwide reference. The system has been widely cited, adapted and used in a large number of projects both for internal performance assessment and metric benchmarking. The constantly revised versions provide the water professionals with a coherent and flexible system, with accurate and comprehensive definitions that in many instances have been accepted as standard. More appealing about the IWA PI System is its adaptability and fitness in different contexts for myriad purposes. Users indicate its versatility, irrespective of the nature and size of the organisation, whether private or public, or the degree of complexity and development. The IWA PI System also describes indicators that suitably cover bulk distribution and the needs of developing countries (IWA Publishing, 2016)

3.2.11.1 Top-down methodologies

Top-down methodologies assess water supply services systems with the main objective of determining the values of indicators that characterise the overall processes in a water utility. The assessment method may be built on external or internal benchmarking. The evaluation is generally conducted on a larger scale and it may be carried out by an external stakeholder. Top-down methodologies may also analyse economic facts about the system. This may relate to the cost of energy as a percentage of all operating costs. The analyses performed under top-down methodologies make it possible to carry out macroeconomic analyses. These analyses are critical in investment and rehabilitation planning for long-standing management.

3.2.11.2 Bottom-up methodologies

Bottom-up methodologies are very detailed in the performance analyses. They utilise mathematical descriptions of processes based on mass and energy conservation laws. Assessments are derived from the outcomes of the model calculations. The assessment is usually performed within utilities, as part of the in-situ analysis of technical robustness and management of infrastructural assets. In these methods, specific attention is paid to identifying the sources and reasons of energy losses in water supply systems. Benchmarking is a critical exercise in the bottom-up methods as the evaluation of performance assessment indicators involves a comparison of the calculated figures with reference values. The reference values may be determined using a modelling technique, usually on the basis of an idealised “optimal” model.

The IWA PI System is widely used due to its considered robustness. However, there are other systems that have been applied successfully in different countries, at different scales and with varied outcomes. Some of the systems and/or models that have been used include the following (Bylka and Mroz, 2019): Sigma software and AWARE-P (used to calculate the indicators of IWA PI for water supply systems); ECAM (for energy and greenhouse gas – GHG emission assessment); EPANET model (for calculation of energy balance of water distribution systems); IBNET (The International Benchmarking Network – a web-based interface for macroeconomic analyses); WATERGY (Energy and Water Efficiency in Municipal Water Supply and Wastewater Treatment); Life-Cycle Energy Analysis of a Water Distribution System among others. Bylka and Mroz (2019) also identify the main differences in the methodologies highlighted above being: approach to assessment (top-down and bottom-up assessment); types of performance indicators and methods of evaluating the reference values, and performance assessment; and the type of model applied to calculate and assess performance indicators.

In energy utilisation analyses, most of the indicators are analysed at the Functional Unit (FU) level. In this instance a unit value of energy usage is determined. Depending on the reference point, a unit value can be referred to as 1 m^3 of sold water, 1 m^3 of produced water, 1 m^3 of water injected to the network, or 1 m^3 of water pumped at 100 m of the head (Danilenko et al., 2014; Alegre et al., 2016). It is idealised that the ratio or difference between the values of indicators calculated using real and ideal models can be utilised for the assessment of the energy use of a water supply system. An ideal model is regarded as one in which there are no head losses through friction and leaks and there is no excess system pressure. This concept is used for setting reference values for indicator assessment. It is notably assumed that in an ideal model, all system parameters correspond to the best performance and by extension, the minimal energy requirement of the system can be determined. Hence the concept of ideal system and minimal energy in indicator assessment (Gómez et al., 2018).

3.2.11.3 Energy balance for water supply systems

Inherently undertaken in both the top-down and bottom-up methodologies of energy assessment is the concept of energy balance for water supply systems. In this case, a quantitative assessment of the energy transformation is presented that compares the amount of energy input that is flowing into the system (combination of natural and booster energy from pump shafts) with the amount of energy suppled at the end user point or lost (dissipated) through limitations of the system. Dissipations of energy in a water supply system majorly relate to limitation resulting to imperfect energy conversions in pumps, frictional losses in pipes and valves, leakages in tanks and pipes as well as excess pressures at the end user point of drawing water from the water supply network. In practical cases, energy balancing is performed using a mathematical model of a water distribution system. The model performs an analysis of water losses and leakages in the network. Results of energy balance for water supply systems can be useful and invaluable input for economic analysis of the system as well.

3.2.12 Framework for rainwater energy nexus (RWEN)

In estimating the energy use potential of an anticipated RWHS, it is imperative to draw parallels to other WEN systems that have been used especially in developing systems for the urban water system. Following up on this development and as a suggested input in the multi-criteria framework for the selection of an optimal RWHS, the framework for the rainwater-energy nexus, herein referred to as RWEN is adopted from the works of Kitessa et al. (2020).

Generally, in light of analysing an urban water cycle, the city is considered the core unit of analysis. Similarly, for WEN research globally, the city is considered the core unit of analysis. The use of EI as a key parameter/indicator for environmental and economic feasibility of designated RWHS is based on its hybrid characteristics in quantifying the energy flows of a water supply system. EI combines the top-down and bottom-up approaches to give a combined quantitative analysis of energy flows of a respective water supply system (conventional urban as well as rainwater harvesting water supply system energy flows). For a typical set of rainwater harvesting sub-systems, the high-level monthly energy intensity of the rainwater harvesting systems can be projected using a top-down model. An accompanying bottom-up model is then set up to calculate detailed energy estimates for a set of rainwater harvesting sub-systems of a given core unit of analysis, for instance an urban, peri-urban or rural water service area or sites. *For the purposes of this work, reference will* *be made to rainwater energy nexus (RWEN) in an attempt to differentiate it from the conventional water energy nexus (WEN) that refers to the conventional water supply systems.*

The methods for energy assessment of a water system depends on the purpose for the assessment, scope and aim for the assessment. The starting point then becomes the purpose that defines the boundaries of the context. Evaluation of the utility operation/performance requires a delineation of unique indicators. Mostly, the performance indicators are technical in nature. This requires setting up the requisite energy metrics. In this instance, the metrics suggested is the EI for its hybrid characteristics of combining both top-down and bottom-up assessment techniques to obtain a combined quantitative parameter that relates a measure of unit energy expended/required in processing a unit of water. The unit of water is processed through sub-systems (detailed assessment, *viz*., application of bottom-up analyses) that make up the entire system (high level assessment, *viz*., top-down methodologies). Figure 3.7 presents a suggested framework of the RWEN analysis for a rainwater harvesting system**.**

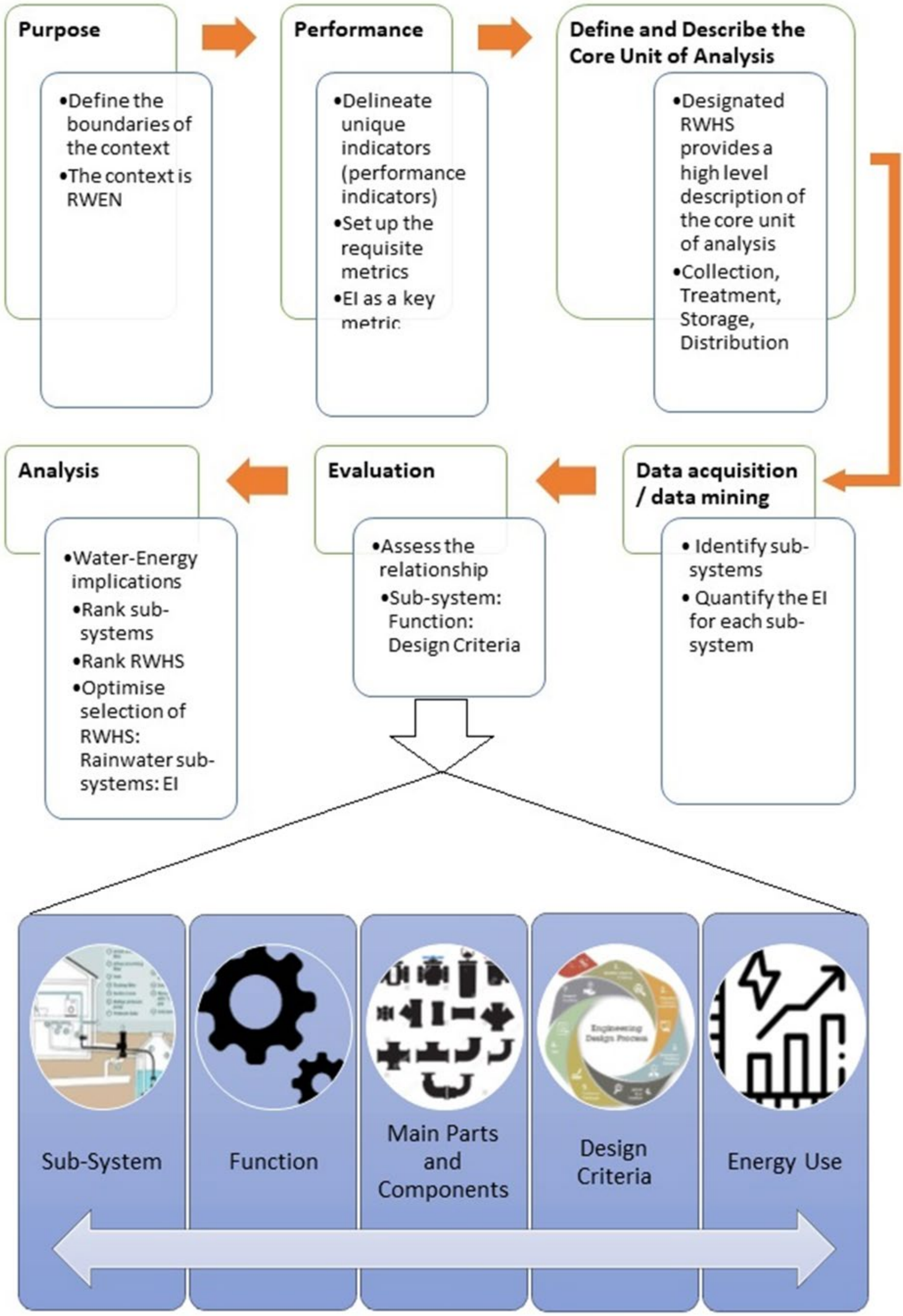


Figure 3.7 Framework of WEN analysis for a rainwater harvesting system

3.2.13 Global warming potential analyses

Estimating GWP is an important exercise in an analysis of the effectiveness of any water supply system that utilises any form of energy in its full or partial operation. The estimation is expressed in many ways and units. However, in the WEN studies, the widely adopted system is that which expresses GWP as the mass of carbon dioxide (a surrogate of the measure of GHG emission) emitted equivalent (in grams) per kilowatt-hour of energy expended (i.e. GWP, gCO_2/kWh). The following section highlights the suggested applications for the developed RWEN.

*3.2.13.1 **IFI TWG default emission factors***

There exists a correlation between energy intensity (EI) and Greenhouse Gas (GHG) emission, an indicator of Global Warming Potential (GWP) analysis for water supply systems. The International Financial Institutions Technical Working Group on Greenhouse Gas Accounting (IFI TWG, 2020) indicate that there are several ways to approach a GHG analysis for water supply projects. A chosen approach depends on what data is available. A common occurrence is that the anticipated project and baseline scenarios' total volume of water is known, but the energy intensity or total amount of energy demand is not known before carrying out the GHG analysis (IFI TWG, 2020). IFI TWG (2020), has developed a set of default values for energy intensity factors for sourcing, conveyance, various treatment technologies, and distribution of water supply systems. These default values are only recommended for use in instances where reliable and accurate local data are not available and/ or not updated for use in the GHG analysis for any given water supply project. The provided default energy intensity information by the IFI TWG is fairly recent (2020, revised and adopted in April 2022) and is specific for conventional water supply systems. It is a living document maintained by the IFI TWG. However, given the similarities between the conventional water supply systems and the domestic rainwater harvesting systems (DRWHS), it is opined by the author, that, parallels can be drawn and the default energy intensity factors customised to be representative of the DRWHS in calculating the default IFI TWG grid emission factor for the given country/region. Country/region specific harmonised IFI default grid emission factors is provided as Appendix A of this document. The instructions on how to use this document is provided as Appendix B of this document. The methodologies used to arrive at the information in Appendix A is available as Appendix C of this document.

WEN is an important factor of analysis in a water services cycle. Water scarcity, greenhouse gas emissions from fossil fuel-based energy generation, and costs for both resources, all create pressure on either side of this nexus (Dziedzic and Karney, 2014). Studies also show that electricity usage is accountable for a substantial part of GHG emissions and for the costs of water distribution. Studies by Stokes and Horvath (2011) on life-cycle analyses of water infrastructure present the operational phase of the water services cycle as responsible for most of the environmental impacts, contributing approximately 67% of GHG emissions due to energy use. The need for alternative water sources (e.g. from groundwater sources, rainwater harvesting, and desalination) and the stringent regulations on wastewater utilities in respect of treated wastewater discharge and re-use lead to higher energy and resource requirements. The environmental implications of these services should be incorporated into design and planning decisions to develop a more environmentally-responsible water and wastewater system (Horvath and Stokes, 2010).

3.2.13.2 Life-cycle energy assessment

Life-cycle assessment (LCA) is a quantitative, comprehensive procedure that can be used to account for energy consumption and energy emissions resulting from extraction of raw materials, processing/manufacturing raw materials to finished goods/products, transporting, constructing, operating, maintaining, and decommissioning infrastructure and to incorporate these implications in decision-making (hybrid life-cycle assessment). An example of such hybrid life-cycle assessment is presented in the work of Stokes and Horvath (2009) – Energy and Air Emission Effects of Water Supply. Process based-LCA, Economic

Input Output (EIO) based-LCA and a decision-support tool, the Water-Energy Sustainability Tool (WEST) were applied in the U.S.A, California State to explore life-cycle air emission effects of supplying water for a typically sized U.S utility in the California State. Horvath and Stokes (2011) extended their study in the same state in evaluating the life-cycle GHGs emission factors (EFs) for common material choices in water supply systems, including pipe materials and tank design.

3.2.13.3 Modelling tools

The Energy Performance and Carbon Emissions Assessment and Monitoring (ECAM) tool software is a popular tool utilised by many researchers, institutions, water and wastewater services utilities in evaluation of energy efficiency and greenhouse gas emissions cf. Fighir et al. (2019) – Environmental and Energy Assessment of Municipal Wastewater Treatment Plants (MWWTPs) in Italy and Romania: A Comparative Study, the aim of the study was, sustainability evaluation of four Italian and Romanian MWWTPs in terms of energy efficiency and greenhouse gas emissions; Motasem et al. (2019) – Baseline carbon emission assessment in water utilities in Jordan, the aim being to reduce direct and indirect emissions; Muhammetoglu et al. (2023)-Assessment of energy performance and GHG emissions for the urban water cycle toward sustainability. This study presents a holistic approach to evaluate energy performance and greenhouse gas (GHG) emissions from urban water supply and sanitation stages, which are important for sustainable water management and climate change mitigation. The study was conducted for Antalya city of Turkey to compare baseline and improved scenario conditions; Tian et al. (2022)-Insight into Greenhouse Gases Emissions and Energy Consumption of Different Full-Scale Wastewater Treatment Plants via ECAM Tool. In this study, the carbon emissions and energy consumption of typical wastewater treatment processes in China were evaluated, starting from different cities and water treatment plants.

3.2.13.4 ECAM tool

The brief on ECAM Tool is derived directly from the operation manual, ECAM official website and cited users and therefore cross-referencing may be read as common in this section.

The Energy Performance and Carbon Emissions Assessment and Monitoring (ECAM) tool is an open-source software developed within the Water and Wastewater Companies for Climate Mitigation (WaCCliM) project. WaCCliM, part of the International Climate Initiative (IKI) is a joint initiative between the Catalan Institute for Water Research (ICRA), the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH and the International Water Association (IWA) (WaCCliM, 2017). It is recommended as a source of valuable information for energy performances at the operational level and for identifying the stages within the urban water cycle where GHG emissions could be reduced (WaCCliM, 2017; Fighir et al., 2019, Silva et al., 2022). The ECAM tool only requires data typically available in utilities. ECAM tool methodologies can be applied to utilities nationwide, facilitating national benchmarking and knowledge exchange between utilities. ECAM results could then be compared with known benchmarks so that hot-spots can be identified, and decision makers can prioritize improvements in the most promising stage, that is, improve energy efficiency of the water pumping systems, improve the water efficiency (reusing treated wastewater), and generate the energy from renewable resources such as solar energy and biogas (WaCCliM, 2017; Fighir et al., 2019, Silva et al., 2022).

The ECAM tool enables the measurement and management of GHG emissions and energy consumption at a system-wide level in water and/or wastewater management, enabling utilities to quantify their GHG emissions and contributions to Nationally Determined Contributions (NDCs), identifying the critical areas for GHG emission reduction, increasing energy savings, and improving overall efficiencies to reduce the costs. It can be very useful for all stakeholders involved in water service management and planning for GHG emission and energy performance assessments and to identify appropriate and operative perspectives to limit overall carbon dioxide emissions. The tool therefore helps link Monitoring, Reporting and Verification of mitigation actions in the water sector to the national level (ECAM as a tool for MRV). The Performance Indicators publications of the International Water Association (IWA) (WaCCliM, 2017; Alegre et al., 2016; Fighir et al., 2019) for water supply and wastewater, along with some additional indicators, are the starting point for the calculation of service levels and energy performance. The energy requirements are translated into GHG emissions using a conversion factor based on the specific country's electricity mix (kgCO_2 (eq.)/kWh) (IFI TWG, 2020). This allows the users to avoid any fluctuation of the GHG emissions that are unrelated to the performance of the utility itself (WaCCliM, 2017, Fighir et al., 2019).

The ECAM tool considers the entire urban water cycle from water abstraction and treatment to wastewater treatment and discharge (full water service cycle. Figure 3.8) in the derivation of the GHG emission reduction in utilities. This is also achieved for utilities with limited data availability. However as per the structure of the programme, one could split the analyses in two, i.e. the water utility and the wastewater utility for independent analyses.

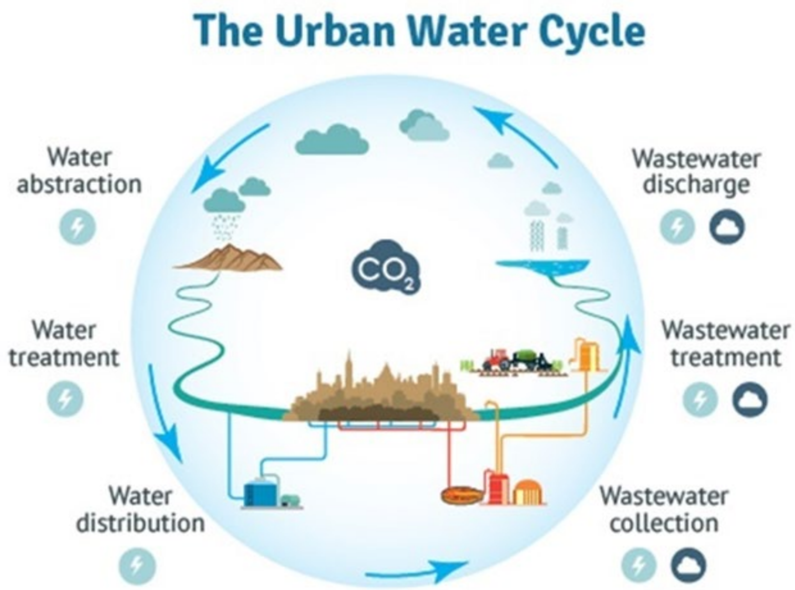


Figure 3.8 The urban water cycle elements applied in ECAM Tool (Adopted from WaCCliM, 2017- www.wacclim.org/ecam)

The ECAM tool is IPCC compliant and therefore the IPCC Guidelines for National GHG Inventories are used as integral part of the data for analysis of the utility energy performance and carbon emission assessment. The emission targets assessing Scope 1 emissions: these are direct GHG emissions from operations that are owned or controlled by the reporting utility; Scope 2 emissions: these are indirect GHG emission from generation of purchased energy consumed by a company (e.g. emissions from electricity the water service utility buys from the grid for use at the utility site); and Scope 3 emissions: these are all other indirect GHG emissions (not included in Scope 2) that occur in the value chain of the reporting company as defined in the IPCC guidelines are applied.

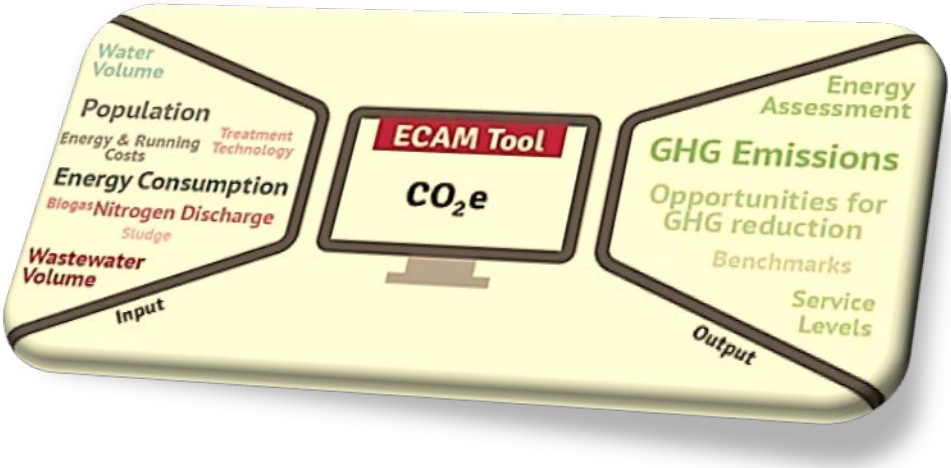


Figure 3.9 A typical summary outlay of input requirements and output expectations in the ECAM Tool domain (Adopted from WaCCliM, 2017)

3.2.13.5 Benefits if using ECAM tool

According to the literature on the official ECAM Tool website https://climatesmartwater.org/ecam/, most water profession practitioners, government institutions and research entities prefer to adopt the tool as their first choice for application based on the following facts.

ECAM Tool is a first step towards a climate-smart urban water management. It therefore sets an origin point for reducing GHG emissions and efficiency in energy usage in the water services sector. A summary of benefits accruing from using ECAM Tool include but not limited to the following (WaCCliM, 2017; Silva et al., 2022):

GHG and energy assessment

The ECAM Tool can calculate the GHG emissions of urban water and wastewater utilities at each stage of drinking water supply and sanitation systems. It can also evaluate energy performance and service level indicators of a water utility at the system-level.

Integrated holistic approach

The tool is designed with a capacity to assess the entire urban water cycle. It is designed to calculate GHG emissions at all stages of the cycle, permitting integrated comparisons and assessments. With such a functionality, the user can create assessments with a choice, based on the objective of the assessments; accounting only some stages of a system, the complete system, or even all the systems of a utility. Additionally, it is also possible to include energy performance and service level analyses calculated by the tool, for instance: topographic energy use; electromechanical efficiency; sludge management; treatment performance; biogas production among other analyses.

ECAM as a Monitoring, Reporting and Validation (MRV) Tool

ECAM output reports/results can be used to report and monitor GHG emissions. It allows users to compare the GHG emissions of a utility over time and with those of other utilities.

Free and Open-Source

As a web interface software, ECAM can be freely used, copied or changed. Its source code is openly available on GitHub. The WaCCliM project team encourages users to improve or make suggestions on how to improve the tool. This is an open invitation that would be enticing to any professional that would like to customise the tool and/or improve the tool to cater for probable shortcomings in relation to his/her project and still make the results valid and sound. The programme can also be operated offline. The user is also allowed to export his/her data by highlighting the desired tables and copying them into a data spreadsheet. This is a desirable feature for portability of information.

Identify opportunities to improve service
The available functionality in the ECAM Tool to develop scenarios on the impact of GHG mitigation measures allows the user assess the points of greatest opportunities for reducing greenhouse gas emissions resulting from alternative measures within the entire urban water cycle. This functionality allows users to identify opportunities for action and facilitates informed decision making.

Secure
ECAM is secure and trustworthy. No information is stored on servers. All data inserted and processed during the ECAM assessment are merely on the users' personal computers. This is important for information protection as well as an enabling factor for the tool's application in non-disclosure projects.

Based on IPCC Guidelines
ECAM is IPCC-2019 compliant. ECAM Tool was developed to be consistent with the IPCC Guidelines for National Greenhouse Gas Inventories and peer-reviewed literature. As a tool for MRV, ECAM can provide the methodology for MRV of GHG emissions in the water sector. This is because it is founded on IPCC guidelines. For building national inventories, only IPCC Guidelines are accepted and recognised internationally (WaCCliM, 2017, Silva et al., 2022). Given its open-source-web interface structure, ECAM also support developing national as well as facility-level GHG inventories.

3.2.13.6 Significance of ECAM tool IPCC-2019 compliance

The following section is an excerpt from the Press Release in KYOTO, Japan, May 13 in 2019 – The Intergovernmental Panel on Climate Change (IPCC) (IPCC Updates Methodology for Greenhouse Gas Inventories, 2019).

The 2019 refinement to the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines on National Greenhouse Gas Inventories (*2019 Refinement*) was prepared by the IPCC's Task Force on National Greenhouse Gas Inventories (TFI). A plenary session of the IPCC Panel in Kyoto, Japan, adopted the report's Overview Chapter and accepted the main report.

Over 280 scientists and experts worked on the *2019 Refinement* to produce many changes to the general guidance as well as methodologies for four sectors: **energy**; **industrial processes and product use**; **agriculture**, **forestry** and **other land use**; and **waste**.

As a requirement of the IPCC, Governments are to report their national greenhouse gas inventories-comprising estimates of greenhouse gas emissions and removals-to the United Nations Framework Convention on Climate Change (UNFCCC) including under processes such as the Kyoto Protocol and Paris Agreement.

The updated IPCC methodology improves this transparency and reporting process by ensuring that the methodology used to determine these inventories is based on the latest science. Apart from the required transparency in reporting and the updates in methodology based on the latest science, the 2019 refinement also portends the following:

- It provides an updated and sound scientific basis for supporting the preparation and continuous improvement of national greenhouse gas inventories,
- It provides supplementary methodologies to estimate sources that produce emissions of greenhouse gases and sinks that absorb these gases.
- It addresses gaps in the science that were identified, new technologies and production processes have emerged, or for sources and sinks that were not included in the *2006 IPCC Guidelines*.

- It also provides updated values of some emission factors used to link the emission of a greenhouse gas for a particular source to the amount of activity causing the emission. Updates are provided where authors identified significant differences from values in the *2006 IPCC Guidelines*.

3.2.14 Socio-economic acceptance index (S-eI)

A survey of the social perception with regards to the possible uptake of rainwater harvesting as either a primary or secondary source of water needs to be conducted. This element is critical in analysing the probable success of implementing a domestic rainwater harvesting system especially at the envisaged scale. Socio-economic acceptance of a preferred RWHS is measured as an index developed from a combination of data analyses, based on responses to selected pertinent leading questions as indicated in the previous sections. As stated in the sections leading to the development of the framework, political will and institutional policy frameworks in place play a key role in determining the final score of the socio-economic acceptance index. In South Africa, and in SDM for instance, a lot of political influence abound on the grounds that the provision of rainwater harvesting systems in the area is akin to rendering second rate service to the residents of the SDM (personal communication from the municipal authorities). This is yet to be factually documented and hence if the social perception survey were to be conducted, one of the hypotheses would be that RWHS(s) are undignified and do not provide high-grade services with respect to the provision of potable water to the households in the municipality.

3.2.15 Technical analysis of domestic rainwater harvesting systems

The rainwater supply and demand flow routes form the basic unit for the volumetric analysis and development of the flow models to be applied in the technical analysis of the DRWH systems. Figure 3.10 shows a simplified flow model that can be used in such case studies.

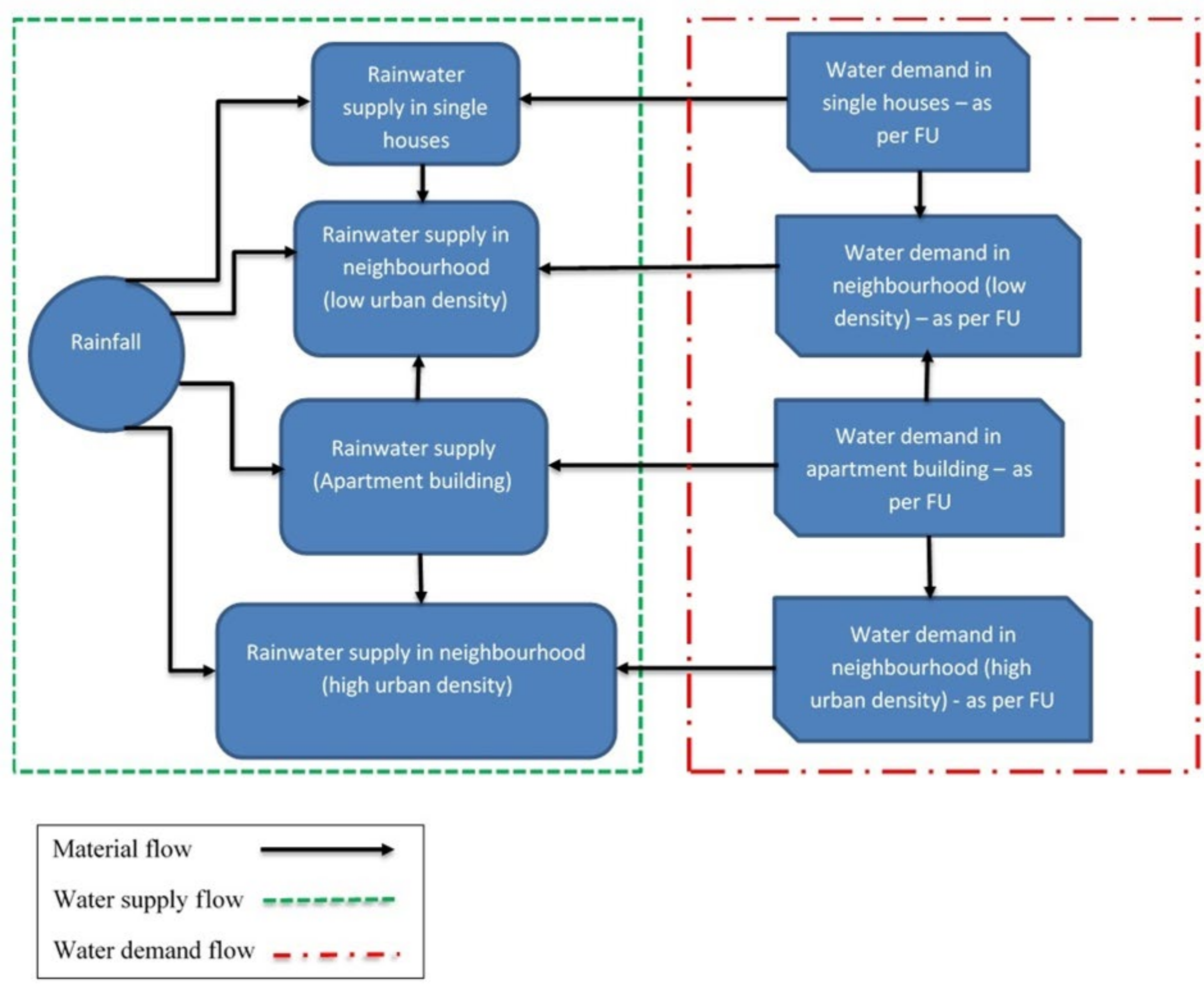


Figure 3.10 A simplified flow model for technical analysis of a DRWH system

CHAPTER 4: A FRAMEWORK FOR DEVELOPING STORMWATER HARVESTING SYSTEMS AND MONITORING

4.1 INTRODUCTION

4.1.1 Stormwater harvesting and management

Viljoen (2014) defines stormwater harvesting as a process that entails the collection, treatment, storage, and use of stormwater runoff from pervious or impervious surfaces. This as opposed to rainwater harvesting which in most literature is considered as the direct capture of rainwater mainly from rooftops. In the context of stormwater management, stormwater harvesting, and reuse is considered a critical tenet of stormwater management. Stormwater harvesting offers an option in the realm of an integrated and sustainable urban water management and can provide multiple benefits/outcomes that include inter alia (Mitchell et al., 2007; Brodie, 2012; www.brisbane.qld.gov.au/water):

- Flood protection, mitigates flood impacts, and erosion control;
- Enhancement of urban stream health through the physical abstraction of the contaminated water, a process that improves the flow regime by alleviating the probable deterioration of water quality in the receiving waters (both surface and groundwater resources);
- Attain and protect natural waterways *in-situ*;
- Reduces the need to construct new supply development;
- Supports local community values and enhances public amenity and lifestyle values; and
- Provides an alternative water source fit for compatible end uses.

Stormwater management should be both safe and sustainable by supporting a socially and environmentally responsible use of the harvested stormwater (www.brisbane.qld.gov.au/water). In which case it would imply the management of both quantity and quality of stormwater in a manner that meets the present needs without compromising the future needs, thus, attaining a balance between economic costs, environmental gains, and societal resilience (Akram et al., 2014).

If not sustainably managed, stormwater may have varied impacts on the waterways and other receiving waters located near the feeder urban or peri-urban locations/settlements. Such impacts may be manifested in terms of (US EPA, 1999):

- Alterations in hydraulic characteristics of streams receiving runoff such as higher peak flow rates, increased frequency and duration of bank-full and sub-bank-full flows, increased occurrences of downstream flooding, and reduced baseflow levels;
- Variations in receiving stream morphology such as increased rates of sediment transport and deposition, increased shoreline erosion, stream channel widening, and increased stream bed scouring;
- Aquatic habitat impacts leading to changes in flora and fauna composition and population resulting in a loss of balance in the ecosystem; and
- Public health and recreation impact such as increased risk of illness due to contact with contaminated water bodies, contamination of drinking water supplies, beach closures, restrictions on fishing, and shellfish bed closures.

Over time, the need to establish resilient and sustainable stormwater management systems have led to the continuous development and refinement of ethos/schemes referred to as the Best Management Practices (BMPs) or Best Planning Practices (BPPs). BMPs can either be structural or non-structural. As stated in Akram et al. (2014), climate change has been identified as a threat to the application of BMPs to attain sustainable stormwater management. Whether structural or non-structural, the benefits of BMPs are site specific depending on several factors such as (US EPA, 1999):

- The number, intensity and duration of wet weather events;
- The pollutant removal efficiency of the BMP;
- The water quality and physical conditions of the receiving waters;
- The current and potential use of the receiving waters; and
- The existence of nearby “substitute” sites of unimpaired waters.

4.1.2 Stormwater harvesting systems

As previously stated, stormwater harvesting refers to the collection, treatment, storage, and use (distribution) of stormwater runoff. The basic components are the collection system; the storage system; the treatment system; and the distribution system. The combination of these systems is dependent on the nature of the site and the end use(r). Since both stormwater harvesting and rainwater harvesting involve the generation of runoff, they have commonalities for instance, the need for a catchment with a given runoff generation characteristics. Figure 4.1 depicts a typical generic stormwater harvesting flow diagram and Figure 1.2 presents a schematic example stormwater harvesting and use system.

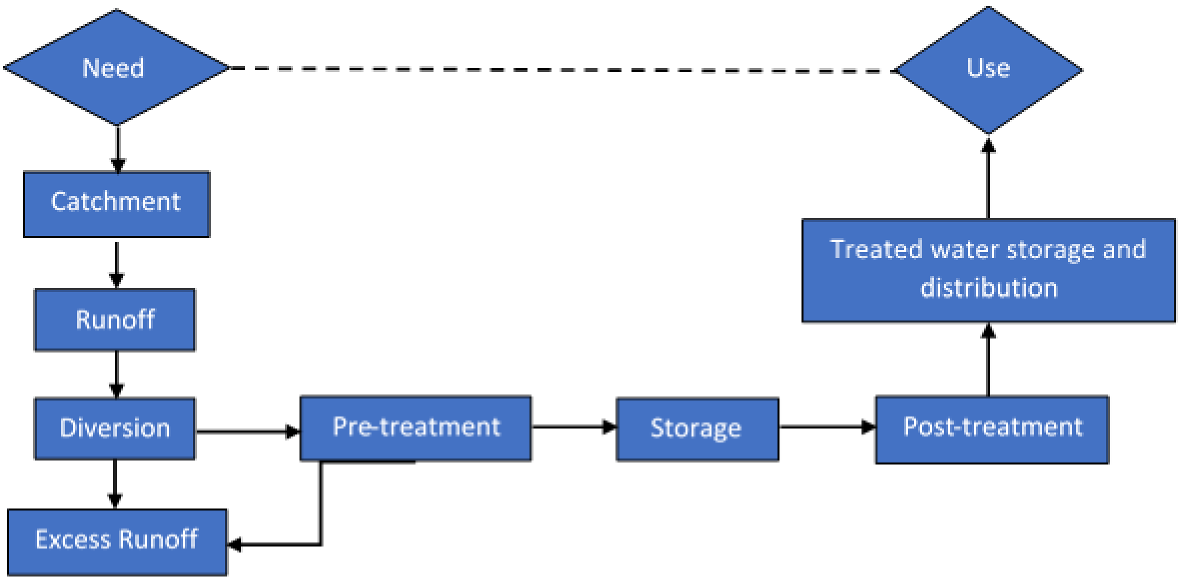


Figure 4.1 A Generic Stormwater Harvesting Flow Diagram (Adapted from Akram et al., 2014)

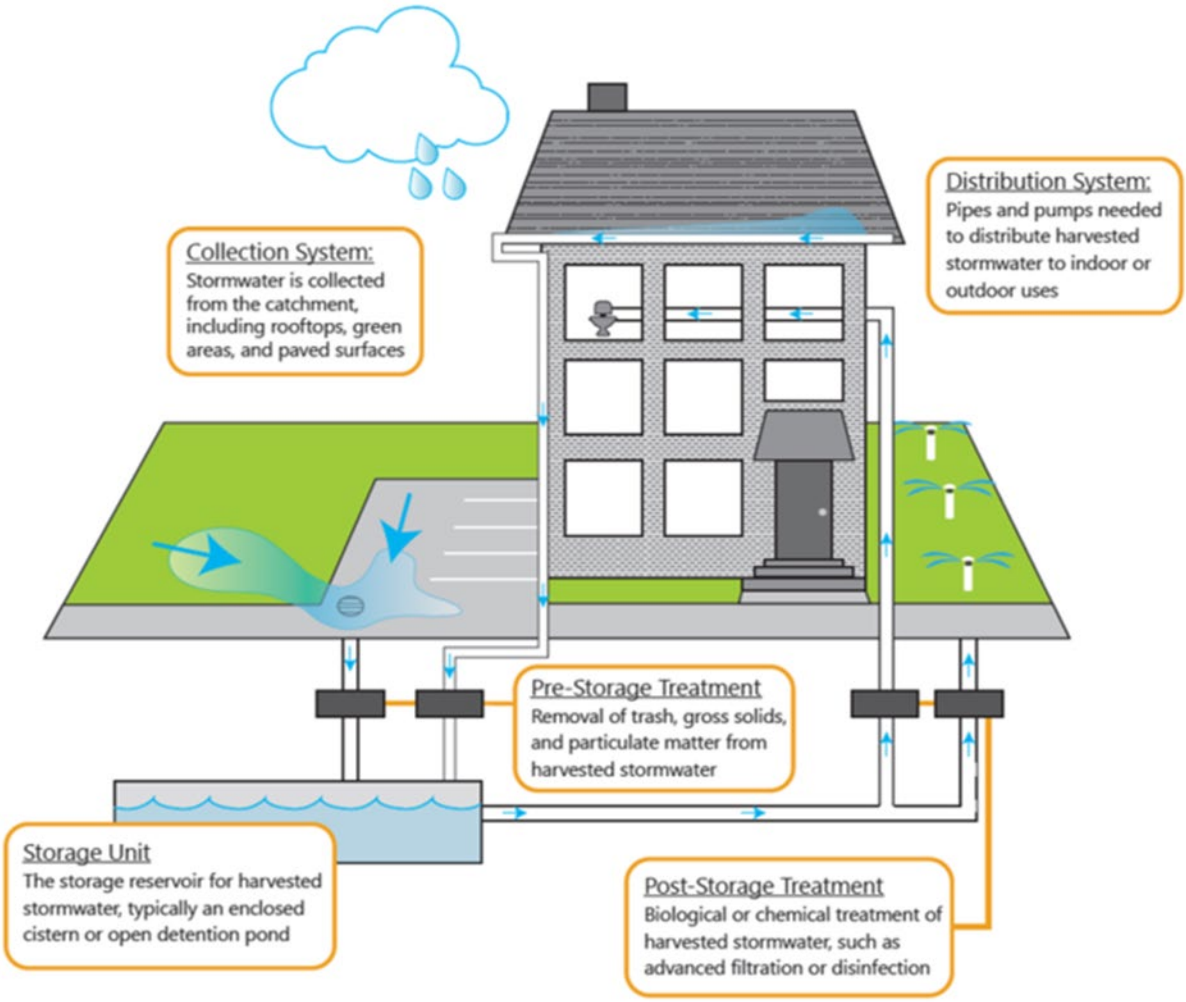


Figure 4.2 Schematic example stormwater harvesting and use system (https://stormwater.pca.state.mn.us/index.php?title=Overview_for_stormwater_and_rainwater_harvest_and_use/reuse)

An important element of the stormwater harvesting system is the treatment system. Treatment is needed to remove pathogens and other undesirable contaminants/pollutants. The degree and intensity of the treatment is dependent on the intended end use as well as the regulatory water quality requirements with regards to the reuse of harvested stormwater. These are based on the risks posed to human health (that is the health criteria), and/or to the environment (for instance irrigation use may result in water logging or salinity of the soils). In some instance, if the use is for industrial purposes, industry-specific standards will apply. The three principal levels of treatment are: the primary treatment whereby physical screening and rapid sedimentation are dominant processes; the secondary treatment whereby sedimentation and filtration processes are dominant; and the tertiary treatment (polishing) whereby the dominant processes vary depending on the end use, level of contaminants as well as the regulatory water quality requirements. The dominant processes at the tertiary level are; filtration, biological uptake, enhanced sedimentation, and adsorption (Akram et al., 2014). In most instances, stormwater schemes are developed for non-potable applications. However, in general, stormwater harvesting, and reuse is the practice of collecting and reusing stormwater for potable or non-potable applications. These applications either potable or non-potable could be termed “beneficial use” of stormwater.

4.1.2.1 Beneficial use of stormwater

Beneficial uses of stormwater include any use of water to meet individual or societal water needs inter alia: Residential uses (drinking, bathing, washing, flushing, firefighting, and cooling), Agricultural and industrial uses; Environmental flow provision, Aquifer storage and recovery (ASR) or Aquifer storage transfer and recovery (ASTR), Urban lakes and ornamental ponds, Constructed wetlands, and Water sensitive urban design among others. Beneficial uses of harvested stormwater are classified as follows (NRMMC et al., 2009; USEPA, 2004):

- Restricted or unrestricted (based on public access control);
- Potable or non-potable (based on water quality criteria);
- Indoor/outdoor, urban/rural, residential/municipal/commercial/industrial, et cetera (based on the setting); and
- Private, neighbourhood, regional et cetera (based on the scale of implementation).

Table 4.1 presents the key considerations in choosing a beneficial use of harvested stormwater.

Table 4.1 Considerations for choosing a beneficial use of harvested stormwater

Factor	Key attributes	Impact
Demand characteristics	Seasonal, constant, or intermittent	• Influence the design of the makeup/deficit supply
Exposure level	• No contact • Limited contact • Unrestricted contact	• Treatment system design • Scale of implementation
Storage availability and point of use	Distance between the water source and beneficial use	• Cost • Rate of adoption / uptake

4.2 THE NEED FOR STORMWATER HARVESTING AND REUSE

Because of the growing global concern of water scarcity, water management is gaining prominence in many urban designs. With the ever-increasing demand on the available conventional water resources, many countries are resorting to new water resources that contribute to bridging the deficit in the water resources in water scarce and water stressed countries (Hamdan, 2009). Despite the use of stormwater harvesting and reuse as a strategy to meet the rising water demand, researchers and policy makers have also intensified their interest in a combined energy and water conservation strategy, as well as increased regulatory emphasis on reducing stormwater runoff volumes and associated pollutant loads (US EPA, 2013). In the concept of Water Sensitive Urban Design (WSUD), there is no one-size-fits-all approach. However, a suite of measures that form a WSUD tool kit is developed. From this tool kit, urban water harvesting and reuse (constituting stormwater harvesting and reuse) forms part of the candidate measures selectable as part of a specific design response suiting the characteristics of any development or redevelopment (retrofitting) (Department of Planning and Local Government, 2010). In augmenting water resources, different countries approach the practice of stormwater harvesting and reuse in different and unique ways to address the generic global water deficit state. For instance, Singapore was among the first cities in the world to harvest stormwater from urban catchments to supplement its water supply (Lim et al., 2011). Australia, in a concerted effort to address its water security challenges, has developed national water conservation programs that focus on the recycling of both urban stormwater and treated wastewater (Akram et al., 2014). The Gaza Strip, Palestine depends mainly on groundwater from the coastal aquifer. However, in the current state, Gaza Strip is experiencing a deficit in the water resources budget with an annual water deficit in the water resources of approximately 70 Mm^3 (Hamdan, 2012). With the many probable options of new water such as desalination, wastewater reuse as well as transboundary transfers being untenable; either due to high cost of implementation, deterioration in water and ground quality as well as political barriers, the government has resorted to stormwater harvesting as a viable option for artificial recharge of groundwater. Hamdan (2012), reports that urban stormwater harvesting has become an important water resource that plays a significant role in enhancement of water resources management in the Gaza Strip, Palestine.

In South Africa, due to the current water crises, there is a need to seek alternative sources of water supply to avert a future water crisis and reduce its reliance on conventional water schemes of surface and groundwater (Carden and Fisher-Jeffes, 2017). As an alternative source of water supply, stormwater harvesting is almost entirely untapped in South Africa. It has a potential to ensure improved water security for town and cities across the country. Carden and Fisher-Jeffes (2017) contend that stormwater harvesting looks to be financially and technically viable in South Africa but it would depend on whether all sectors of society would be willing to use harvested stormwater, and for the required municipal policy and regulatory processes to be put in place.

4.3 BEST MANAGEMENT PRACTICES (BMP)

Resilient and sustainable stormwater management requires implementation of innovative solutions to secure the available water resources. In the management of stormwater such solutions are referred to as Best Management Practices (BMPs) or Best Planning Practices (BPPs). According to business dictionary, Best Management Practice is described as a set of methods or techniques found to be the most effective and practical means in achieving an objective (such as preventing or minimizing pollution) while making the optimum use of the firm's resources (http://www.businessdictionary.com/definition/best-management-practice-BMP.html).

According to the North Carolina Forest Service (2017), Best Management Practice (BMP) means a practice, or combination of practices, that is determined to be an effective and practicable (including technological, economic, and institutional considerations) means of preventing or reducing the amount of pollution generated by nonpoint sources to a level compatible with water quality goals. A storm water best management practice (BMP) is a technique, measure or structural control that is used for a given set of conditions to manage the quantity and improve the quality of stormwater runoff in the most cost-effective manner (US EPA, 1999). BMPs are recognised as an important part of the National Pollutant Discharge Elimination System (NPDES) permitting process to prevent the release of toxic and hazardous chemicals (US EPA, 1993).

A BMP can be either structural or non-structural. Structural BMP is an engineered and constructed system to improve the quality and / or control the quantity of runoff. For instance, detention ponds, constructed wetlands, runoff diversions, silt fence, stream buffers and groundcover vegetation over bare soil areas. Non-structural BMP refer to a process or part of a process used to plan, conduct and close-out pollution routes. This may include institutional, education or pollution prevention practices designed to limit the generation of stormwater runoff or reduce the quantities of pollutants contained in the runoff (US EPA, 1999). No single BMP is all inclusive of all stormwater problems. The performance thereof is limited depending on several factors such as the drainage area served and available land space, cost, pollutant removal efficiency, as well as a variety of site-specific factors such as soil types, slopes, depth of groundwater table, et cetera. Careful consideration of these factors is necessary in order to select the appropriate BMP or group of BMPs for a location (US EPA, 1999).

4.3.1 Selection of BMPs

Young et al. (2010) and Aceves and Fuamba (2016a, 2016b), contend that the selection of stormwater BMPs could be a complex process due to conflicting stakeholder input, varying levels of performance of BMPs across an array of criteria such as local, regional and state pollution control guidelines, site physical characteristics, etc. Planners and engineers are therefore expected to examine a wide range of criteria when selecting a BMP for a given application (Young et al., 2010).

Selecting a single BMP from a pool of competing options require an analysis of various factors. The factors can be classified as follows (Young et al., 2010):

- Physical site limitations: these include the practice's contributing drainage area, site soil type(s), topography and other geologic factors;
- Functional performance objectives: these objectives/goals include reducing the peak rate and volume of runoff from the developing site, removal or reduction of targeted pollutants from runoff;
- Practice's aesthetic benefit;
- Implementation and maintenance cost; and
- Public safety concerns related with the BMP

In general, in order to meet goals of stormwater BMPs, the implementation should target to address three key factors vis-à-vis flow control, pollutant removal and pollutant source reductions.

Flow control: this involves managing both the volume and intensity of storm water discharges to receiving waters. For urbanised regions, BMPs that provide flow attenuation are often applied. In regions under new development or undergoing redevelopment, the operational method of regulating impacts from stormwater discharges is to limit the amount of rainfall converted to runoff. This can be achieved through application of site design methods that integrate on-site storage and infiltration and reduce the amounts of directly coupled impervious surfaces to reduce the amount of runoff generated from a site.

Pollutant removal: well-designed, constructed and maintained structural BMPs can effectively remove a wide range of pollutants from the urban runoff (US EPA, 1999). Dominant pollutant removal processes in stormwater BMPs are physical and biochemical processes. The efficiency of the resulting BMPs depends on various site-specific variables such as:

- The soil types and soil characteristics, topography and geological composition of the site;
- The rainfall intensity and duration, the length of antecedent dry periods;
- Temperature, solar radiation, wind speed and characteristics;
- Size and drainage characteristics of the contribution watershed;
- Properties and characteristics of the pollutants, and
- The size, type and design of the BMP.

The pollutant removal mechanisms include the following:

- Sedimentation;
- Floatation;
- Filtration;
- Adsorption;
- Biological uptake;
- Biological conversion; and
- Degradation.

Pollutant source reductions: this is an effective non-structural technique of regulating the quantities of pollutants inflowing the stormwater runoff. This can be achieved through the removal of contaminants from the urban surface prior to a rainfall event. Other processes include: reducing on the use of fertilizers, pesticides and herbicides; scheduled street cleaning to rid of trash and other debris from streets; collection and disposal of lawn debris; scheduled cleaning of catch basins; regulating the processes of dumping of used oil, antifreeze, household cleaners, paint, etc. into storm drains; and identification and elimination of illegal cross-connections between sanitary sewers and storm sewers (US EPA, 1999).

4.4 POTENTIAL LIMITATIONS TO STORMWATER HARVESTING AND REUSE

Every coin has two sides and in as much as stormwater harvesting and reuse schemes have numerous advantages, there are also disadvantages to stormwater harvesting and reuse. The probable limitations depend essentially on the kind of the scheme and the local environment. Key limitations are:

Variable rainfall patterns:
As a main limitation for stormwater harvesting schemes, variable rainfall influences the reliability of stormwater flows from a catchment (Department of Environment and Conservation NSW, 2006). The magnitude of this variability depends on local climatic conditions. Variable rainfall patterns can affect the viability of stormwater reuse schemes through:

- Increasing the needed storage volume, that results in larger land area requirements for above-ground storages;
- Increasing the requirement for back-up water supplies and/or demand management when demand cannot be met from harvested stormwater;
- Causing significant fluctuations in the water level in storages, because of the variability in streamflow and demand, mostly for irrigation schemes. This may lessen the aesthetic appearance of an aboveground storage – especially where it doubles as an urban lake or other landscape feature – with denuded banks, possible algal blooms, and turbid water.

The required storage volume increases for a given reliability of supply as the demand becomes more variable (for example for irrigation) or when else poorly matched to the availability of stormwater. The best system is therefore one where the stormwater supply closely matches the pattern of demand.

Environmental impact of storages:
A storage constructed straight on a drain or stream usually consists of a dam wall or weir to retain stream flows. Planning for such storages would need to consider the potential impacts on the environment as well as on people and would need to address various statutory requirements in the site under development. The environmental impacts of such storages may include inter alia:

- Forming a potential barrier to the passage of fish and other aquatic fauna that seasonally migrate upstream or downstream to grow, reproduce or feed;
- Acting to retain coarse sediment, which not only causes siltation but also reduces the capacity of the storage over time. Consequently, results in downstream bank erosion where the sediment transport capacity of the stream exceeds the supply (a familiar occurrence in fluvial geomorphology);
- Aggregate the potential for upstream flooding – this can also apply to diversion structures (e.g. weirs) constructed for off-line storage;
- Providing potential habitat for mosquitoes and associated mosquito-borne diseases; and
- Posing a risk to human safety, especially to children.

Potential health risks:
If contact is not restricted or controlled, pathogens in stormwater for reuse can pose public health risks. These risks can be reduced by treating and disinfecting the harvested stormwater and/or limiting public access for some applications (Fletcher et al., 2006; Department of Environment and Conservation NSW, 2006).

4.5 PUBLIC PERCEPTIONS IN ADOPTING STORMWATER HARVESTING AND REUSE PRACTICES

A key indicator of a successful stormwater harvesting, and reuse project is the community acceptance. Akram et al. (2014), identify the fact that user acceptance greatly depends on the need for alternative water sources. The higher the water stress level, the higher is the possibility of reuse applications to be accepted by the community. Campisano et al. (2017), reiterate that the challenges to the social acceptance of Rainwater harvesting and to a larger extent the wider water reuse have historically focused on the water quality, as well as the environmental and health risk perceptions. Generally, through studies, irrigation of gardens and open spaces has been determined to be the commonest type of end use (Hatt et al., 2006). However, other end uses that are gradually gaining acceptance are toilet flushing, car washing, environmental flows, groundwater recharge, and fire fighting among others. Other studies also indicate that stormwater and reuse has been successfully introduced as part of the water sensitive urban design at different scales (Department of Environment and Conservation NSW, 2006; Hatt et al., 2006; Department of Planning and Local Government, 2010). A literature study by Akram et al. (2014), also indicate that it is not always a given that if a community agrees with the necessity of reusing water that they themselves will willingly adopt the practice. Exall et al. (2004), identify the values of rigorous proactive communication and education programs for the community, essential for the success of reuse schemes and further enlist the main objectives of establishing an effective communication process as:

- To inform and educate the community,
- To incorporate the community input to the development plans, i.e. let the community be part of the process from the initiation stage to full implementation so that they own the project,
- To raise issues early and avoid surprises, and
- To identify the project opponents and their issues. This implies that no one's issues/concerns are too small to be ignored at any point of the project.

4.6 RISKS ASSOCIATED WITH USING STORMWATER

Public safety and risk management is a critical planning phase variable in a stormwater harvesting and reuse project. Many issues need consideration in terms of ensuring public safety. Risks fall into three main categories-public health and community safety, environmental protection and operations (www.brisbane.qld.gov.au/water). Some of the common ones are listed in Table 4.2

Table 4.2 Common potential hazards associated with stormwater harvesting and reuse

Domain	Hazard
Public health and community safety risks	• Stormwater contamination: Contaminants may include pathogens (bacteria, viruses, protozoa, helminths), inorganic chemicals (metals, nutrients) and organic chemicals such as pesticides, hydrocarbons • Unsafe storages and infrastructure (for instance open water storages, embankment failure, storage overflow) • Water stagnation over time • Breeding mosquitoes and other vector populations
Environmental risks	• Stormwater contamination from nutrients, pesticides, and oils • Maintenance of environmental flow for instance over-extraction of stormwater • Loss of natural habitat and vegetation • Storage constructed on natural watercourses • Flooding above any diversion weir • Surface water pollution by run-off • Groundwater pollution • Soil contamination

Domain	Hazard
Operational risks	• Potential for failure of stormwater diversion mechanism or pump system • Equipment damage from high sediment loads, build-up and clogging; and • Increases in maintenance time and cost associated with poor system design and layout

Department of Environment and Conservation NSW (2006); www.brisbane.qld.gov.au/water

Campisano et al. (2017), address the issues associated with risks and water reuse. In their study, Campisano et al. (2017), point out that as part of a social acceptance campaign, knowledge to minimise the impact of health and environmental risk perceptions in water reuse is constantly being generated and disseminated. With respect to water quality, confidence is being built through recommendations to the users to use the risk assessments and water safety plans as part of the planning process. It is ideal to manage risks at the planning phase to enable many significant hazards to be managed during the project's design. If risk assessment and management are left to the operational phase of a project, the costs of effective mitigation may be considerably higher than if they were considered during the planning phase (Department of Environment and Conservation NSW, 2006). A systematic risk management approach should be adopted during the planning, design, and operation phases in order to identify and manage risks to both public health and the environment. This approach to risk management will help to control hazards, improve reliability, incorporate redundancy, and enhance the overall performance of a stormwater harvesting system (Alan Plummer Associates, Inc. 2010). Mitigation measures should be incorporated during the collection of stormwater, treatment, storage, and delivery stages of the scheme. Table 4.3 presents a consolidated Risk Management Framework as developed by the Department of Environment and Conservation NSW (2006) and adopted by the Texas Water Development Board (Alan Plummer Associates, Inc. 2010). Risk management for stormwater harvesting schemes can also be addresses through development of stormwater harvesting quality objectives, screening investigations, as well as project design.

Table 4.3 A systematic approach to risk management: A risk management framework

Description	Action	Procedure
Commitment	Develop Manage	• Involve appropriate regulatory agencies • Construct a team of qualified individuals • Comply with applicable regulations • Engage stakeholders • Develop appropriate organizational policy
Assessment	Identify Assess	• All sources, uses, and exposure routes • Hazards, risks, and appropriate risk levels
Prevention	Identify Implement	• Preventive measures to mitigate risks • Critical control points
Procedures	Identify Develop Establish Ensure	• Operation & maintenance procedures • Monitoring protocol • Operational performance goals • Appropriate materials/equipment throughout system
Verification	Develop Collect Review Implement	• Goals for treated stormwater quality • Water quality monitoring plan for the system • Plans for individual users • System for managing issues
Emergency Management	Establish Implement	• Communication procedure • Protocol during emergencies and incidences • Develop corrective action procedures

Description	Action	Procedure
Education	Develop	• Employee awareness and training
	Provide	• Public education and communication
Documentation	Manage	• Appropriate record documentation and submittal
	Produce	• Reports for internal and external stakeholders
Evaluation and Improvement	Conduct	• Review processes and procedures
	Develop	• Review additions to system to ensure compliance with procedures
	Validate	• Long-term data to assess performance • Management review of systems and procedures • New technologies

Department of Environment and Conservation NSW (2006) and adopted by the Texas Water Development Board (Alan Plummer Associates, Inc. 2010).

4.6.1 Conventional risk assessment methodology

Protection of the environment and the receiving waters from the hazards of stormwater harvesting and reuse requires a proactive rather than a reactive approach. The basic steps in advancing a proactive approach are summarised as follows:

1. First step is to examine systematically all the potential hazards associated with stormwater harvesting and reuse (i.e. identify what might happen and how it might happen);
2. Assess the risk from each hazard through estimating the likelihood of its occurrence (the likelihood that it will happen and the consequences of its occurrence);
3. Assess the impact;
4. Develop a risk score = likelihood of occurrence x level of impact;
5. Rank risk scores to support prioritisation of risks; and
6. Ensure that existing preventive measures are enough to control the hazards, and to improve or replace such measures if necessary.

Tables 4.4 to 4.7 give a sequent methodology for prioritising risks to receiving water quality from stormwater discharging from different sources. This methodology permits experts to identify optimal corrective strategies for reducing the impacts of nonpoint/diffuse pollution.

Table 4.4 Conventional risk assessment methodology: Description of components identified for urban stormwater as a specific nonpoint source pollution (Adapted from Lundy et al., 2012)

Tenet	Description
Identify potential hazards	Total suspended solids (TSS); Biochemical Oxygen Demand (BOD), Metals, Hydrocarbons, Microorganisms, PPCPs, etcetera
Likelihood of occurrence	Probability of a specific pollutant discharging to receiving waters via stormwater flow
Level of impact	Consequence of discharge on receiving water ecosystem
Likelihood of occurrence x level of impact	Risk score
Rank risk score	Support prioritisation of risk

Table 4.5 Conventional risk assessment methodology: A guide to grading the likelihood of a specific pollutant from an identified source occurring in urban stormwater (Adapted from Lundy et al., 2012)

Likelihood of occurrence (Probability)	Possible descriptors for relative grading	Value associated with likelihood
Very high	Widely established that pollutant enters stormwater from multiple materials/activities/processes with pollutant build up Even Mean Concentrations (EMCs) an order of magnitude greater than background levels	5
High	Field data from several studies indicate pollutant enters stormwater from a single material/activity/process with EMCs consistently greater than background levels	4
Medium	Field data from a single study indicates presence of pollutant in stormwater flows with EMCs occasionally above reported background levels	3
Low	Field and modelled data indicate presence of pollutant in stormwater flows during storm events	2
Very low	No field or modelling data available relating to presence of pollutant in stormwater	1

Table 4.6 Conventional risk assessment methodology: A guide to grading the level of consequence of discharging to receiving waters (Adapted from Lundy et al., 2012)

Level of consequence	Possible descriptors for relative grading	Value associated with consequence
Critical	Total system compromise, e.g. consistent failure to meet Environmental Quality Standards (EQS) during < 1-year storm; Dilution Factor (DF) required to meet EQS > 100	5
Damaging	Consistent failure to meet regulatory requirements for < 1-year storm, e.g. temporary loss of receiving water ecology; DF required to meet EQS: 50-100	4
Significant	Moderate impact with occasional EQS exceedance; potential to cause public/political concern; tangible ecological/amenity damage; DF to meet EQS: 11-50	3
Minor	Minor: minimum impact mainly associated with specific accidental discharges; some additional costs/efforts required; DF to meet EQS: 2-10	2
Insignificant	No impact felt on receiving waters and no mitigation required; DF to meet EQS < 2	1

Table 4.7 Conventional risk assessment methodology: A guide to grading the level of consequence of urban stormwater discharging to receiving waters (Adapted from Lundy et al., 2012)

Likelihood of occurrence	Severity of consequence: Insignificant (1)	Minor (2)	Significant (3)	Damaging (4)	Critical (5)
Very low (1)	1	2	3	4	5
Low (2)	2	4	6	8	10
Medium (3)	3	6	9	12	15
High (4)	4	8	12	16	20
Very high (5)	5	10	15	20	25

4.7 TECHNICAL TOOLS IN STORMWATER STUDIES

Stormwater management requires a critical understanding of the dynamics involving the generation of the quantity as well as the processes influencing the quality. Studies involving stormwater runoff quality from land use, urban, agricultural cropland, pasture and forest can relate to many environmental problems. Management of quantity and quality stormwater runoff is a serious concern in urban and rural environmental management. To protect the environment, water quality studies must be conducted. Some water quality problems require water quality modeling. Specific modeling objectives are required to provide definitive guides to modeling exercise and approach. Models may be used for the following objectives:

- Characterise runoff quantity and quality as to temporal and spatial details, concentration/pollutant load ranges, etc.
- Provide input to a receiving water quality analysis.
- Determine effects, magnitudes, locations, etc.
- Perform frequency analysis on quality parameters.
- Provide input to cost-benefit analyses.

Modeling of runoff quality are relatively difficult and largely depends on catchment characteristics/land-uses. The models use conventional methods for contaminant generation and treatment such as buildup-wash off conceptual models and first order decay processes.

Successful environmental management of urban stormwater requires understanding of:

- Relationship between rainfall and runoff,
- Pollutant generation from differing land-uses and catchment characteristics,
- Performance of stormwater treatment measures, and how it may vary with design specifications,

- Long-term performance of proposed stormwater strategies against water quality standards,
- Resultant impacts on receiving ecosystems, before and after implementation of the proposed stormwater strategy.

Many models have been developed to simulate the movement and characteristics of stormwater across the watershed in response to precipitation and other watershed conditions. These models include very simple conceptual models to complex hydraulic models (Akram et al., 2014). Stormwater models can be classified in several ways. Stormwater models can be either stochastic or deterministic. Deterministic and stochastic models can either be conceptual or empirical and further classified as either event or continuous model. A stormwater model can also be used as a planning, operational, or design model. A few models that are used in stormwater studies and management are described in the following sections. These are just but selected examples, as the list is not exhaustive.

4.7.1 Stormwater Management Model (SWMM)

The EPA SWMM is a dynamic hydrology-hydraulic water quantity and quality simulation model. It is used for single even or long-term (continuous) simulation of runoff quantity and quality from primary urban areas. The model is widely used for planning analysis and design related to drainage systems in urban areas. The runoff component operates on a collection of sub catchment areas that receive precipitation and generate runoff and pollutant loads. Runoff Water Quality illustrates how to model the build-up, wash-off and routing of total suspended solids (TSS). Runoff Treatment shows how to simulate removal of TSS.

The newest versions of the model provide an integrated Windows environment for editing input data, running simulations and viewing the results in the form of thematic maps, graphs, tables, profile plots and statistical reports (Gironás et al., 2010). The intended uses of the model are as follows:

- Post-Development Runoff
- Surface Drainage Hydraulics
- Detention Pond Design
- Low Impact Development
- Runoff Water Quality
- Runoff Treatment
- Dual Drainage Systems
- Combined Sewer Overflows
- Continuous Simulation

The equations and parameters are as follows (Dotto et al, 2010):

Model 1

$$C_t = aI_t^b$$

Model 2

$$C_t = aR_t^b$$

Model 3

$$Buildup\colon \frac{d\overline{M(t)}}{dt_d} = k_1\left(M_0 - \overline{M(t)}\right)$$

$$Washoff\colon \frac{d\bar{C}\left(t + t_f\right)}{dt} = k_2.\overline{M(t)}.I(t)^{k3}.A_i$$

Where C_t – pollutant concentration at time t (mg/L)

I_t – rainfall intensity (mm/hr, over the timestep, t)

R_t – routed runoff (average, in mm/hr, over the timestep, t)

a and b – parameters to be calibrated

$\overline{M(t)}$ – amount of pollutant available on the surface averaged over the area (g/m^2) during the dry weather period (t_d)
M_o – maximum amount of the pollutant that can be stored at the surface (g/m^2)
k_1 – accumulation constant (day^{-1})

Model 1 and Model 2 are simple regressive models, in which concentrations are estimated within a timestep as a power function of rainfall intensities and routed runoff, respectively. Model 3 is a buildup-washoff based approach. Buildup is the process in which pollutants accumulate in the surface over a dry weather period. Washoff is the process of removing the accumulated pollutant load by rainfall and incorporating it to the surface runoff (Dotto et al, 2010).

4.7.2 Model for Urban Stormwater Improvement Conceptualisation (MUSIC)

MUSIC model is used to simulate rainfall, stormwater flow and pollution generation. It is also simulating pollution removal and flow reduction through stormwater management systems such as sediment ponds, wetlands, bioretention and harvesting. It can analyse catchments area ranging from 0.01 to 100 km^2 (Modaresi, 2009). By simulating the performance of stormwater quality improvement measures, MUSIC provides information on whether a proposed system conceptually would achieve flow and water quality targets. The model is used to determine the likely water quality emanating from specific catchment; predict the performance of specific stormwater treatment measures in protecting receiving water quality; design an integrated stormwater management plan for each catchment; and evaluate the success of specific treatment measures (Wong et al., 2002).

An exponential decay process of contaminants concentrations is described by the first order kinetic (or k-C*) model.

$$C_{out} = C^* + (C_{in} - C^*)e^{-k/q}$$

where
C* – equilibrium or background concentration (mg/L),
C_{in} – input concentration (mg/L),
C_{out} – output concentration (mg/L)
k – (decay) rate constant (m/y)
q – hydraulic loading (m/y)

4.7.3 The System for Urban Stormwater Treatment and Analysis Integration (SUSTAIN)

SUSTAIN is a decision support that assist with developing and implementing plans for flow and pollution control measures to protect source waters and meet water quality goals. It performs hydrological and water quality modelling in watersheds urban streams.

4.7.4 Source Loading and Management Model (SLAMM)

SLAMM is an urban watershed pollutant source area identification and management tool. It was originally developed to better understand the relationships between sources of urban runoff pollutants and runoff quality. It simulates rainfall runoff to analyze an urban drainage area. SLAMM determines the runoff from a series of normal rainfall events and calculates the pollutant loading created by these rainfall events. The model is mostly used as a planning tool, to better understand sources of urban runoff pollutants and their control. Emphasis has been placed on small storm hydrology and particulate wash-off in SLAMM.

SLAMM calculates mass balances for both particulate and dissolved pollutants and runoff flow volumes. It was design to give relatively simple answers, for example pollutant mass discharges and control measure effects for a very large variety of potential conditions. It predicts the relative contributions of different source area, e.g. roof, streets, parking areas, landscape area, undeveloped areas, etc.

4.7.5 RUNQUAL Model

The RUNQUAL model provides a continuous daily simulation of surface runoff and contaminants loads form the pervious and impervious surfaces. The model can be used to assess the effectiveness of three best management practices (BMPs) for runoff controls; detention basins, infiltration retention and vegetated filter (buffer) strips.

4.7.6 P8-Urban Catchment Model (UCM)

P8 – UCM model is used to predict the generation and transport of stormwater runoff pollutant in urban watershed. The simulations are driven by continuous hourly rainfall and daily air temperatures time series. The model has been developed for designing and evaluating runoff treatment schemes for existing or proposed urban development. The model equations and parameters are the same at the SWMM model.

4.7.7 StormTac

StormTac model is used as a tool for action planning in urban water management, and it is suitable for water quantity and quality calculations within watersheds (catchment area). Its primary intended use was management of lake catchments and conceptual design of storm water treatment. It integrates processes of runoff, transport, recipient, treatment and flow detention. Metal and nutrients are example of pollutants in storm water that may cause toxic and eutrophic effects in the receiving waters. The model can be used in the development of a more sustainable storm water management.

StormTac model is user-friendly and it easily integrates the watershed properties and the pollutant transport calculations with the relevant recipient processes and the design of facilities in the stormwater treatment model (Larm, 2005). The model is capable of the following:

- Calculating stormwater runoff volumes, pollutant concentrations and load in the discharge points.
- Comparing sampled data to calculate values.
- Identify the largest pollutant sources.

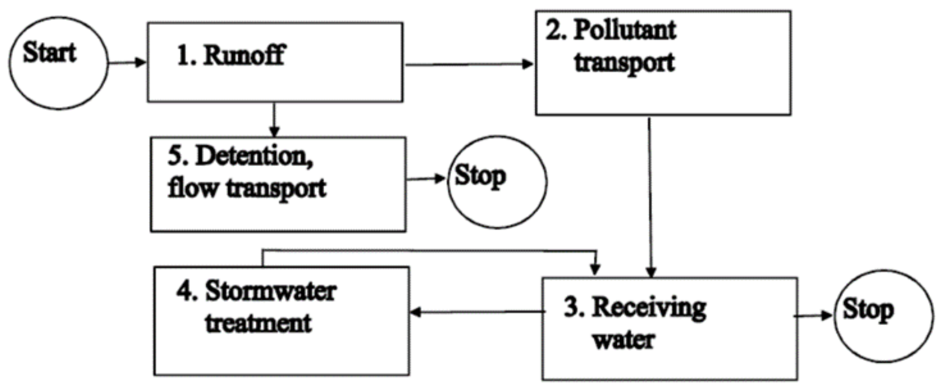


Figure 4.3 Flow chart of the StormTac model. (Larm, 2005)

4.7.8 Some stormwater management modelling case studies

Sterrem et al. (2014) used the XP-SWMM model to model a lot scale rainwater tank. The objective of using this model is to simulate the behavior of a lot scale rainwater tank system covering both the water quantity and quality. The model was used to present calibration and validation of a lot scale rainwater tank system by utilizing data collected from two rainwater tank systems located in Western Sydney, Australia. Run-off peak and volume in and out of the tank system and also a number of quality parameters (Total Phosphorus (TP), Total Nitrogen (TN) and Total Solids (TS)) were considered in the modelling. The results showed that XP-SWMM can be used successfully to develop a lot scale rainwater system model within an acceptable error margin. Total Phosphorus and Total Solids can be predicted more accurately than Total Nitrogen. The results also showed that a significant reduction in storm water run-off discharge a can be achieved.

A sensitivity analysis results showed a high sensitivity to maximum build-up of TN and wash-off parameter *k*, whilst TP shows a high sensitivity to maximum build-up, wash-off parameter *k* and initial TP concentration. The validation run confirmed that the calibrated model can be used to simulate the rainwater tank water volume and outflows. It also showed a correlation of 0.56 in water depth with an RMSE of 486 mm, with a correlation of -0.06 for the overflow volume, which influenced the water quality. The results showed a fit between the modeled and measured data. TP could be predicted with reasonable success with a relative error of -50% for both the tank and overflow. The TN was difficult to model, and it was considered unsatisfactory, while the TP in the tank overflow and the TN in the rainwater tank was considered acceptable. TS was successfully modeled showing a relative error of -44% in the rainwater tank and -17% in the overflow. The results showed that the water quality and quantity can be successfully modeled on a lot scale rainwater tank using XP-SWMM within an accepted error margin.

Ouyan et al. (2012) conducted a study to identify the urban storm rainfall runoff pollution from diverse underlying surfaces. The focus of the study was on storm rainfall runoff pollutant discharge loading from different underlying surfaces in Beijing; assessment of the first flush effect for three storm rainfall pollutants (COD, TP and TSS); and a potential application of urban storm rainfall pollution control by impervious rate optimization of underlying surfaces. The simulation period was discussed in the three items: surface drainage hydraulics, runoff water quality, and dual drainage system.

The dominant parameters of each conceptual component must be determined for the calibration and validation of the SWMM system, so that the outputs can present the real response of the catchment. The validated SWMM model could simulate the pattern of storm rainfall runoff and the pollution discharge from three underlying surfaces. The results showed that TP had the largest removal rate ranging from 40% to 67%, from street sweeping and surface runoff. The simulation showed that the first flush effect was significant, more than 50% of TP was shifted by the initial 20% of the runoff. The first flush effects for COD and TSS were smaller as compared to TP, roughly 20% of total COD and TSS loads were shifted by the initial 20% of the runoff. SWMM demonstrated to have the potential to evaluate the pattern of urban rainfall and pollution prevention planning.

In the study conducted by Cambez et al. (2008), SWMM 5 was used to simulate hydraulics and water quality in a 110 ha urban area, which is divided in four catchments of difference characteristics. SWMM was used for continuous simulation using historical rainfall series data and it was applied in the long-term modelling of urban area. Results obtained from the hydraulic model calibration and verification were satisfactory, however, there were limitations found in the SWMM catchment hydrological description. It is reported that long-term simulations allowed to compare the benefits of different scenarios of storage and sewage treatment plant capacities for the reduction of the overflow discharge.

MUSIC is widely used, in Australia, to estimate pollutant transport from catchments and stormwater treatment through different systems. Imteaz et al. (2012) studied the accuracy of MUSIC simulations for different stormwater treatment options used in Australia and abroad. It was found that MUSIC can simulate flow conditions with good accuracy; however, MUSIC's predictions on the removal efficiencies of Total Soldis (TS), Total Phosphorus (TP) and Total Nitrogen (TN) are varying.

A case study was conducted in Australia to demonstrate the application of MUSIC and involves the formulations of a stormwater quality improvement strategy for a built-up area. Several number of options for retrofitting stormwater quality improvement measures were investigated (Wong et al., 2006). The four options considered were as follows:

- Option 1: Retrofitting a stormwater treatment wetland onto an existing retarding basin,
- Option 2: Option 1 and construction of a further two wetlands on public open space,
- Option 3: Option 2 and construction of bioretention systems and vegetated swales,
- Option 4: Option 3 and construction of bioretention systems to further treat stormwater discharge from the three wetlands.

There are several major limitations to the effective design, prioritisation and evaluation of urban stormwater treatment strategies. The limitations are caused by uncertainties regarding the likely water quality from catchments, uncertainties of the performance of stormwater treatment measures and inability to compare the performance. Music provided urban catchment managers with an easy to use decision support tool, which they can evaluate and compare alternative strategies aimed at protecting aquatic ecosystems from the urbanization.

Dotto et al. (2011) compared MUSIC and KAREN models for the prediction on catchment runoff. MUSIC simulated runoff from both impervious and pervious areas, as well as detention of flow in pipes, whilst KAREN simulated only runoff from impervious surfaces using the time-area method. It was found that rainfall-runoff model MUSIC is not sensitive to pervious are parameters when applied to urbanized catchment. Both models were insensitive to dry weather-related parameters for all catchments. This indicates that rainfall events could be regarded independently instead of continuous simulation. It was confirmed that the residuals between measured and modelled data, for both model and catchments, was not satisfactory.

4.8 STORMWATER QUALITY

4.8.1 General perspective

Under favourable conditions, scarcity of water requires the conservation and re-use of stormwater runoff to augment the available water resources. However, its utilisation is strongly reliant on its quality. Impervious surfaces on built landscapes convert precipitation to stormwater runoff causing water quality and quantity problems. Traditionally, the management of stormwater flow has relied on pipes and sewers, termed grey infrastructure, to convey stormwater to treatment facilities or into surface waters. Consequently, stormwater runoff is initiated at a lower threshold, and storm flow volumes are routed across the landscape into centralized wastewater collection systems. Larger volumes of runoff may lead to flooding, sewer system malfunction, and impairment of surface and subsurface water resources (Berland et al., 2017). Technologies designed to facilitate stormwater infiltration have been commissioned. Such technologies require adequate planning and caution with special attention to rainfall patterns to circumvent groundwater mounding and sewer backups. Several countries have progressed in the adoption of stormwater management and utilisation for various applications in Australia, New Zealand, USA, Sweden, France, United Kingdom, Indonesia and People's republic of China (Bakri et al., 2008; Lucke and Nichols, 2015; Mangangka et al., 2015; Richards et al., 2017).

Not much progress has been documented in Africa including South Africa on stormwater harvesting and management with a deliberate plan for its use for targeted fit-for-purpose uses. Therefore, a lot still need to be accomplished in developing stormwater management policies that outline clear stormwater quality management strategies to facilitate its use for fit purposes.

4.8.2 Factors influencing stormwater quality

Although stormwater is a promising alternative water resource, it can be heavily polluted by chemical and microbial contaminants. Pavements are universal in establishments although during planning and infrastructure development seldom considers stormwater flooding and water quality issues.

The principal stormwater pollutant sources and types can be deposited from the atmosphere, automobile emissions, pesticides and fertilisers, roof surfaces as depicted in Figure 4.4.

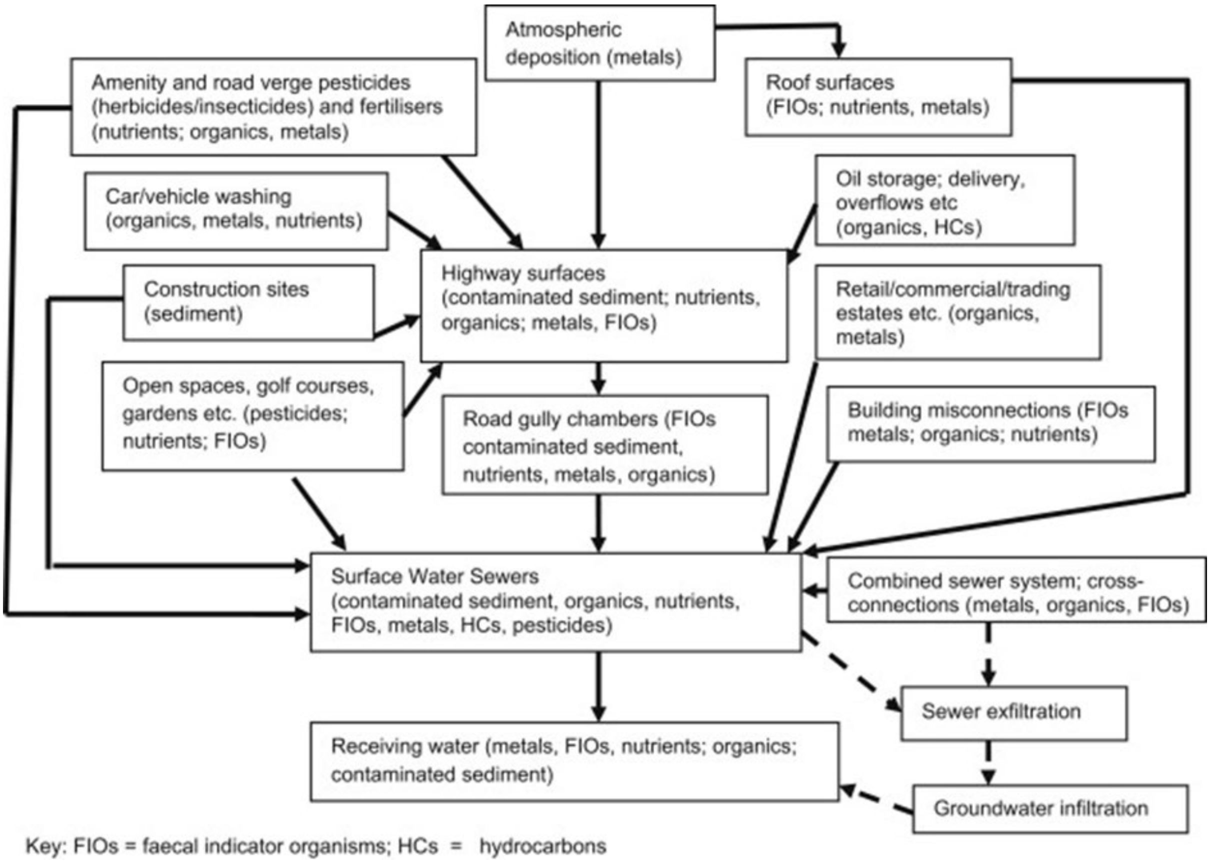


Figure 4.4 Principal stormwater pollutant sources and types (Lundy et al., 2012)

A vast number of microbial pathogenic organisms can be found in stormwater including bacteria, viruses and protozoa. These microorganisms render the water unfit for use even for recreational purposes as they can lead to waterborne diseases. Contaminated stormwater can cause external contact related illnesses and can therefore not be used even for bathing. The quality of the runoff must also ensure that it is reusable and does not pose any detriment to the receiving waters. That necessitates the commissioning of best management practices to reduce non-point-source pollution whether its heavy metals, pathogens or nutrients (Youngblood et al., 2017).

4.8.2.1 Chemical contaminants in stormwater

The potential impact of stormwater runoff as a source of non-point source pollution has been recognised and legislated in the USA, Australia and the UK. Guidelines have been adopted that include gross pollutant traps, retention basins, infiltration and bio-retention ponds, wetlands and others. The choice of commissioned BMPs is strongly reliant on the type of prevailing contaminants and intended use of treated stormwater (Greenway 2017; Richards et al., 2017). Pollutant concentrations are not only dependant on run-off volumes but also intensity, event duration and antecedent conditions.

The runoff from urban settlements is responsible for introducing nitrogen and P into receiving waters (McAndrew and Ahn, 2017). The removal of N and P has been achieved by detention and retention ponds though nutrient removal is heavily reliant on pond design and influent characteristics. Treatment performance requires that soil-based filter media be chosen on its ability to effectively remove total suspended solids and heavy metals (Hatt et al., 2009).

Heavy metals are common stormwater pollutants which are deposited by automobile and industrial activities. Dry seasons favour the heavy metal build up on impervious surfaces which are subsequently washed off during rainfall episodes leading to polluted receiving waters. The toxicity and the bioavailability of heavy metals in receiving waters poses health risks (Lucke and Nichols, 2015; Wijesiri et al., 2016).

Bio-retention basins has been widely implemented to manage stormwater by reducing peak flows and downstream pollution loads in various countries such as Australia, Malaysia and Toronto (Kim et al., 2012; Alias et al., 2014; Mangangka et al., 2015). Pollution performance removal has been found to be influenced by site rainfall characteristics and the basin outflow and inflow limits (Mangangka et al., 2015). A study conducted by Lucke and Nichols (2015) investigated the stability and efficiency of bioretention basins within five- and ten-year periods. The heavy metal and hydrocarbon levels were still well removed and the filter media was also still within acceptable Australian limits even after 10 years in operation. The type of filter media remained fit for use and did not require special disposal procedures in ten years of operation.

Total suspended solids (TSS) are produced in motorway environment through the erosion of road surfaces, automobile emissions, seasonal maintenance practises and import from adjacent areas through atmospheric deposition processes (Lundy et al., 2012). An investigation by Hatt et al. (2009) investigated the performance of stormwater pollutant removal at field scale in Australia. Total suspended solids (TSS) and heavy metal removal were successfully treated and eliminated. However, nutrient removal was highly variable. The choice of filter media though was found to contribute to leaching of P which alleviated P effluent levels. Automobile emissions are one of the most significant anthropogenic sources of air pollution. Emissions stem from exhaust fumes, brake wear, tyre wear emissions.

Traditionally roadway design only focused on automobile transportation with emphasis on motorist and pedestrian safety and flow capacity. Green streets are designed and are characterized by impervious-reducing surfaces. In North America, seventeen jurisdictions with official green street programs have only one that did not incorporate stormwater treatment as a primary goal. All the others designed the green streets with the intention of stormwater runoff minimization. Other than the provision of attractive landscapes and minimization of urban heat island effect, green streets also improve air quality (Shaneyfelt et al., 2017).

4.8.2.2 Microbial contaminants in stormwater

An integrated urban stormwater recycling system must provide four core-functions: collect runoff, treat it for fit-for-purpose use, store the treated water and distribute it to the end user. There are various potable end uses for harvested stormwater. The microbial quality of the stormwater strongly influences what the water can be utilised for (Hatt et al., 2006). Pathogens found in stormwater can be a major concern for public health, whether meant for recreational or used as alternative water sources. This does not however mean that stormwater cannot be utilised for a variety of purposes to augment depleting sources and mitigate against rapid population growth experienced in urban and peri-urban areas (Chandrasena et al., 2014; Bichai and Ashbolt, 2017).

Hatt et al. (2006), documented the various treatment methods that can be used to meet the required objective. Bioretention systems have been used extensively for stormwater treatment as part of BMPs in the US, Australia and New Zealand (Trowsdale and Simcock, 2011; Li et al., 2011; Chasandrena et al., 2014). A typical bioretention unit consists of water storage space, vegetation, mulch, soil filter media and gravel layer. When stormwater passes through the bioretention unit, the pollutants are removed via sedimentation, filtration and adsorption on munch and soil layers, plant uptake and biodegradation by soil microorganisms as indicated in Figure 4.5.

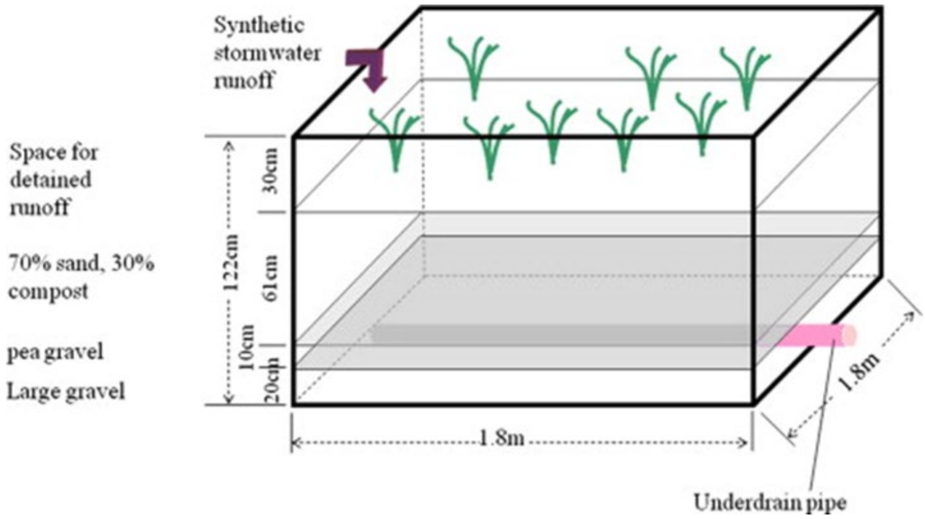


Figure 4.5 Schematic representation of a biofiltration unit (Li et al., 2011)

Numerous studies have detected the presence of faecal contamination in stormwater (Kim et al., 2012; Deletic et al., 2012 and Chandrasena et al., 2016). A laboratory study was conducted in Melbourne to assess the efficacy of biofilters to remove bacterial endospores (*Clostridium perfringens* spores), *E. coli* and F-RNA coliphages using standard and saturated zone biofilters. *Clostridium perfringens* spores served as indicators of protozoan cysts. The saturated zone was beneficial for eliminating the negative effects of dry periods on the removal of *E. coli* and nitrogen (Li et al., 2012). Their findings led to suggestions that stormwater can be utilised for secondary contact recreational purposes as it met the Australian standards pertaining to *E. coli*. That highlights that biofilters can be configured to yield water that is suitable for various non-potable purposes.

The removal of *E. coli* by five pilot bioretention units with different vegetations in hot and semi-arid climate in Texas was investigated. Texas native grasses, grasses specified for highway applications, shrubs and common weeds were selected. The bioretention unit with shrubs showed best performance whilst the unit with no vegetation outperformed those with vegetation at 87% and 97% respectively. The pilot study was developed under semi-arid conditions compared to warm and humid climate studies and achieved approximately 70% removal comparatively. Longer hydraulic times resulted in increased *E. coli* removals which was also supported by an earlier study that suggested a positive correlation between *E. coli* removal and hydraulic retention time (Hunt et al., 2008 and Kim et al., 2012). Various vegetation types also create different rhizosphere environments, soil porosity and even the development of various paths which result in changes in hydraulic retention times. Such findings were also supported by Li et al. (2011) on increased total suspended solids and heavy metal removal.

4.8.2.3 Vegetation

Plants are an attractive stormwater control measure because they provide a subsidiary of social, economic, and environmental benefits. Although certain studies have found little benefit of shrubs and sedges in bio-retention units, trees were found to reduce stormwater runoff by canopy interception loss, transpiration, facilitating infiltration and by incorporating other green technologies such as bio-swales and structural soils (Berland et al., 2017).

To improve coordination of tree planting and management of stormwater, communication and information sharing must be fostered between formal and informal organizations involved in street tree management. Blecken et al. (2009) investigated the ability of vegetated biofilters with and without a submerged zone (SZ) to efficiently remove heavy metals under different drying and wet conditions. The role of the submerged role was further scrutinized for its ability to mitigate the negative effects of metal removal during dry spells. Pb and Zn removal during wet periods was not enhanced by the presence of SZ with or without additional carbon. Although it had positive effects on Cu removal through metal sorption under anoxic conditions. Decreased metal removal was observed after drying. That could be attributed to leaching of already accumulated metals from previous events. During dry periods, plant metal uptake is also reduced which enables oxidation of accumulated metals in the filter medium to be washed out during wetting periods. Therefore, the increase in metal outflow after dry seasons cannot be circumvented.

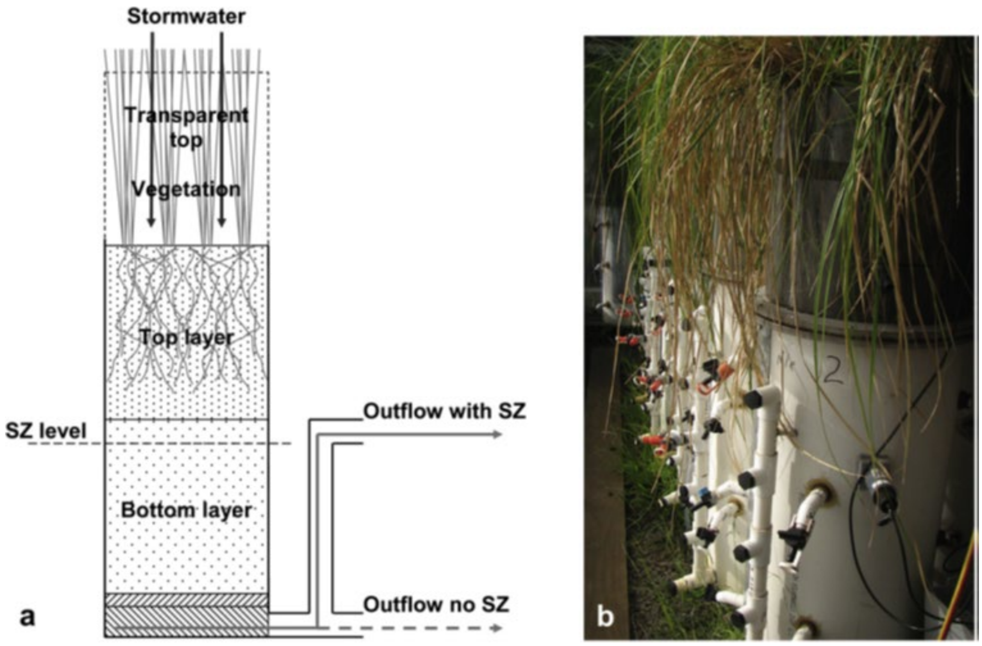


Figure 4.6 Biofilter columns: (a) configuration and filter media, and (b) columns in greenhouse extrapolated from Blecken et al. (2009)

C. appressa was shown by laboratory scale studies to have remarkable nitrogen removal capacity. Therefore, vegetation and denitrification should be favoured by chosen biofilter designs as it promotes the elimination of highly soluble nitrogen forms. Floating wetlands have also been observed to improve nitrogen removal in detention and retention ponds (Hatt et al., 2009; Hartshorn et al., 2016).

Extended dry periods result in low moisture content of filter media which can subsequently enhance the treatment capacity of bio-retention systems by improving the quantity that the unit can retain. The presence of vegetation with high water absorbing capacity will further result in increased filter media porosity potential. This phenomenon will enhance the runoff retention capacity and improve treatment performance (Mangangka et al., 2015).

Richard et al. (2017) investigated the possibility of bio-retention ponds to be utilised to produce vegetables without compromising the quality of the effluent. Such an application requires that the choice of filter sand such as loamy sand be replaced with choices that can support vegetables. Potting mix could potentially lead to nutrient enrichment. However, if used at a shallow location within the filter with sand on top, it was not found to leach N. Other options such as pine bark and other composted organic matter can be used to advance vegetable growth whilst maintaining stormwater retention and improved water quality outcomes.

4.9 STORMWATER TREATMENT SYSTEMS

Mitigation of stormwater pollution is important to safeguard the environment. There has been widespread recognition that direct discharge of stormwater runoffs introduces pollutants to aquatic ecosystems. Epidemiological studies detected faecal coliforms and pathogens in water bodies that were introduced by urban stormwater runoffs. Hydrological and pollutant removal performance has also been identified in order to manage the quality and quantity of stormwater (Hatt et al., 2009; Gaffield et al., 2003 and Kim et al., 2012). Hence a range of stormwater treatment technologies have been developed. Pollutant loads discharged through point sources can be quantified because the point of entry is generally fixed (Bakri et al., 2008).

4.9.1 Wetlands

Runoffs from impervious surfaces lead to increased levels of heavy metals, nutrients, microorganisms, oils and greases into receiving waters (McAndrew and Ahn, 2017 and Shaneyfelt et al., 2017). Constructed wetlands have been commissioned to reduce the effects of urbanisation on stormwater by improving stormwater quality.

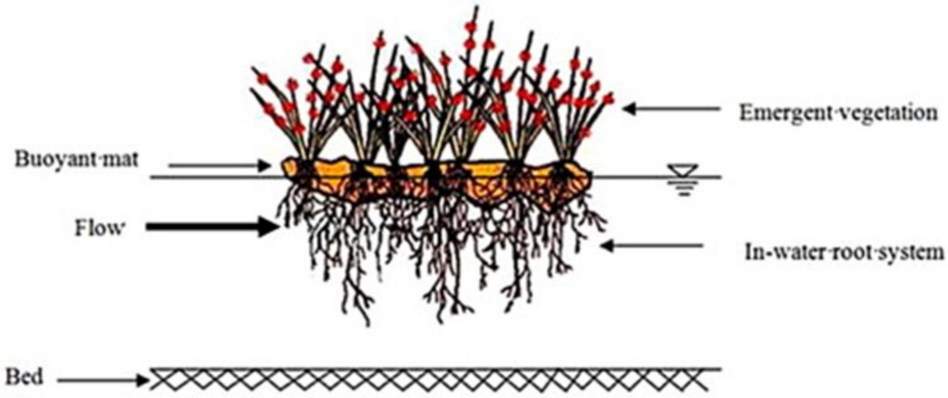


Figure 4.7 Schematic representation of floating wetlands (Palvinera et al., 2017)

Ponds and wetlands have become widely accepted as urban stormwater treatment devices over the past two decades and are increasingly being integrated into WSUD practices. The application has been largely due to the fact that pond and wetland-based systems have low-maintenance and operationally simple treatment. It also enhances habitat and aesthetic values within the landscape, over the fundamental principles of storage and quality improvement. However, a number of limitations have emerged with the application of wetland and pond systems for stormwater treatment. Although ponds are generally effective at attenuating hydraulics and removing coarse suspended sediments, they are less effective at removing finer particulates and dissolved contaminants. To enhance treatment capabilities, wetlands are often used in combination with ponds (Greenway 2017).

Floating treatment wetlands (FTWs) are in many ways a hybridisation of all of these systems, employing rooted emergent plants growing on a mat floating on the surface of a pond-like water body rather than rooted in the sediments. Amongst the advantages of floating wetlands in the ability to improve nutrient removal of the stormwater. The choice of vegetation used is influenced by the type of influent and the desired quality of the effluent (Greenway 2017; Palvinera et al., 2017).

4.9.2 Biofiltration ponds

Bioretention basins are the most used stormwater treatment measures that rely primarily on filtration supported by evapotranspiration, sorption and biotransformation. Retention ponds trap pollutants as the water traverses through the ponds as the reduced velocity encourages sedimentation of suspended particulates (Kim et al., 2012; Mangangka et al., 2015). The efficiency of the retention pond is strongly reliant on adequate hydraulic residence time (HRT) within the pond (McAndrew and Ahn, 2017). The primary function of the retention ponds is to attenuate the flow of stormwater in order to reduce stream bank erosion and flooding downstream. The removal of N and P from ponds has been documented although it is influenced by pond design and influent characteristics.

4.9.2.1 Nutrient removal in bioretention ponds

Phosphorus is primarily removed through sedimentation whilst N is removed through microbial denitrification and assimilation into plant biomass (Lucke and Nichols, 2015). A floating wetland (FW) was designed by McAndrew and Ahn (2017) to improve stormwater quality. The model suggested that FW can be adopted for sustainable stormwater management as their technology revealed elevated N removal. Direct plant uptake alone could remove up to 20% of pond N. The consistency and reliability of the uptake was influenced by pond size and hydrology, FW design and the primary productivity of the stocked plants. Studies conducted by Li et al. (2012) found that biofilters with a saturated zone with carbon source at the base had enhanced levels of nitrogen removal. Stormwater runoff from rural Australia was found to contain high concentrations of nutrients, therefore the choice of stormwater treatment systems should be influenced by the activities of the community Bhakri et al., 2008).

Another challenge of bioretention basins other than basin size, hydrologic and nutrient removal potential is the antecedent dry period before storm events (Manganaka et al., 2015). Lucke and Nichols (2015) found no significant influence of soil moisture content on hydrological and pollutant removal performance of street-side bioretention basins. However prior studies revealed the ability of F-RNA coliphages to survive dry periods within biofilters highlighting its resilience (Li et al., 2012). *E. coli* that was retained within the biofilter during proceeding events was able to survive 14 days of dry weather and leached during subsequent rainfall episode.

4.9.2.2 Bioretention for removal of microbial contaminants

It is important to reduce the level of pathogenic microorganism present in stormwater in order to limit human health risks for the integrity of receiving water bodies. The source of faecal matter in stormwater can be attributed to anthropogenic and birds and livestock sources. That led to studies that focused on pathogens from both source pollutants. *Campylobacter* is a pathogen from bird and livestock faecal matter.

The ability of bio-filters to remove *Camphylobacter* species and *E. coli* was investigated under extremely high influent volumes and microbial concentrations, and antecedent dry weather periods. *E. coli* served as an indicator organism and *Campylobacter* as a reference pathogen at Royal Melbourne golf club and Monash carpark biofilters. The outflow *E. coli* and *Campylobacter* spp. concentrations revealed significant log reductions in two field-scale biofiltration systems with *E. coli* obtaining higher log reductions. The saturation zones were not supplemented with carbon but utilised shrub and sedge combinations as vegetation. The hydraulic retention time occasionally exceeded the 24-hour period and continuously filtered the water over two to three days. The ability of *Campylobacter* to persist longer and lower adsorption due to cell surface charges may have led to lower log reductions. Microbial leaching was observed of previously retained *Campylobacter* species in the media was observed in Monash car park (Chandrasena et al., 2016).

4.9.3 Detention basins

Stormwater wet detention ponds are constructed to act as water reservoirs to provide flood mitigation, pollution prevention, downstream erosion control, increased aesthetics and recreational purposes. Although the detention ponds have been commissioned in states such as Florida to treat stormwater pollution, eutrophication deteriorates the transient ecosystem. N and P are essential nutrients in a healthy aquatic environment, but when excessive concentrations reach the detention pond, toxin producing algal species are favoured. That leads to a complete collapse of the aquatic system. Hypereutrophic detention ponds can be successfully treated by aiding in nutrient removal by incorporating floating wetland. Pollutant removal is facilitated by three distinct actions:

- Plants directly uptake the water though biological intake;
- Microorganisms grow on the floating mat and root systems whilst utilising organic matter in the water through microbial decomposition; and
- Root systems filter out sediment and associated pollutants.

The presence of cyanobacterial toxins called *Microcystis aeruginosa* in detention ponds requires innovative methods such as floating wetlands to eliminate its presence. Physical excavation of algal blooms does not offer preventative measures and requires appropriate disposal measures. Hartshorn et al. (2016) successfully augmented detention basins with floating wetlands to successfully eliminate hypereutrophic detention ponds.

4.9.4 Summary on treatment options

Depending on the quality of stormwater collected and the intended end use, treatment of stormwater can range from basic and/ or intermediate level to advanced options. Table 4.8 provides a summary of the treatment options and the potential uses of the captured stormwater.

Table 4.8 Stormwater treatment levels and potential uses

	Treatment type	Quality of water (following treatment)	Potential uses
Treatment Level 3: **Basic treatments**	• Gross pollutant traps • Bar screens • Trash rack	**Removes**: Leaves, litter & large materials **Does not remove**: Fine sediments, pathogens, dissolved contaminants, and organic material	**<u>Public access to water must be controlled</u>** **Controlled irrigation**: Spray/drip irrigation, subsurface irrigation of open spaces, parks & sportsgrounds **Industrial use**: Dust suppression, construction site use **Ornamental use**: Ornamental water bodies with access controls
Treatment Level 2: **Intermediate treatments**	• Sand filters • Sedimentation/settling ponds • Porous pavers • Bio-retention • Constructed wetlands	**Removes**: Sediments, dirt, grit and some associated metals, nutrients, some pathogens (reduces levels but does not completely remove) **Does not remove**: All pathogens	**<u>Fit for many uses</u>** **Irrigation:** Spray/drip irrigation of open spaces and sportsgrounds **Industrial use:** Dust suppression, construction site use, process water **Firefighting** **Ornamental**: Water features with high chance of public contact
Treatment Level 1: **Advanced treatments**	• Membrane technology • Electrolysis • Disinfection: ozone, UV, chlorination	**Removes**: All Level 2 & 3, Pathogens	**<u>Fit for uses that have close public contact</u>** **Reticulated non-potable water fit for**: • Garden watering • Toilet flushing • Car washing

4.10 STORMWATER FEASIBILITY FRAMEWORK

Stormwater harvesting schemes, either large or small provide a sustainable alternative water source for establishments and development projects with the potential to capture or temporarily store adequate volumes of water for use on their premises, and, for those with the capability to regularly use large volumes of water on their premises (www.brisbane.qld.gov.au/water). The following category of establishments and developments are most likely to benefit from exploring the option of stormwater harvesting as an alternative water source:

1. Learning institutions: these include schools, universities and other institutions;
2. Recreational spaces such football fields and golf courses;
3. Properties in large urban developments; and
4. Business and industry with high water needs of non-potable water quality

In order to propose and develop a stormwater harvesting project, the planners and designers need to determine the proposed site's suitability for stormwater harvesting. In confirming the suitability for a site's stormwater harvesting, the following steps need to be followed (www.brisbane.qld.gov.au/water):

4.10.1 Determine site suitability

The suitability of a site depends on the intended reuse of the harvested stormwater. The characteristics are site specific and include slope and drainage; infiltration and discharge rates; land availability; type of vegetation; soil type; and current land use.

4.10.2 Formulate a water balance assessment

Stormwater harvesting is runoff specific and therefore depends on the level of reliability of captured runoff and the volumes required. A highly variable rainfall pattern cannot guarantee a consistent supply (right volumes at the required time). This requires that a proper water balance assessment should be conducted. In conducting a water balance, there need to be a balance between the environment and the water supply. A schematic depiction of a typical water balance calculator is as shown in Figure 4.8.

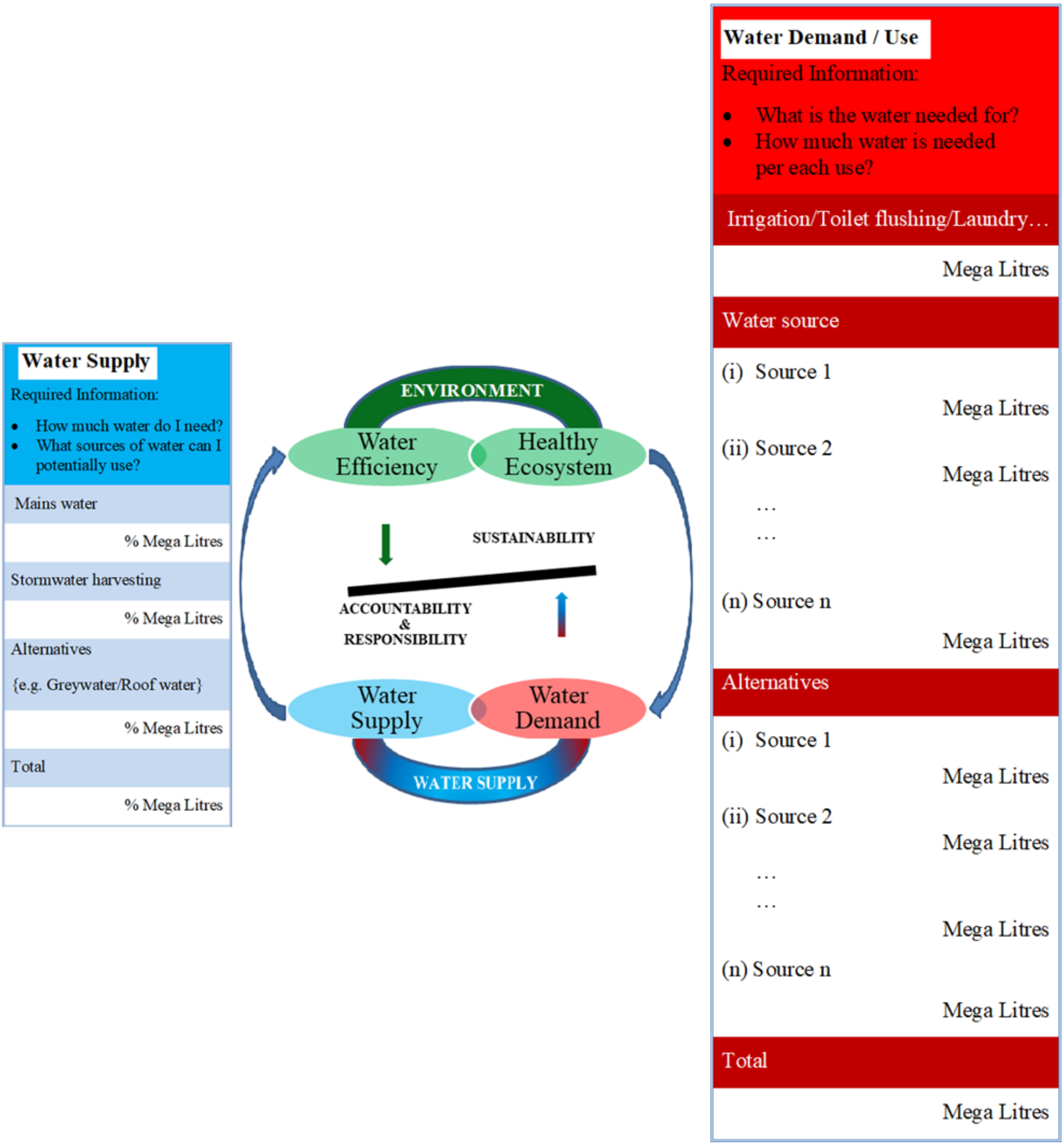


Figure 4.8 Water balance calculator schematic

4.10.3 Perform a risk assessment

An appropriate design should be conducted with risk minimisation as a priority. The process of risk assessment should be carried out in all stages with mitigation measures instituted during the capture, treatment, storage and delivery stages of the project. This implies that a systematic approach as described in the previous sections (Section 4.6) should be followed throughout the planning, design, and operation stages of the stormwater harvesting project (Alan Plummer Associates, Inc. 2010).

4.10.4 Cost analysis and funding options

One of the drawbacks identified in the implementation of stormwater harvesting schemes is the financial viability of the schemes. In most instances, the analysis shows that the financial viability is far from being acceptable. However, a proper scrutiny of the tools used for financial viability analysis indicate that the financial models used usually emphasise only on the advantages accrued in terms of drinking water conservation with little regard to the numerous non-secondary benefits. This implies that a multi objective – multi criterion decision-making aid methods that integrate multiple stakeholder priorities and BMP combinations need to be developed and optimally applied (Aceves & Fuamba, 2016; Campisano et al., 2017).

4.10.5 Review of statutory requirements

Different municipalities develop different by-laws that respond to their unique operating environments and locations and therefore all these should be adhered to in tandem with the National laws regulating the capture and use of stormwater. Some of necessary approvals that need to be attained could include but not limited to the following:

1. Permit/licence to connect to a municipal stormwater drain;
2. Licence/permit to access municipal/council stormwater infrastructure;
3. Plumbing approval;
4. Water extraction licence;
5. Waterway protection permit, etc.

4.10.6 Stakeholder consultations

This is necessary for the success of any stormwater harvesting scheme. Stakeholders' views and participation should always be sort and in all phases of the stormwater harvesting scheme. Further details are provided in the discussions under the purpose for and the need to develop social indices to guide in the monitoring and evaluation of the successes of stormwater management schemes (see section on social index).

4.11 POTENTIAL FOR STORMWATER HARVESTING

Assessing the feasibility of stormwater harvesting requires a set of data collection and analysis. The potential for a given municipal stormwater harvesting is affected by many factors that need to be determined and/or considered before a decision is made on the scale of harvesting, the use of the harvested water (be it multiple or single use) as well as whether to prioritise stormwater as the primary source or as a supplementary/secondary source of water in the targeted area. Among other factors, supply, demand and implementation may affect a region's potential for stormwater harvesting. Table 4.9 (adapted from Alan Plummer Associates, Inc. 2010) gives a summary of the factors that may affect a region's potential for rainwater harvesting.

Table 4.9 Summary of the factors that affect a region potential for stormwater harvesting (Adapted from Alan Plummer Associates, Inc. 2010)

Domain	Factor	Required data
Water Supply	Rainfall volume	Annual average
	Rainfall frequency	Number of rainfall days
	Rainfall timing	Monthly average rainfall volume
		Design storm rainfall volume
	Runoff potential	Soil types
		Land use/land cover
	Evaporative losses	Average annual
Water Demand	Municipal water needs	Projected municipal water needs (Quantity and Quality)
	Water demand timing	As per the water user
	Air temperature	Monthly average
Implementation	Cost of municipal alternatives	Projected municipal water management strategies as per the Master and Development Plan
	Aquifer storage and retrieval potential (where applicable and available)	Well logs
		Hydraulic conductivity
		Transmissivity
		Groundwater levels
Sustainability & Risk Management	Stormwater quality	Municipal records/field studies / modelling tools
	Environmental impacts	Field studies / modelling tools
	Environmental flow needs	Department of Water Affairs and Sanitation/ national Water Resources Strategy Document
	Public Health Risks	Department of Water Affairs and Sanitation / Department of Environmental Affairs
	Public Uncertainty	Comprehensive regional data source
	Water availability for downstream water rights	Department of Water Affairs and Sanitation

4.12 FEASIBILITY OF STORMWATER HARVESTING: CHALLENGES IN THE DEVELOPMENT OF STORMWATER AS AN ALTERNATIVE SOURCE OF WATER RESOURCE

In many cities, urban stormwater poses as a nuisance rather than a benefit to their water resources development. By virtue of their infrastructural developments, urban spaces are largely impervious and thus provide a guaranteed source of runoff, particularly in cities with high rainfall (McArdle et al., 2011). However, the water quality of most harvested stormwater and/or recycled stormwater has largely relegated its use to non-potable options (McArdle et al., 2011; Akram et al., 2014). Regarding the reuse of recycled stormwater, Akram et al. (2014), reiterate that the existing stormwater recycling practice is not in tandem with time, research and technology and therefore suggest a need for applying modern and robust technologies for assessing feasibility of stormwater harvesting and reuse for instance the use of Decision Support Systems that incorporate numerical models, GIS and the available database for a proper management of a stormwater harvesting project. Emmons and Olivier Inc. (2013), also indicate that in contemporary urban settings, settlements, and cities, the proliferation of centralised, energy-intensive potable water systems has also reduced the reliance on stormwater reuse despite its immense potential as a new water resource as well as a promising best management practice in areas with limitations to other practices such as infiltration, due to site constraints. Typical site constraints could be type of soils, contaminants, or shallow bedrock.

Despite the many water quality challenges of stormwater, Lim et al. (2011) indicate that with effective pollutant source management, urban stormwater harvesting is a feasible means to supplement the water supply in cities with high rainfall. McArdle et al. (2011), corroborate this finding from a study conducted in Newcastle, Throsby Creek catchment. In this study, the authors used Multi-criterion optimisation to identify Pareto optimal solutions for harvesting, storing and treating stormwater. Their findings indicate that harvesting and treating stormwater from as small a catchment as 13 km^2 could provide viable and cost-effective options of water supply as the pressure on conventional supplies grow.

Campisano et al. (2017), note that even though the practice of rainwater harvesting can be traced back millennia, the extent of its modern implementation varies significantly across the world, often with systems that do not maximise potential benefits. In many instances, the challenges of stormwater reuse include quantifying stormwater benefits of reuse given the variability of rainfall and adapting stormwater to different climatic regions. The general lack of technical guidance on quantification of the benefits of stormwater harvesting with regards to runoff volume reduction and water quality treatment is a cause for concern to many researchers (Emmons and Olivier Resources Inc., 2013). In their study, Campisano et al. (2017), reiterate that in analysing rainwater harvesting systems (including stormwater harvesting systems), a lot of emphasis is placed on the design protocols and the primary objective of conserving water with little regard and attention on other potential benefits associated with the multi-purpose nature of rainwater harvesting. Campisano et al. (2017), also point out the lack of high-quality datasets associated with the multiple objectives of rainwater harvesting such as: water saving, stormwater management, energy consumption, and greenhouse gas emissions and recommend the need for improved modelling of these multiple benefits. Campisano et al. (2017), further conclude that depending on the context, the overall economic viability of rainwater harvesting can be improved by incorporating multiple environmental benefits into the evaluation process. Other impediments include:

- lack of available funding;
- need for public education; and
- political support and policies.

4.13 STORMWATER HARVESTING FRAMEWORK: A LOW IMPACT DEVELOPMENT (LID) AND WATERSHED APPROACH

Sekhukhune District Municipality (SDM) is a mainly rural district with 117 administrative wards and a total of 764 villages. The District is made-up of four Local Municipalities, namely; Elias Motsoaledi, Ephraim Mogale, Makhuduthamaga and Fetakgomo Tubatse. The main towns in the district being: Burgersfort, Steelpoort, Groblersdal, Marble Hall, Apel, June Furse, Mohlaletsi, Driekop, Penge Mine, Prakiseer, Motetema and Mosterloos. 46% of the total area of the SDM is State-owned land (46% of SDM is designated as Municipality Area). 48% is designated as Traditional Authority Area (Department of Rural Affairs and Land Reforms – DRDLR, RSA, 2019). The Traditional Authority Area is made up of villages that are scattered throughout the area. Therefore, providing centralised service delivery is quite a challenge to the municipality. The implication therefore is that service delivery systems are distributed. By extension, development of stormwater and direct roof rainwater harvesting systems is also distributed.

As noted in the SDM Development Plan 2021, 10.26% of the households in the district have piped water inside the dwelling; 38.82% of the households in the district have piped water inside the yard; 17.88% of the households in the district have access to communal piped water at RDP-level of service that is less than 200 m from their dwelling; 16.40% of the households in the district have access to below RDP-level of service of communal piped water located more than 200 m from their dwelling; and 16.64% of the households have no formal piped water. These statistics translate to approximately 33% of households in the district living in below RDP-level service to no service at all that require alternative sources of potable water. This scenario presents an opportunity for the district to explore the direct-roof-rainwater harvesting and stormwater harvesting systems as alternative water supply sources for domestic use.

Captured stormwater requires treatment of some level before use. Low Impact Development (LID) and Traditional development are two typical configurations of treatment trains that meet the definition of stormwater treatment trains currently utilised by site designers. The focus of LID, also referred to as hydrologic source control, is, to endeavour to retain the site's pre-development (pristine) hydrologic regime. This is attained by a combination of impervious area controls with small scale BMPs and consequently reducing the wet weather flows and the associated nonpoint source pollution (NPSP) and the subsequent stormwater treatment needs. LID systems and practices mimic natural processes that result in the infiltration, evapotranspiration or use of stormwater in order to protect water quality and associated aquatic habitat. They create functional and appealing site drainage that treat stormwater as a resource rather than a waste product. Several practices that adhere to these principles include but not limited to rain gardens, bioretention facilities, rain barrels, vegetated rooftops, and permeable pavements (https://www.epa.gov/nps/urban-runoff-low-impact-development). Traditional development typically employs filtration and sedimentation practices such as swales and constructed ponds and wetlands. These practices may or may not treat rainwater close to its source but generally have minor impacts on stormwater volume. Where feasible, LID practices are favoured from a stormwater management practice as they reduce both stormwater volume and pollutant loading. LID practices, however, are often constrained by site factors, such as the existing soil profile (depth to bedrock – depending on whether shallow or deep, this has an impact on infiltration of stormwater and therefore the objective of stormwater volume management is dependent on this as a factor); soil or groundwater contamination (either from agricultural activities, waste disposal, mining or any other economic activity that has an impact on the soil properties and quality of the groundwater – this will impact on use of stormwater for groundwater recharge purposes for example); and space limitations (economic development growth nodes / corridors pose a challenge in developing LID systems, fast expanding urban and peri-urban spaces also pose a challenge in LID systems development).

A combination of LID and traditional BMP (aggregate LID-BMPs) yields the concept of Green Infrastructure (GI). This combination is necessary when developing stormwater treatment trains for larger regional and landscape scales as it provides opportunities to augment the advantages of LID with those of traditional BMPs. As part of the implementation of Water Sensitive Urban Design principles, applications of a combination of Low Impact Development (LID) and Green Infrastructure (GI) have gained traction over the overall sole implementation of traditional stormwater management systems. Contemporary studies extend the works of Allen (2012) that presents a case for a concise and protected definition and development of a framework that intends to preserve the original intent of the concept and current implementation of the practice of Green Infrastructure (GI) at all scales (site, regional, and landscape for both rural and urban setups). In certain disciplines, LID and GI are used interchangeably. For instance, USEPA (2011) defines GI as "an approach to wet weather management that is cost-effective, sustainable, and environmentally friendly". Green infrastructure management approaches and technologies include those that do infiltration, evapotranspiration, capture, and reuse of storm water to maintain or restore natural hydrology of the watershed (http://cfpub.epa.gov/npdes/home.cfm?program_id=298). At both the site and regional scale, LID/GI practices aim to preserve, restore and create green spaces using soils, vegetation, and rainwater harvest techniques.

The approach described in this section is generic and not specific to the study area. It can therefore be applied in any area that requires a stormwater management system with stormwater harvesting for beneficial use/purposes as a key objective set by the resource managers.

4.13.1 Addressing water quality challenges using a watershed approach

Daily life activities in a catchment can be devolved to a watershed scale. Therefore, addressing water resources challenges using a watershed approach presents the most effective framework to protect a region's water resources (USEPA, 1999). The effectiveness of such an approach is derived from the fact that a watershed is hydrologically defined (it drains a common waterway), it involves all the stakeholder, and it purposefully addresses priority water resource goals of water quality, flora and fauna.

Pollutants in runoff are a threat to the health of downstream ecosystems, as evidenced by harmful algal blooms in receiving waters. Arid and semi-arid regions of South Africa are struggling to meet their daily water demand requirements from new and clean water sources. Studies have shown that the rainwater harvesting (direct roof rainwater harvesting and stormwater harvesting) could offset the water demand deficit in such regions. Given the water quality concerns of such alternative sources, and depending on the specific end-user requirements, at least some minimum level of treatment is required to ensure that captured rainwater / stormwater is safe for direct use or aquifer recharge. Considering these challenges, and with specific reference to stormwater harvesting, innovative solutions for stormwater management are needed. Reductions in hydraulic or pollutant loads are commonly achieved through a set of distributed stormwater solutions, (Burns et al., 2012; Hamel et al., 2013) such as wetlands or bioretention ponds.

4.13.2 BMP selection: The treatment train approach

On a watershed scale, a stormwater management system comprises of a sequence of practices as presented in Figure 4.9 (Minnesota Pollution Control Agency, 2023).

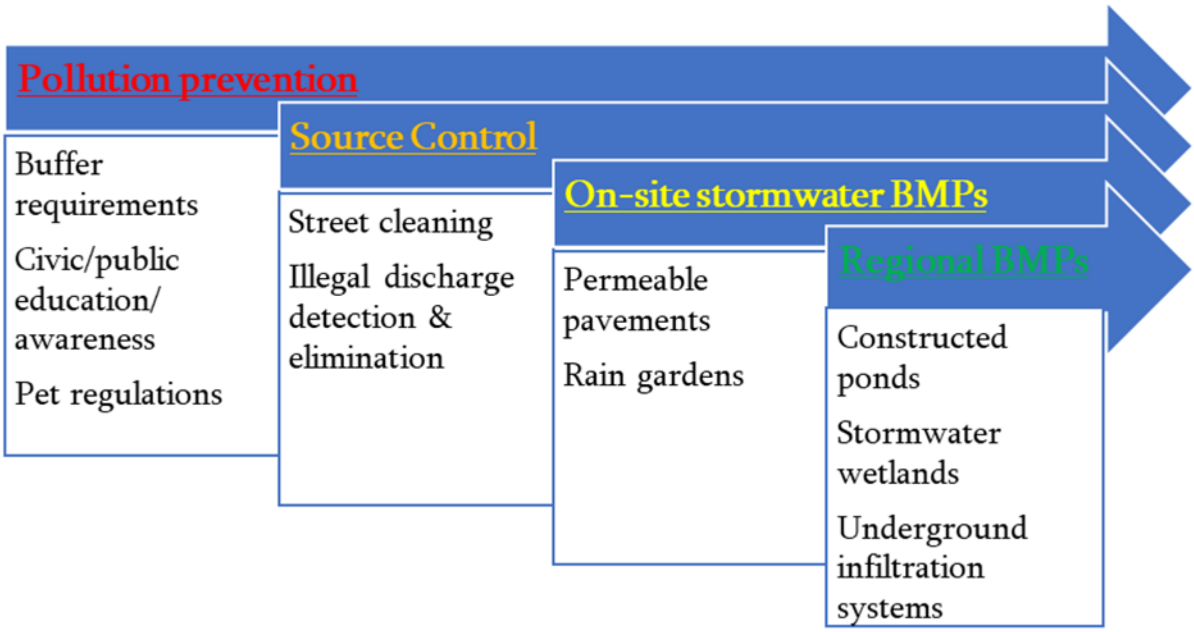


Figure 4.9 A sequence of overlapping stormwater management practices at a watershed scale

Treatment train implies application of practices and processes to treat or remove of stormwater volume or pollutants. By this definition, prevention and source control practices are therefore not treatment practices. They are, however, an integral part of the stormwater management system given that in establishing a stormwater management system, the designers and project owners should consider both non-structural practices as well as structural BMPs. A comprehensive stormwater management system as indicated in the Figure above includes:

- practices that control the development of runoff;

- practices that prevent generation of pollutants;
- practices that remove pollutants before contact with rainfall; and
- BMPs that utilize multiple processes that remove pollutants in stormwater runoff.

The following sections detail the process of developing the structural practices, or treatment portion, of the stormwater management system. Components making up the BMPs eliminate pollutants by way of a combination of several processes, *viz*., hydraulic, physical, biological, and chemical or other: thermal control.

4.13.3 Differentiating stormwater management practices from stormwater management processes

According to the Minnesota Pollution Control Agency (2023), stormwater practices (also referred to as the Unit Operations in other literature) are the stormwater controls whereby the pollutant control process(es) occur. They describe the primary process employed by that BMP and they represent the stormwater Best Management Practices. By the same token, a stormwater management process describes the mechanism by which pollutants are removed. For instance, to control/manage the stormwater volume, infiltration and evaporation are different processes for managing stormwater volume.

Each stormwater BMP employs multiple processes to perform its function. The processes of which could be a combination of hydraulic, physical, biological, and chemical or other: thermal control. Table 4.10 gives a presentation of the Processes for removing pollutants from stormwater runoff as derived from Design of urban stormwater controls (Water Environment Federation-WEF, 2012). Table 4.11 gives a presentation of the Practices for controlling pollutants in stormwater runoff (Water Environment Federation-WEF, 2012), and Table 4.12 gives a presentation of a summary of processes and practices for stormwater management (Strecker, 2005; WEF, 2012)

Table 4.10 Processes for removing pollutants from stormwater runoff (Water Environment Federation-WEF, 2012)

Process Category	Process Mechanism	Definition	Primary Pollutant
Hydraulic / Volume Management	Attenuation	Temporary detention of water for the purpose of controlling the rate of outflow	Peak flow
	Infiltration / runoff reduction	Water flowing into soils which does not become stormwater runoff	Runoff volume
	Evaporation	Water returning to atmosphere from water surfaces	Runoff volume
	Transpiration	Water returning to atmosphere through plant metabolism	Runoff volume
Physical	Screening	Separation of gross pollutants from water by straining through large openings	Gross pollutants, vegetation
	Sedimentation	Process by which solids are removed from the water column by settling	Heavy suspended solids
	Filtration	Sedimentation and physical retention of smaller particles passing through media	Suspended solids
	Flotation	Separation of oil/grease and litter upward through the water column through buoyancy	Oil/grease, litter, vegetation
	Laminar separation	Movement of water through non-turbulent conditions to effectively separate particles	Oil/grease
	Swirl concentration	Movement of water to the centre of a hydraulic vortex and of particles to the outer edges of the vortex via inertia and gravitational force	Suspended solids
Biological	Plant metabolism	Uptake of nutrients from the water by plants for the purpose of metabolism	Phosphorus, dissolved
	Pathogen die-off	Die-off of pathogens by natural methods	Pathogens
	Nitrification / denitrification	Process of nitrogen removal by bacteria that results in nitrogen release to atmosphere as a gas	Nitrogen
Chemical	Precipitation	Joining of two inorganic dissolved pollutants into a heavier particle that can be settled or filtered	Dissolved inorganic pollutants
	Coagulation	Joining of small particles of one pollutant into a heavier particle that can be settled or filtered	Colloidal solids
	Absorption	Pollutant penetrating into the molecular level of the media	Dissolved pollutants
	Adsorption	Attachment of a pollutant to the surfaces of a media	Dissolved pollutants
	Ion Exchange	Capture of a dissolved pollutant, typically heavy metals, in a media through the exchange of ions between the media and the pollutant	Heavy metals
Other	Thermal / temperature control	Cooling of water that has been heated through contact with pavements and other surfaces	Temperature

Table 4.11 Practices for controlling pollutants in stormwater runoff (Water Environment Federation-WEF, 2012)

Practice Category	**Best Management Practice**
Constructed Basins	Pond forebay
Constructed Basins	Wet detention pond
Constructed Basins	Stormwater wetland
Constructed Basins	Dry pond
Filters	Biofiltration
Filters	Media filter
Filters	Green roof
Filters	Surface sand filter
Filters	Perimeter sand filter
Filters	Underground sand filter
Filters	Enhanced sand filter
Filters	Permeable pavement w/underdrain
Infiltrators	Bio-infiltration / rain garden
Infiltrators	Infiltration basin
Infiltrators	Infiltration trench
Infiltrators	Permeable pavement
Infiltrators	Tree trench / tree box
Infiltrators	Underground infiltration
Manufactured Devices	Catch basin inlets
Manufactured Devices	Grit chambers
Manufactured Devices	Hydrodynamic separators
Manufactured Devices	SAFL Baffle
Manufactured Devices	Oil / water separators
Manufactured Devices	Sump manhole / catch basin
Pollution Prevention and Public Education	Local By-Laws / Regulation
Pollution Prevention and Public Education	Pet Waste Regulation
Pollution Prevention and Public Education	Education
Pollution Prevention and Public Education	Fertilizer Regulation
Pollution Prevention and Public Education	Tree Regulation
Pollution Prevention and Public Education	Buffers
Source Controls	Sweeping
Source Controls	Construction Erosion and Sediment Control
Source Controls	Chemical storage
Source Controls	Salt management
Source Controls	Storm sewer / outfall maintenance
Source Controls	Illicit Discharge Detection & Elimination – IDDE
Storage, Harvesting and Reuse	Irrigation
Storage, Harvesting and Reuse	Municipal uses
Storage, Harvesting and Reuse	In-building uses
Storage, Harvesting and Reuse	Industrial uses
Swales and Strips	Dry swale
Swales and Strips	Filter strip / grass buffer
Swales and Strips	Grass channel
Swales and Strips	Level spreader
Swales and Strips	Wet swale

Table 4.12 Matrix of BMP Processes and Practices (Source: Strecker, 2005; WEF, 2012)

PRACTICES		HYDRAULIC PROCESSES				PHYSICAL PROCESSES						BIOLOGICAL PROCESSES			CHEMICAL PROCESSES			OTHER
Practice Category / BMP	Pretreatment	Attenuation	Infiltration / Runoff reduction	Evaporation	Transpiration	Screening	Sedimentation	Filtration	Flotation / Skimming	Laminar Separation	Swirl concentration	Plant metabolism	Pathogen die-off	Nitrification / denitrification	Precipitation	Coagulation	Sorption/Ion Exchange	Thermal / temperature
Bioinfiltration / rain garden			✓		✓		✓	✓				✓	✓	✓			✓	✓
Infiltration basin		✓	✓		✓		✓	✓				✓	✓	✓			✓	✓
Infiltration trench		✓	✓		✓		✓	✓				✓	✓	✓			✓	✓
Permeable pavement			✓					✓					✓				✓	✓
Tree trench / tree box			✓		✓			✓				✓	✓	✓			✓	✓
Underground infiltration		✓	✓				✓	✓	✓								✓	✓
Swales and Strips																		
Dry swale		✓					✓	✓					✓					✓
Filter strip / grass buffer	✓					✓		✓					✓					✓
Grass channel		✓					✓	✓					✓					✓
Level spreader	✓																	
Wet swale		✓		✓	✓		✓	✓	✓			✓	✓				✓	✓
Filters																		
Biofiltration					✓		✓	✓				✓	✓	✓			✓	✓
Media filter								✓									✓	
Green roof								✓				✓	✓	✓			✓	
Surface sand filter		✓						✓										
Perimeter sand filter								✓										
Underground sand filter		✓						✓										
Enhanced sand filter								✓									✓	
Permeable pavement w/underdrain								✓										
Constructed Basins																		
Pond forebay	✓						✓											
Wet detention pond		✓					✓		✓				✓	✓	✓	✓		
Stormwater wetland		✓					✓		✓			✓	✓	✓	✓	✓	✓	
Dry pond		✓					✓											
Manufactured Devices																		
Catch basin inlets	✓					✓												
Grit chambers	✓								✓									
Hydrodynamic separators	✓								✓		✓							
SAFL Baffle	✓					✓			✓									
Oil / water separators	✓					✓			✓	✓								✓
Sump manhole / catch basin	✓																	
Storage and Reuse																		
Irrigation		✓																
Municipal uses		✓																
In-building uses		✓																
Industrial uses		✓																

4.13.4 Characteristic stormwater treatment train

A combination of at least two processes to treat stormwater is termed a stormwater treatment train. Stormwater treatment entails the removal of pollutant or stormwater volume once they have been generated. The multiple stormwater treatment processes and/or practices are combined in a way that certifies management of all pollutants that could affect a receiving water.

Using the background information on the generated runoff characteristics, a treatment train can be built/developed by coupling the information from Tables 4.10 to 4.12 to build a stormwater treatment train that meets the stormwater management goals and objectives. All constraints including regulatory requirements must be taken into consideration. A well-developed stormwater treatment train will combine these processes in a manner that ensures management of all pollutants that have been identified as affecting the receiving water. If the correct combination of processes is struck and built up, the resulting stormwater treatment train can achieve the following objectives:

- minimize the rate of runoff by applying a hydraulic process (stormwater peak attenuation);

- remove bulk solids by employing a physical process (screening/sedimentation);
- remove settleable solids and floatables by utilising a physical process (sedimentation/floatation);
- remove suspended and colloidal solids by utilising a physical, biological or chemical process (coagulation/filtration); and
- remove colloidal, dissolved, volatile, and pathogens by using a biological or chemical process (coagulation/absorption / pathogen die-off).

Wong et al. (2002), and Strecker (2005), (cited in Minnesota Pollution Control Agency, 2023) illustrate that while executing the laid-out framework for pollutant removal, particulate size of the pollutant(s) of concern should be matched to the stormwater practice that is best suited to remove that pollutant from stormwater runoff. Wong et al. (2002), in conjunction with the American Society of Civil Engineers (ASCE) have developed a tool that can be applied to determine the appropriate stormwater management processes based on particulate sizes that are commonly found in stormwater runoff. This is a characteristic of the stormwater runoff that can be determined visually, in the laboratory through laboratory tests and, or in-situ in the field. The tool is presented in **Figure 4.10**.

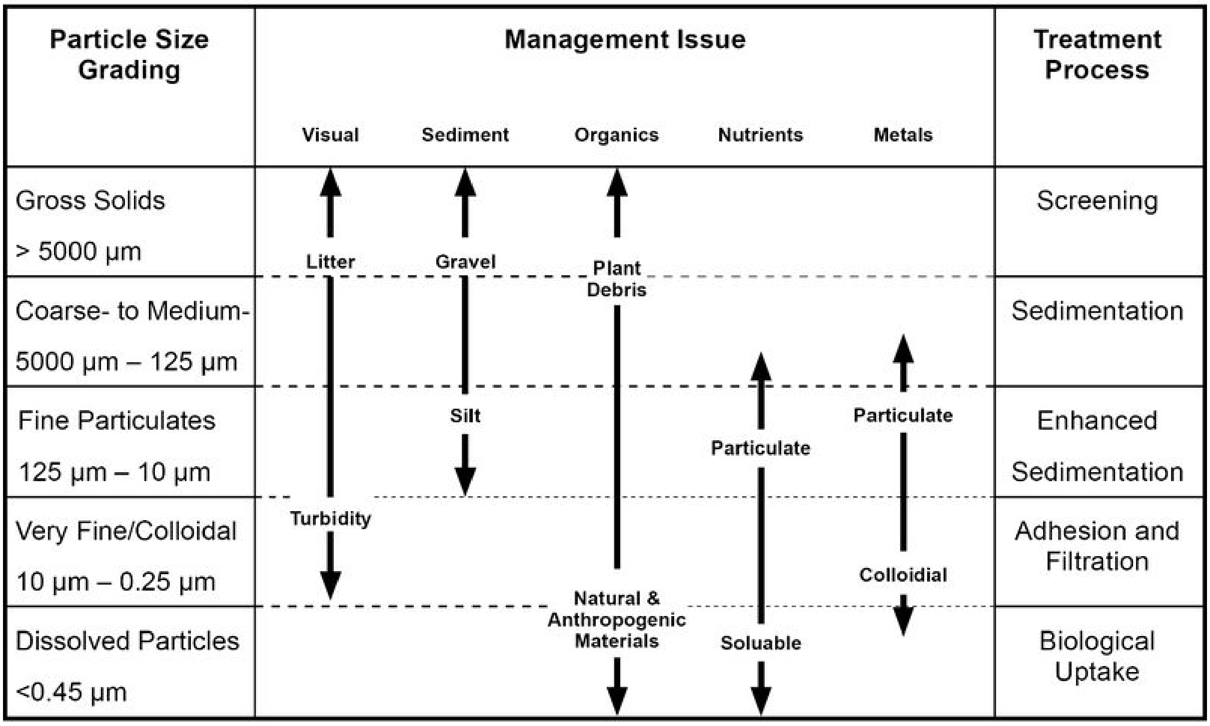


Figure 4.10 Tool to determine stormwater management processes based on particulate sizes (Adopted from Wong et al., 2002)

A stormwater treatment train is defined by a multi-BMP approach to managing the quantity and quality of stormwater runoff. The holistic event also includes prevention and source control practices. Depending on the situation being assessed, a selected stormwater treatment train may contain BMPs characterised by one or multiple practices. Some of the considerations include but not limited to physical site conditions, available space and regulatory requirements. In the treatment train, the combination of the BMPs may operate in series or parallel to each other. A summary of probable stormwater management processes and practices is given in Tables 4.11 and 4.12. In certain instances, the subsequent stormwater treatment train may result in a single BMP that by characteristics, inherently, employs multiple treatment train processes. For instance, a stormwater wetland. Such a BMP can be considered a stand-alone stormwater treatment train (Minnesota Pollution Control Agency, 2023).

LID and Traditional development are still in contention for application in our local municipalities' stormwater management practices and therefore need to be addressed. However, with the drive towards the implementation of the Water Sensitive Urban Design (WSUD) principles in infrastructure development in our municipalities, the bias in stormwater management is towards the LID practices at both the site and regional scales. For the purposes of this framework, a comparison is sort on how the two systems could be set up in a typical scenario. An excerpt from the Minnesota Pollution Control Agency (2023), is presented as shown in Figure 4.11 (schematic) for illustration purposes. It is critical to note that a scenario-based approach works best in development of effective stormwater management practices as each scenario presents a unique set of challenges that have their unique set of solutions. It is therefore not a one-size-fit all approach. Examples of these two types of treatment trains are provided below and illustrated in the schematic. In the schematic, examples of stormwater management and practices are provided for each system treatment train. In the LID example, water falling on a rooftop is filtered through a green roof, which stores some water for eventual uptake by plants and routes the remaining water to a permeable pavement and then to an infiltration BMP. The traditional configuration routes water off-site through a swale, which provides some treatment, before the water is discharged to a regional system (Minnesota Pollution Control Agency, 2023). Figure 4.11 presents examples of stormwater treatment train for LID site on the left and for traditional development on the right.

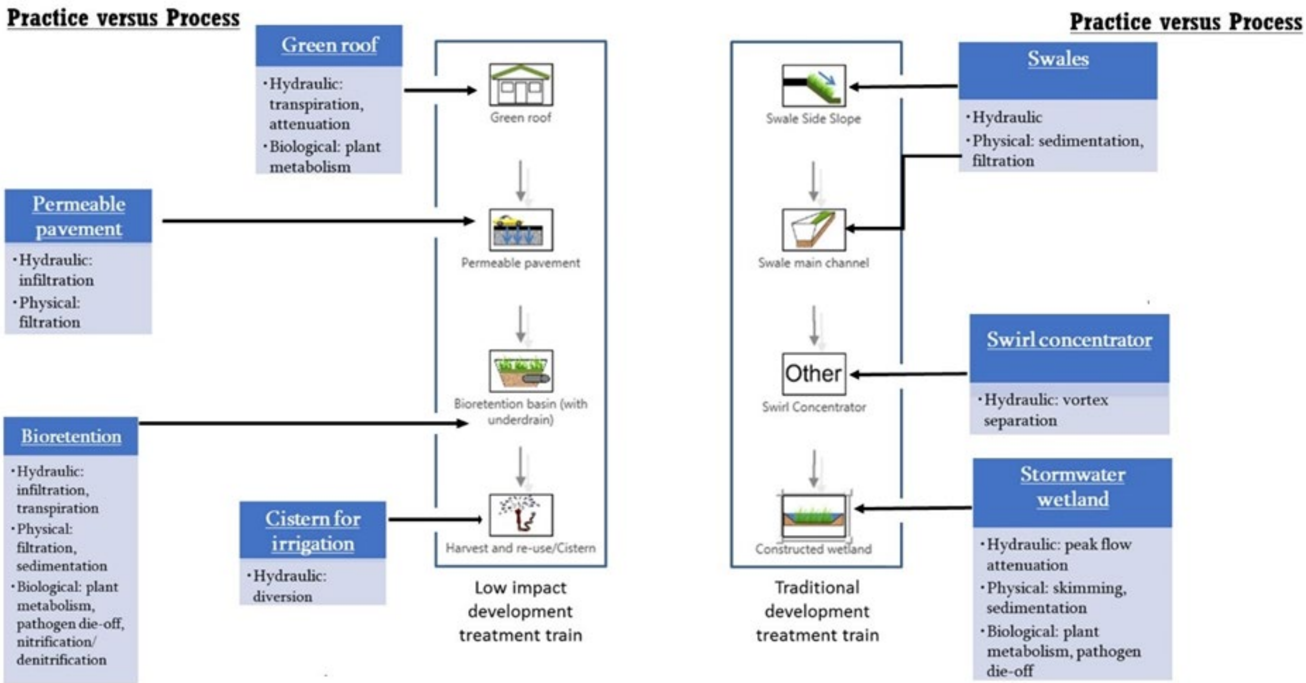


Figure 4.11 Schematic showing typical treatment trains for Low Impact Development and Traditional Development scenarios

4.13.4.1 Important notes from findings on performance of treatment trains

Effectiveness

According to the Minnesota Pollution Control Agency (MPCA) (2023), case studies have shown that on-site treatment trains that maintain runoff on-site while allowing ample time for treatment processes, *viz*. hydraulic, physical, biological, and chemical/or thermal processes to take place are the most effective.

The efficiency in terms of pollution reduction of treatment train BMPs is higher on an on-site scale as compared to a catchment or watershed scale.

Commonly, the highest level of pollutant reduction is achieved in the first BMP, with each successive BMP becoming less effective. The theory of why this occurs is based on the concept of irreducible pollutants (Schueler, 1996; 2000). The basics is that the second, third, and subsequent BMPs in the treatment train are receiving runoff that has considerably less concentration of pollutants and which at some point are below the theoretical irreducible concentration for the BMP to process. Schueler (2000) and Scholes et al. (2007) recommend that to adjust for the uncertainties caused by irreducible pollutants state in the treatment train, the modeler needs to prepare a list of prioritised BMPs that are ranked as per the pollutant removal effectiveness for each pollutant identified in the stormwater and targeted for removal. By way of multi-objective analyses, the modeler will be able to select the most appropriate BMP for that treatment train slot.

Costs

There is little mention in the current body of literature on any study that has been conducted to assess the cost effectiveness of stormwater management treatment trains. This therefore presents itself as a gap in this field of study that requires further exploration. A deductive approach could be applied to suggest an objective estimation of the cost comparisons. However, such approaches provide just but estimations which could either be over or under the actual cost (CAPEX and OPEX). The assumption put forward in the estimations is that the total cost is the summation of individual practices/processes within the stormwater treatment train. Suggested costing comparison studies should consider the following:

- Assess the cost through the life cycle of the BMPs;
- Assess the cost through comparisons of the economy of scale;
- Assess the cost through a comparative analysis of the cost of retrofit versus installation of BMPs in new construction projects; and
- Assess the full cost of the project considering CAPEX, OPEX, cost of land, design, permitting, and contingency in terms of climate action (global change versus climate change).

The suggestions on the appropriate costing model above are indicative of a need for developing a multi-objective-multi-criterion decision-making aid method for implementation of stormwater harvesting systems. Such methods interrogate multiple stakeholder priorities where BMP combinations are developed and applied optimally.

4.13.5 Stormwater treatment train approach

4.13.5.1 Developing a stormwater treatment train

Development of a stormwater treatment train is an iterative process that balances site constraints, project goals, and available budget. Figure 4.12 presents a developed framework for establishing a stormwater treatment train. The requisite accompany actions are explained in the steps that lay out the process for establishing a stormwater harvesting and treatment train. The results of one of the steps may cause designers to reconsider earlier decisions on sizing, siting, etc., as the project progresses.

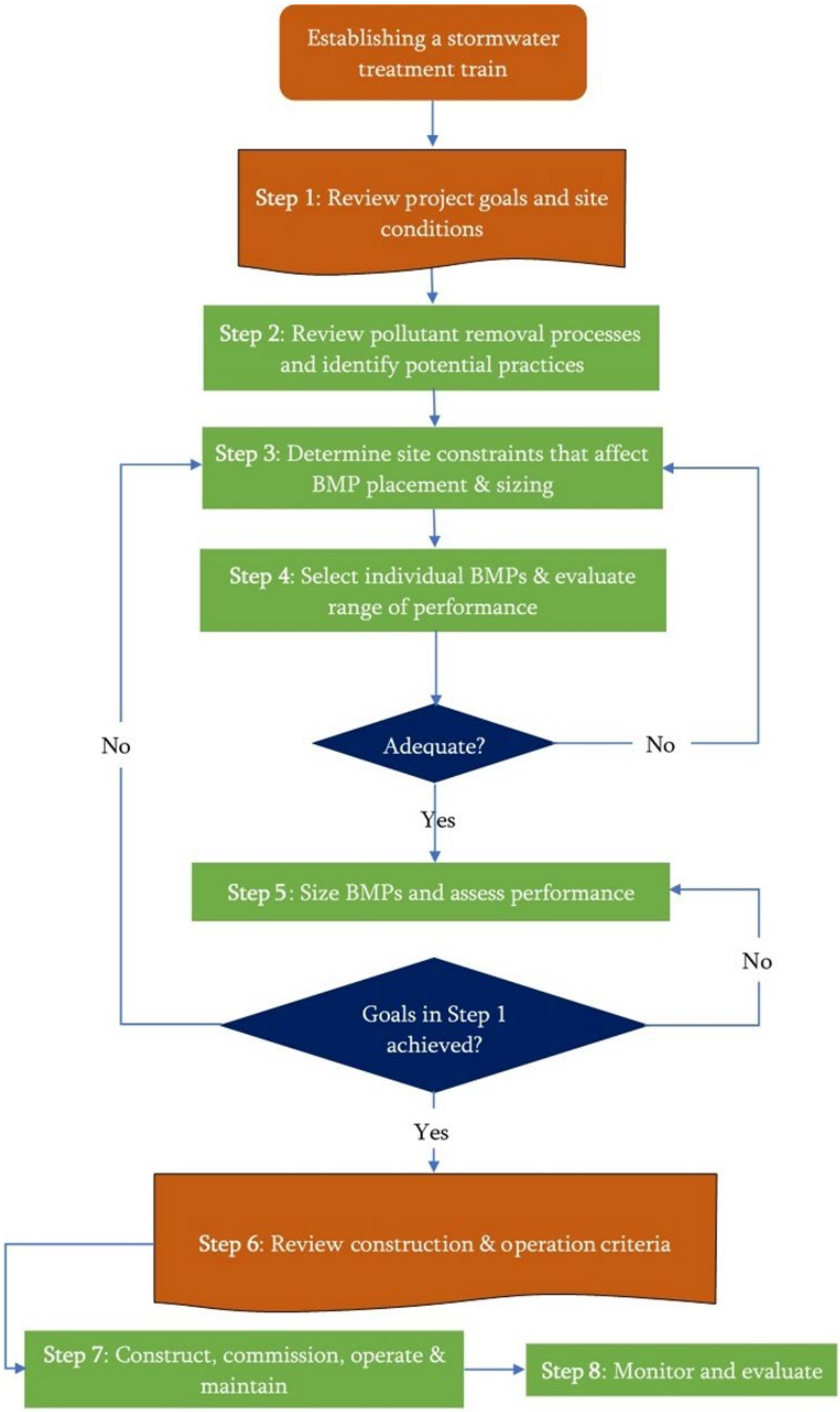


Figure 4.12 A framework for stormwater harvesting and treatment: establishing a stormwater treatment train

Step 1 – Review project goals and site conditions

The site conditions, regulatory requirements, and project purpose will vary from site to site and from municipality to municipality. Information to assemble include:

- Project goals: as earlier stated, stormwater treatment implies removal of stormwater volume or pollutants that have been generated. Therefore, the project goals are centred on runoff volume or water quality. As a first step therefore, the designers need to determine the intended project goal (expected outcome(s) of the project that define its success) for instance; is the project intended to solve a drainage problem, meet regulatory requirements, or both? The answer to this question determines whether the goals are related to runoff volume or water quality. If the objectives are related to water quality, the pollutants of concern need to be identified. The pollutants load also need to be estimated by determining the nutrient and sediment loads from different land uses.
- Regulatory requirements – are there any regulatory requirements that will influence the stormwater system?
- Site conditions: collect information on impervious surface, drainage area, runoff quality, soils, and topography among others.

Step 2 – Review pollutant removal processes and identify potential practices

The purpose of this step is to create a list of BMPs that work together to remove the pollutants of concern identified in Step 1.

- Select processes required to manage pollutants (make use of information from Tables 4.10 to 4.12 and Figure 4.10), and
- Identify combination(s) of BMPs that include the processes required to manage the identified pollutants.

Take into consideration the concept of irreducible pollutant concentrations that are discharged from the BMPs. Apply the proposed adjustment to manage the uncertainty caused by irreducible pollutant concentration conditions as explained in the previous section above – list and prioritise)

To make these determinations, use Table 4.12 which provides a summary of processes and practices.

Step 3 – Determine site constraints that affect BMP placement and sizing

Site constraints will affect the sizing, location, and performance of the BMPs identified in Step 2. The purpose of this step is to narrow down the BMP options based on such site constraints as:

- Available space,
- Access for maintenance,
- Limitations on infiltration related to soil type, soil contamination, depth to groundwater, presence of structures (concreted underground due to high density of concrete foundations limit both lateral and vertical movement of water), utility conflicts (separation of water, wastewater and electrical networks), and/or depth to bedrock,
- Regulatory requirements that affect the BMP volume or footprint, and
- Compatibility with other site uses, including green space requirements, public spaces, and structures among others.

Step 4 – Select individual BMPs and evaluate range of performance

Review each BMP identified in Step 3 to confirm that each pollutant removal process identified in Step 2 is present in the combination of BMPs selected in Step 3. If not, then Step 3 should be reviewed and alternative BMPs proposed.

Step 5 – Size BMPs and assess performance

Size the BMP and assess the performance. Review results against goals set in Step 1. If goals are not fully achieved, then resize the BMPs or return to Step 3 to select alternative BMPs.

Step 6 – Review construction and operation criteria
Designers should assess construction and operation considerations that need to be incorporated into the construction plans and/or the Operations and Maintenance Manual that are necessary to ensure the BMP operates as designed and is properly maintained. Costing and costing review are also critical at this point. Assess the full cost of the project considering CAPEX, OPEX, cost of land, design, permitting, and contingency in terms of climate action (global change versus climate change).

Step 7 – Construct, commission, operate and maintain
In following the review of the construction and operation criteria, proper costing, and upon passing the required levels of project approvals, the project needs to undergo the actual construction, commissioning, operation and maintenance schedules. During the commissioning, the checks and balances should be put in place to ensure that the BMPs operate as designed and follow the appropriate maintenance schedule.

Step 8 – Monitor and evaluate
Monitor the progress of the stormwater management project. In this phase, the resource managers need to establish appropriate sets of social indicators. The social indicators are required for the review of the performance of the stormwater management (BMP) project.

4.14 A FRAMEWORK FOR MONITORING PROGRESS OF STORMWATER HARVESTING PROJECTS

The quality concern of the stormwater generated during rainfall/precipitation events is commonly evaluated by the level of contamination of the stormwater through Nonpoint Source (NPS) Pollutants. In dealing with NPS pollution of stormwater, the development of an effective monitoring schedule requires the following:

- Development of tools that calculate the nutrient and sediment loads from different land uses, and
- Monitoring the load reductions that would result from the implementation of various best management practices (BMPs).
- Learn more about your watershed by setting up a system for using social indicators to help you plan, implement and evaluate Nonpoint Source (NPS) management projects (Genskow et al., 2011).

The first and second point can be dealt with during the development of the stormwater treatment train. The third point requires a holistic approach that deals with the participation of and collaboration between the resource managers and the community at the watershed level.

4.14.1 About social indicators

4.14.1.1 Overview

Water quality problems have accumulated over many decades and may take decades to amend. Checking that awareness and attitudes are changing, and behaviours are being adopted in a watershed is one way that projects can demonstrate progress toward water quality goals (Genskow et al., 2011). Social indicators provide consistent measures of social change within a catchment / watershed and can be used by resource managers at local, provincial and national levels to estimate the impacts of their efforts and resources in achieving set control or regulatory targets.

4.14.1.2 Purpose of social indicators

The adage “you cannot manage what you cannot measure” works true with respect to stormwater management and by extension stormwater harvesting. In harvesting stormwater as an alternative source of water, the stormwater quality is one of the essential indicators that qualifies its use and/or application for a selected purpose. Nonpoint Source (NPS) Pollution is an essential characteristic of stormwater. The nature of its generation and the severity is greatly influenced by both natural and anthropogenic factors. It generally results from land runoff, precipitation (including snowmelt), drainage, seepage, atmospheric deposition, or hydrologic modification. The endpoints of generated stormwater and its characteristic NPS pollutants are; rivers, lakes, wetlands, groundwaters, and coastal waters. The pollutants therefore have harmful effects on drinking water supplies, recreation, fisheries and wildlife. The Nonpoint source pollution can comprise the following (Genskow et al., 2011):

- Excess fertilizers, herbicides and insecticides from agricultural lands and residential areas;
- Oil, grease and toxic chemicals from urban runoff and energy production;
- Sediment from improperly managed construction sites, crop and forest lands, and eroding streambanks;
- Salt from irrigation practices and acid mine drainage from abandoned mines
- Bacteria and nutrients from livestock, pet wastes and faulty wastewater treatment systems (wastewater treatment plants and septic systems)
- Atmospheric deposition and hydromodification. Hydromodification activities include channelization and channel modification, dams, and streambank and shoreline erosion (USEPA, https://www.epa.gov/nps/nonpoint-source-hydromodification-and-habitat-alteration).

Effective management of NPS water pollution requires addressing both environmental conditions and the choices people make that impact the environment (Genskow et al., 2011). The choices people make constitute social behaviour which can be quantified through characteristic social indicators.

4.14.2 Social Indicators (SI)

According to European Environmental Agency (EEA) Glossary, (EEA, 2004), Social Indicators are *a set of indicators that measure progress towards the policy objectives designed for promoting employment, combating poverty, improving living and working conditions, combating exclusion, developing human resources, etc.* (https://www.eea.europa.eu/help/glossary/eea-glossary). The USEPA defines Social Indicators as *measures that describe the capacity, skills, awareness, knowledge, values, beliefs, and behaviours of individuals, households, organizations, and communities* (Genskow et al., 2011). Genskow et al. (2011) have developed a Handbook; The Social Indicator Planning & Evaluation System (SIPES) for Nonpoint Source Management. In the Handbook, social indicators for NPS management provide information about awareness, attitudes, constraints, capacity, and behaviours that are expected to lead to water quality improvement and protection.

A sustainable stormwater harvesting system requires a sustainable stormwater quality management and improvement. In the NPS pollution management, this necessitates an improvement of water quality via changing people’s conduct. People’s behaviour could be changed by influencing their awareness, attitudes, capacity and skills, or restrictions related to water quality improvement (Genskow et al., 2011). A proper mapping of the social indicators in the project area is thus of essence as it provides a basis for confirmation that awareness and attitudes are changing. It also provides a basis to demonstrate that behaviours are being adopted in the project area to meet the targeted water quality goals and objectives. Given the scientific approach applied in qualifying social indicators (SI), SIs provide reliable/dependable measures of social transformation within a watershed and can be employed by catchment/watershed managers to assess and approximate the impacts of their efforts and resources in NPS pollution management and improvement in water quality.

Social perceptions towards embracing the use of stormwater for domestic purposes (fit for purpose) as well as treating stormwater as a valuable and alternative source of water other than viewing stormwater as waste has a direct influence on the social behaviour. Social behaviour has a direct link to the resultant stormwater quality as indicated above in respect of the constitution of the NPS pollution. Figure 4.13 below illustrates the link between social indicators and eventual improvement of water quality.

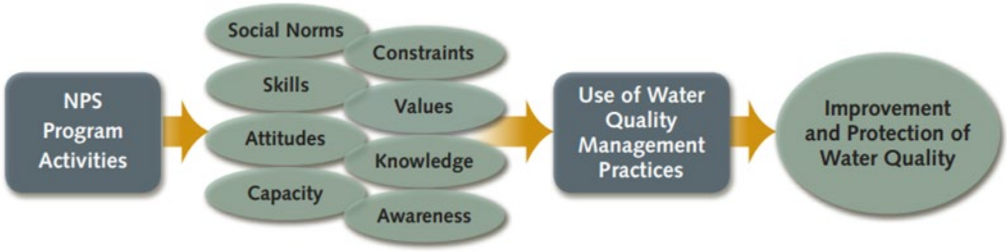


Figure 4.13 Conceptual model of social indicators and water quality (Genskow et al., 2011)

According to a United Nations document (United Nations, 1994 cited in Noll (2002)), Social indicators are important as they are used to "*identify social problems that require action, to develop priorities and goals for action and spending, and to assess the effectiveness of programmes and policies*".

4.14.3 Principal social indicators

Most literature on social indicators direct the definition and focus on living conditions in areas of social concern and the function of trend monitoring. They also elaborate on the function of identifying problems, setting priorities, assessing programmes and policies thereof (United Nations, 1994; McEwin, 1995; Noll, 2002; Genskow et al., 2011). Analyses of these literature consolidates the SIs for NPS pollution management under intended outcomes to achieve set goals of the programme. Depending on the nature, location, scale, and severity of the programme, among other factors, a varied list of SIs can be generated that provide important information for planning, implementing, and evaluating NPS pollution projects. A typical consolidation is as given in Table 4.13 as adopted from Genskow et al. (2011).

Table 4.13 Goals, intended outcomes, and core social indicators for NPS pollution management

GOAL 1: INCREASE TARGET AUDIENCE AWARENESS	
Awareness Outcome 1:	Increase awareness of relevant technical issues and/or recommended practices in critical areas
Awareness Indicator 1:	Awareness of consequences of pollutants to water quality
Awareness Indicator 2:	Awareness of pollutant types impairing water quality
Awareness Indicator 3:	Awareness of pollutant sources impairing water quality
Awareness Indicator 4:	Awareness of appropriate practices to improve water quality
GOAL 2: CHANGE TARGET AUDIENCE ATTITUDES	
Attitudes Outcome 1:	Change attitudes to facilitate desired behavior change in critical area
Attitudes Indicator 1:	General water-quality-related attitudes
Attitudes Indicator 2:	Willingness to take action to improve water quality
GOAL 3: REDUCE TARGET AUDIENCE CONSTRAINTS	
Constraints Outcome 1:	Reduce constraints to behavior change
Constraints Indicator 1:	Constraints to behavior change
GOAL 4: INCREASE ORGANIZATIONAL CAPACITY	
Capacity Outcome 1:	Increase capacity to leverage resources in critical areas
Capacity Indicator 1:	Resources leveraged by grant recipient in the watershed as a result of project funding (including cash and in-kind resources)
Capacity Outcome 2:	Increase capacity to support appropriate practices in critical areas
Capacity Indicator 2:	Funding available to support NPS practices in critical areas
Capacity Indicator 3:	Technical support available for NPS practices in critical areas
Capacity Indicator 4:	Ability to monitor practices in critical areas
GOAL 5: INCREASE TARGET AUDIENCE ADOPTION OF NPS MANAGEMENT PRACTICES	
Behavior Outcome 1:	Increase adoption of practices to maintain or improve water quality in critical areas.
Behavior Indicator 1:	Percentage of critical area receiving treatment
Behavior Indicator 2:	Percentage of target audience implementing practices in critical areas

4.14.4 Steps to measure social indicators

Measuring the Social Indicators of a given project can be accomplished in seven iterative steps as illustrated in Genskow et al. (2011) in line with their developed tool, the Social Indicators Planning and Evaluation System (SIPES). The identified steps are iterative and form part of a constant process of planning, implementing, evaluating, and adapting your management efforts. A brief explanation of the tenets of the steps is presented in the following sections.

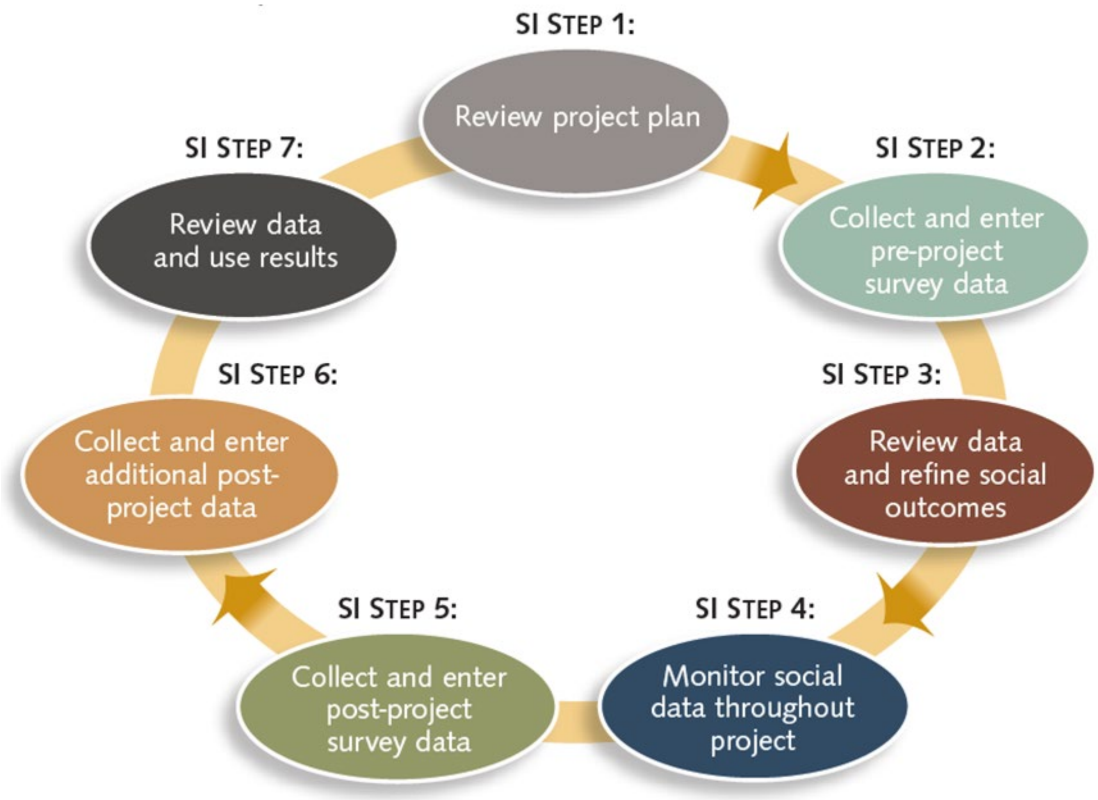


Figure 4.14 The seven steps in Social Indicator Planning and Evaluation System-SIPES (Adopted from Genskow et al., 2011)

The starring and guiding key questions in undertaking a measurement of the social indicator in the project life cycle are as follow:

1. What is your project goal?
2. What are the critical areas that contribute to the problem to be solved?
3. Who are the target audiences that the project will address?
4. What are the expected inputs from the target audiences about the project?

During the project, the answers recorded for the four staring questions set the stage for the resource managers to focus and evaluate the project implementation efforts. Table 4.14 presents the description of each step and the key activities to be undertaken in each step. The outcomes are evaluated iteratively to assist in creating a dynamic and evolutionary project implementation and evaluation environment.

Table 4.14 Description of steps and activities in developing social indicators for NPS pollution monitoring projects

Step	Description	Activity
	Steps 1-3: Project Planning	
Step 1	Stage for focusing and evaluating the project implementation efforts	• Identify the specific NPS problem to be addressed • Identify critical area(s) for project focus • Identify target audiences • Identify the potential actions for the project target audience to take
Step 2	Based on principal social indicators, develop a set of questionnaires to collect data about the NPS awareness, attitudes, constraints, and behaviours of your target audience.	• Select a BMP practice • Compile contact list(s) for your target audience(s) • Determine sample size • Select sample • Create questionnaire • Determine dates for administering various pieces of your survey • Create advance letters, and cover letters • Develop Quality Assurance Project Plan (QAPP) • Administer questionnaire • Code and enter responses
Step 3	Based on the analysis report from the entered data in Step 2, refine the social outcomes and the plan for outreach and education activities.	• Analyse results • Interpret results • Establish social outcomes • Develop an outreach and education plan
	Steps 4-7: Project Implementation and Evaluation	
Step 4	Continuous monitoring of social data to ensure the activities are leading towards the envisaged social outcomes as set out in Step 3	• Develop your monitoring plan • Collect data based on plan • Review data based on plan • Adapt project activities as necessary
Step 5	Measure the social impact of the project by comparing the post-project survey data with the pre-project data, the social	• Create questionnaire (if need be-you may make minor amendments to questionnaires used in Step 3.) • Update contact list(s) for target audience(s) • Review sample size; modify if necessary, depending on the first action • Select new sample if need be • Determine dates for administering various pieces of questionnaires • Create advance letters, and cover letters • Administer questionnaire • Code and enter responses

Step 6	Complete a post-project worksheet addressing the questions that are related to the following: the capacity indicators, project outcomes, and lessons learned.	• Schedule input session for end-of-project questionnaire • Invite participants to input session • Develop questions for input session • Conduct focus group or other method to gather information from stakeholders • Complete post-project worksheet
Step 7	Statistical analysis of the survey data for reporting on the project's success	• Review statistical analysis based on the analysis tool used • Interpret statistics • Report data • Use knowledge gained to adapt approaches for future projects

CHAPTER 5: CONJUNCTIVE WATER USE MODEL OF SURFACE AND GROUNDWATER RESOURCES: A CASE STUDY OF ELIAS MOTSOALEDI LOCAL MUNICIPALITY, LIMPOPO PROVINCE

5.1 INTRODUCTION

Scarcity of water is a major problem in rural and urban areas of South Africa. Based on water availability per person, South Africa is classified as “water stressed” falling below the threshold of 1000-1666 m^3 per capita per year (Wallingford, 2003). Growing population further aggravates the situation; pollution of neighbouring water bodies and increasing demands for water among competing users. The fact that the country annual average rainfall is below 500 mm, pressures on available water resources are exacerbated. It is envisaged that the current water situation will worsen due to negative climate change impacts on water availability globally, and the fact that urban development across South Africa is not slowing down in developing. Transitions towards alternative approaches of managing water demand and supply dynamics are therefore of utmost importance. Traditionally, South Africa heavily depends upon surface water as an important source for provisions of water. It readily supplies the majority of the urban, industrial and irrigation needs through bulk water supply systems. However, studies show that through the local municipalities’ role as water service providers, the challenges remain to not only bring the water to the consumers but also supply the ever-increasing demands. In addition to being readily available, surface water is susceptible to a hydrological variation due to high evapotranspiration.

Alongside surface water is aquifer abstraction which is extensively utilised providing about 15% of the total volume consumed (DWAF, 2002). Over 300 towns and 65% of the population completely depend upon the groundwater resource for their water supply. Generally, in arid areas of South Africa, groundwater is the main source providing small towns with potable water. It is mostly perceived and associated with increased water security, which can be defined as “an acceptable level of water-related risks to humans (Bakker, 2012). However, from historical perspectives, given the focus on technology to the management of natural resources, surface water and groundwater development are not always without setbacks in South Africa. This can be attributed to the lack of systematic operationalising of sustainable water systems. Other obstacles facing the expansion of water resources range from piping costs to low yield from groundwater systems.

Excessive withdrawal of groundwater has been known to lead to serious environmental impact. Problems of groundwater contamination by human activities, particularly in locations with high population densities or concentrations of economic activity, land subsidence and seawater intrusion in coastal areas are among other associated with groundwater utilisation. Apart from obstacles in adding a new source, centralised urban water management approaches are experiencing “entrapment” by technology path dependencies (Brown et al., 2011). Specifically, it is easier to abide by the status quo than finding an alternative solution despite default arrangements not fulfilling their maximum potentials. However, being locked-in to conventional water systems has been known to limit urban or rural water development from accepting new more flexible approaches, which could increase resilience to increasing water stress (Brown et al., 2011). Against this background, conjunctive use of surface water and subsurface water can enhance the reliability of freshwater supplies (Yang et al., 2009). By this means, a robust water system can be developed where surface water fulfils most water demands during surplus rainfall while allowing subterraneous recharge of groundwater. Subsequently, the subterraneous stores of groundwater can provide a stable water supply during prolonged dry periods. The advantage of this approach has not been fully utilised in the urban water supply management of South Africa.

While supply can be increased by building new dams, South Africa storage capacity is already relatively well developed with a dam capacity equivalent to about two-thirds of the average annual flow in all its rivers (Muller et al., 2009). As the prospect of expansion of current water supply system is becoming slim, still there has been little work done in the past to integrate the decision with respect to the conjunctive use; a methodical allocation of surface water and pumping from the aquifer, to supply communities. A useful tool to develop conjunctive use management models is simulation-optimisation utilising the power of linear and nonlinear formulations to solve the large problems concisely (Singh, 2012). Therefore, an effort towards the formulation of a conjunctive model based on a simulation-optimisation approach to achieve operating rules is necessary and feasible. Optimisation techniques for water resources allocation through conjunctive use can be an important measure for ensuring water security for Sekhukhune District Municipality.

5.2 SEKHUKHUNE DISTRICT MUNICIPALITY: OVERVIEW OF WATER RESOURCES

Sekhukhune District Municipality is situated in Limpopo Province, the northern part of South Africa. The area is located within the summer rainfall region of South Africa, receiving more than 80% of its rainfall between November and March (Ziervogel et al., 2006). The region is characterised by a hot climate and unreliable rainfall and occasional droughts. Due to its peculiar topographic configuration, rainfall patterns are highly variable over intra- and inter annual time scales. Outside the band of wet periods, it is typically dry in most areas. The occurrence of rain is scarce and water availability can peak to crisis level most especially during sustained drought. Over the past decades, pressure on water demand continues to grow due to rural economic growth, increasing population and agricultural development as well as tourism. Therefore, increasing demand for water further places more challenges on water supply management in Sekhukhune District Municipality. This is especially true in surface and groundwater management. Water resources development is one of the key action programmes identified by the Limpopo Provincial Government in addressing contextualised priority areas to guide service delivery. The provision of sustainable water supply remains the key priority in the district municipality with the establishment of ward-based water committee to achieve the goal (IDP, 2018).

Being a Water Services Authority (WSA) and Water Services Provider (WSP), Sekhukhune District Municipality is more under pressure to deliver water to the estimated 740 villages within its area of jurisdiction. Water being the highest basic need of the local communities, the high needs for water supply vary from total lack of municipal water supply to intermittent water supply or boreholes that have dried up. In addition, another aspect outlined in the National Development Plan strategies for consideration by municipalities includes reducing demand. Current planning assumes it will be possible to achieve an average reduction in water demand of 15% below baseline levels in urban areas by 2030 (IDP, 2018). Achieving demand reductions on this scale will require programmes to reduce water leakage in distribution networks and improve efficient domestic and commercial water use that comes with prohibitive costs. Therefore, aligning the needs of the municipal district with appropriate water supply strategies is imperative for sustainable water supply in the municipal district.

The main water supplies sources in Sekhukhune District Municipality are surface water and groundwater. From records, the annual surface water from water treatment works, which is not all available to Sekhukhune District, is about 179.74 million litres per day (SDF, 2018). The annual groundwater supply is about 9.35 million m^3 that constitute roughly 50% of the Total Water Demand (SDF, 2018). Groundwater resources are a very important contributor to the total water supply, and groundwater is used all the year round in more than 75% of communities that solely dependent on groundwater. Information from the observation wells and monitoring wells indicated that the groundwater consumption is 25.61 million litres per day. Groundwater drawdown due to this practice of groundwater abstraction is more severe in Sekhukhune District Municipality. Groundwater levels are not only affected by hydrological characteristics of the area, but also by the drawdown-recovery cycle, which depends in part on the rate of groundwater use. While the part of goals of conjunctive use is to control the impacts of groundwater abstraction, the development of conjunctive use and evolution of policies will provide key inputs for this goal. This will ensure improved access to basic water services as projected from 83% in 2014 to 90% by 2020 (IDP, 2018).

Establishment of the National Water Act (NWA), (DWAF, 1998) divided South Africa into 19 water management areas (WMAs) for management purposes (Figure 1). The division lines follow the distribution of major river basins in the country (Muller et al., 2009). From National Water Resources Strategy report, nine of the 19 WMAs are suffering from a substantial deficit, which means they are using more water than what was reliably available from surface and groundwater (DWAF, 2004). In Limpopo Province and in particular Sekhukhune District Municipality, which is situated in the Olifants Water Management Area is affected with a substantial deficit (Table 5.1, Olifants WMA in comparison to other WMAs). The Water Management Area is highly stressed whilst also characterised by a fast growth in terms of population and development. There is limited opportunity for further water resources development and future development will need to rely on local sources of water. Although, an estimate of water availability in the NWRS include underground water which in most cases constitutes about 8% at the national level (Muller et al., 2009). Therefore, resources challenge begins at individual river basins and best addressed at that local level.

Table 5.1 Reconciliation of water requirements and availability (million m^3 p.a.)

Water management area	Reliable local yield	Transfers in	Local requirements	Transfers out	Balance
Usutu to Mhlathuze	1010	32	693	114	235
Upper Vaal	1723	1443	1204	1481	481
Olifants	611	172	971	8	(196)
Lower Vaal	50	651	653	0	48
Middle Vaal	201	791	389	605	(2)

Note: Bracket indicates deficits

With the lowest access to infrastructure, Sekhukhune District Municipality has water supply challenges for residential and agricultural use. Water availability is a lingering problem in the District due to a lack of stock water facilities and many boreholes are dysfunctional. Sekhukhune District Municipality hosts three (3) dams that are not completely for bulk water supply. Flag Boshielo Dam, which is located in Marble Hall, has been raised by five meters to boost district water capacity. The Flag Boshielo dam has been identified as a candidate to provide an opportunity for tourism development and water source for agricultural purposes. Loskop Dam irrigation water scheme is situated in Ephraim Mogale Local Municipality within an intense farming area and De Hoop Dam in Makhuduthamaga Local Municipality, which hosts two (2) growth points; Jane Furse Provincial Growth point and Phokwane municipal growth point. The later growth point is regarded as an agricultural node.

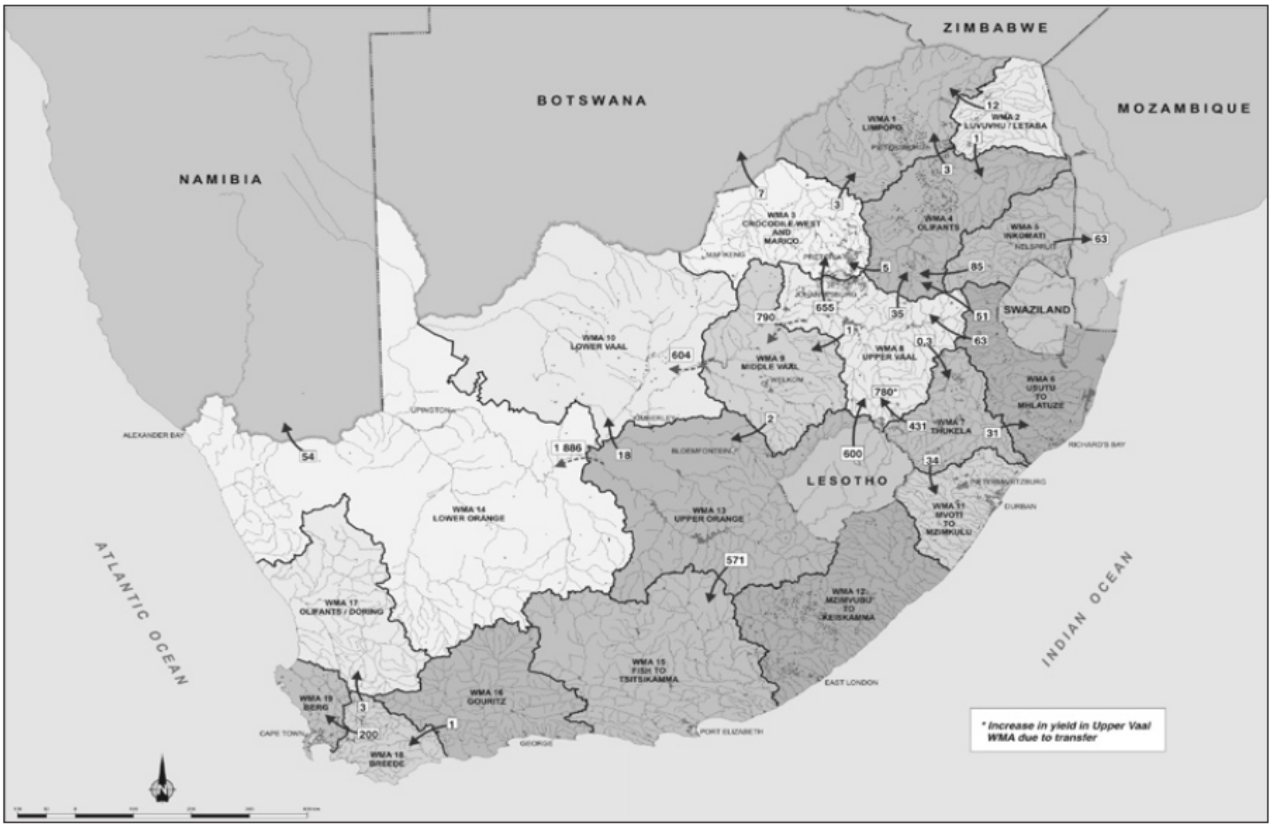


Figure 5.1 Location of water management areas and inter-water management area transfers

In Sekhukhune District Municipality (SDM), Ephraim Mogale and Fetakgomo local municipalities have the best water reticulation in the district but with no bulk water supply. Elias Motsoaledi, Makhuduthamaga and Greater Tubatse local municipalities are experiencing the most challenges in water access. Groundwater is a major water resource for most Sekhukhune households with 92% of households in Tubatse, 87% in Fetakgomo and 16% in Ephraim Mogale solely reliant on groundwater. Apart from surface reservoir and groundwater, other forms of water sources found in Sekhukhune District Municipality are wells, rivers, and pools.

Given the noted water deficit in SDM (Table 5.1) and the noted reliance on groundwater by the residents in the district, a delicate management system of the surface and groundwater resources need to be put in place to safeguard against over-utilisation of these resources in a bid to meet the consumer water demand in the district. Previous studies and outcomes of this study, which was done through consumer need surveys, indicate that the use of groundwater in meeting the daily demand is prevalent and will continue to be so especially in the rural parts of the district. One such management tool is the development of operational rules on the conjunctive utilisation of surface and groundwater.

5.3 AN OVERVIEW OF THE OPTIMISATION TOOLS FOR CONJUNCTIVE USE

The optimisation models for conjunctive use of surface water and groundwater allocation are often complicated, nonlinear, and computationally intensive, especially when different stakeholders are involved that have conflicting interests (Bazargan-Lari et al., 2009). Similarly, Conjunctive use management model for optimising operating rule to boost water supplies for Sekhukhune District Municipality is a complex problem. This is due, in part, to the challenges of managing conflicting interests in both surface water and groundwater separately. The difficulty increases as one must represent the response of both systems interactions and develop management strategies that simultaneously address surface water and aquifer regulation (Safavi et al., 2009). In addition, while some simulation model may use analytical equations to predict physical system response to management (Peralta et al., 2004), explicit solution through direct use of analytical approaches is feeble in the cases of conjunctive use that involve abstraction wells. Therefore, conjunctive use models are generally formulated as optimisation models (Reichard, 1995, Safavi et al., 2013, Wu et al., 2016).

Traditionally, conservative approaches based on simulation-optimisation models that are parameterised by parameters, which are already covered by existing generalised modelling tools are usually employed (Wu et al., 2016, Seo, 2018, Yousefi et al., 2018, Sepahvand et al., 2019). This increases the accurate operation of a conjunctive use model, by capturing the behaviour of physically independent and integrated surface water and groundwater systems, such as a reservoir (or a lake) and its connected aquifer (Pan et al., 2016). The decision variables of the optimisation model are usually allocations of surface water and groundwater in each planning period.

According to Vedula et al. (2009), since the governing partial equations for complex heterogeneous groundwater and stream-aquifer systems are not amenable to closed-form analytical solution; various numerical models have been used for the solution. For a problem under consideration, the conjunctive use models can be grouped, into linear programming models, dynamic programming models, hierarchical optimisation models, nonlinear programming models, evolutionary algorithms, and simulation-optimization models based on assumption used (Safavi et al., 2010).

Linear programming has been applied successfully in conjunctive use optimisation modelling (Ghahraman et al., 2004, Mani et al., 2016, Seo et al., 2018) and extensively most often used for irrigation management because of its easy formulation and application (Zhao, 2017). In a recent study, El Amami et al. (2019) applied a chance constraint linear programming model. It was used to analyse the economic profitability of irrigation under hydrological risk. The model incorporated the uncertainty of water supply at certain exceeding probability thresholds, which gauged the impact of a small dam on the profitability of the local farming economy. As reported by Yang et al. (2009), an optimal cropping pattern for optimal use of water resources for maximisation of net benefits has been examined by Deepak Khare and Jat (2006). This proposed a simple economic engineering optimisation model using linear programming with various hydrological and management constraints.

To explore the possibilities of conjunctive use of surface and groundwater, Raul and Panda (2013) considered linear programming as one of the best optimisation tools for optimal allocation of land and water resources in irrigated agriculture. However, in various optimisation studies based on linear programming, all functions and constraints must be defined as linear because the programming is linear. This negates both discrete and nonlinear terms of surface and groundwater system.

Conjunctive use models based on dynamic programming have been used due to their benefits in sequential decision-making processes and their applicability to nonlinear systems (Safavi et al., 2010). Rao et al. (1988) established a dynamic programming optimisation model for irrigation scheduling for a single crop that is applied to a field problem for cotton. In another study, Chen et al. (2014) successfully applied hierarchical optimisation models for the large-scale conjunctive use of surface water and groundwater resources. The approach aimed to maximise public and irrigation water supplies subject to groundwater-level drawdown constraints.

Largely because most conjunctive use problems are nonlinear, nonlinear programming, which is capable of handling nonlinear problems has been reported (Garg and Dadhich 2014, Zarghami et al., 2015). Matsukawa et al. (1992) solve optimisation model using a large scale, nonlinear programming algorithm. The results of the study indicated that conjunctive use management is a viable tool for multi-objective water resources planning problems.

The complexity of groundwater-management problems, especially in the conjunctive use of surface and groundwater resources, usually leads researchers to use evolutionary algorithms (EAs), which are search methods that take their inspiration from natural selection and survival of the fittest in the biologic world (Bazargan-Lari et al., 2009). An EA is a subset of evolutionary computation, a generic population-based metaheuristic optimisation algorithm. Evolutionary techniques such as genetic algorithm (GA), simulated annealing (SA), etc. have been used as a tool for solving the optimum conjunctive management models, because of their relative efficiency in identifying global optimal solutions especially for nonlinear non-convex problems (Safavi et al. 2010). Fanuel et al. (2018) presented reviews of a set EAs and their application to solving the multi-objective problem in agricultural water management. The paper focused on different application aspects, which include water allocation, irrigation planning, crop pattern and allocation of available land. As reported by Ikudayisi et al. (2018), the major difference between the classical optimisation techniques and soft computing, according to Azamathulla et al. (2008), is that in classical methods, the optimal solution is derived, whereas, in the soft computing techniques, it is searched from a randomly generated population of possible solutions. Evolutionary algorithms (EAs) go for the discovery of the optima from a population of solutions rather than from a single point which makes them suitable for solving complex design issues (Reddy and Kumar, 2007).

According to Reddy and Kumar (2006), traditional mathematical programming techniques have failed to offer several elements of Pareto set on a single run. Some of the mathematical programming techniques are very sensitive to the shape or continuity of the Pareto front. As already known, conjunctive use management problems are nonlinear in nature, despite that fact, the application of nonlinear programming has been rather limited (Vedula et al., 2005). The reason for this may be the complex nature and slow rate of convergence of the nonlinear programme algorithms, as well as difficulty in considering stochasticity and probability of getting a local instead of the global optimal solution. In general, the accuracy of the model prediction depends on the reliability of the estimated parameters as well as the accuracy of prescribed initial and boundary conditions.

Based on snags in the approaches, the conjunctive use problem is best formulated as a combined simulation-optimisation model. Gorelick (1983) established the fact that it is almost impossible to achieve optimal groundwater management alternatives by using simulation techniques alone. Therefore, the combined use of simulation and optimisation models needs to be considered. In recent years, researchers have actively sought to couple acquired simulation models with mathematical optimisation techniques to address important groundwater management issues. Xuefung chu et al. (2001) identified joint simulation and optimisation modelling techniques that provided optimal water planning and management strategy for the decision makers. Embedding technique and response matrix approach are the two methods generally used to incorporate the simulation model within the management model (Gorelick, 1983). Shirahatti and Khepar (2007) incorporated a simulation model of a groundwater flow model with a chance-constrained linear programming model, developed for surface water allocation and coupled with response matrix to assess water availability, water need and water balance.

Simulation models account for the physical behaviour of surface water-groundwater systems, whereas optimisation models account for the conjunctive management aspects of the system (Basagaoglu and Mariño, 1999). One of the primary advantages of the simulation-optimisation model is that; it provides a structured means to evaluate trade-offs between the sustained rate of groundwater withdrawals and surface water depletion (Barlow et al., 2003). Furthermore, when there are multiple objectives to fulfil, there is a tendency no single optimal outcome and trade-offs occur between them. Despite the development of conjunctive use analysis techniques, efficient large-scale optimisation models are lacking. As such, the linked simulation and optimisation approach is more appealing. In addition, this is due to its accountability for the complex behaviour of the groundwater flow system. It identifies the best management strategy under consideration of the management objectives and constraints. Simulation optimisation can assess the benefits of conjunctive use and identify optimal operation policies or capacity expansion of the system. Based on the capability to handle complexities of the problems, therefore, the management tool considered for the surface water and groundwater optimisation of Sekhukhune District Municipality was simulation-optimisation.

5.4 THE CONJUNCTIVE USE MANAGEMENT TOOL

Urban water use through conjunctive use of water from different sources adds a new dimension of usage and management issues compared to single source use of water. Thus, require that a set of decisions be made at both the application level and the water resource level that enables water users to make the best possible use of all available water.

Managing the aspects of the surface water, the study considered the stream flow distribution and storage capacity of reservoirs for the conjunctive use management tool. The complex nature of the groundwater flow system such as the geology of the subsurface water basin and hydrology of the surface water system are given due weights. In the groundwater flow system, safe yield, transmissivity, response recovery time and interaction with existing wells are considered.

For planning development of the conjunctive use management tool, the embedded mathematical model simulates and predicts the system response to the management and pulse stimulus (such as pumping for a brief period) upon hydraulic heads at point of interest throughout a system (Shirahatti and Khepar, 2007). The simulation model output is linked to the optimisation model for optimal and feasible ways to increase water resources use efficiency.

In the light of this, in Sekhukhune District Municipality, the following three rules are considered for the development of conjunctive use management tool:

1. Enable full use of surface water; decrease possible reservoir surplus.
2. Utilise the interference wells and the regulatory functions of aquifer space and minimise aquifer depletion.
3. Utilise first the surface water embedded within minimum reservoir storage.

5.5 MODEL FORMULATION

Primarily in this section, an overview of the overall model is presented. The model mechanisms with its associated components used in model development are shown. The concept of a conjunctive use model as used in the present study is discussed. The methodology of arriving at a conjunctive use model and its application in Sekhukhune District Municipality are presented in the next section.

5.5.1 Overview of the model framework

A schematic framework of the conjunctive use system is presented in Figure 5.2. The main components of the conjunctive use management tool consist of surface and groundwater reservoir. The dynamic relationships and mutual effect on each other are quantified by the mathematical formulas.

For development of water resources management tool with the aim of optimising the conjunctive use of surface and groundwater in Sekhukhune District Municipality, the objective function was chosen for minimising water supplies deficit by considering constraints applied in the model. The methods in the model development and requirements for each of the components are discussed in the following sections. Figure 5.2 presents a conjunctive use simulation-optimisation framework.

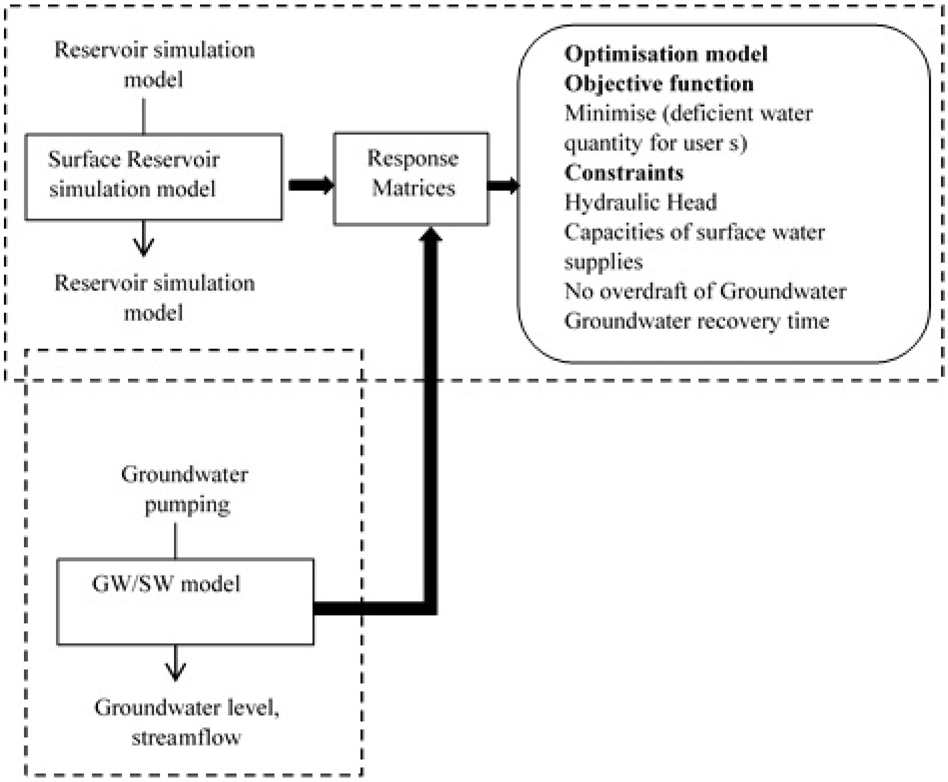


Figure 5.2 Conjunctive use simulation-optimisation framework

5.5.2 Model development

The numerical groundwater flow model is central to the developed conjunctive use management tool for Sekhukhune District Municipality. The substrate of the model development is a groundwater flow model upon which others are coupled. Based on water requirements and hydrogeological settings of Sekhukhune District Municipality, a quasi-two-dimensional groundwater simulation model was developed through a numerical finite difference approach. The numerical unsteady groundwater flow model forms a compound model, consisting of heterogeneous isotropic confined and the unconfined aquifer mimicking the study area. The study area was divided into rectangular cells.

A divergence of the mathematic model into a finite difference equation was achieved by Gaussian regression process, from which procedures are programmed to solve the equation. The calibration and verification of the model were conducted by comparing the model output with the corresponding measured values. A different set of measured data was used to validate the model and generate response functions used in developing a transient response matrix. The flow simulation model and the optimisation model are coupled by the response matrix for optimal groundwater abstraction. Each unit response describes the influence of a pulse stimulus. By coupling the groundwater simulation model with multi-objective optimisation programming model, a supply-demand conjunctive use water resources management model was achieved.

In optimisation, an optimisation model with the objective minimisation of total deficiency was applied. The model assumed the initial facilities for water supply are fixed and are not changed with time. The objective function consists of minimising the total water deficiency while satisfying all water demands in the command area. Equations 5.1 to 5.6 provide the numerical expressions (models) used in building up the final model.

$$Min.\, x_m = \sum_{i=1}^{n} Q_{D,i,m} \qquad i = 1,2,3, \ldots \ldots n \qquad [5.1]$$

Where: $Q_{D,i,m}$=Total water demand of user *i* in the command area, m, [L^3]

For the prevention of groundwater resources from been depleted through well-sustained pumping, contamination and degradation of well, a weighting factor is allotted to Equation 5.1. Thus, the final objective function is given as:

$$Min.\, x_m = \sum_{i=1}^{n} \beta_i Q_{D,i,m} \qquad [5.2]$$

Where: β_i= weighting factor for groundwater depletion objective function for *i*

The objective function in the optimisation problem was subjected to the following set of constraints linking the hydraulic head of the unconfined and confined aquifers (Equations 5.3-5.4), capacities of the surface reservoir water supplies (Equation 5.5) and obstruction of overdraft of groundwater resources (Equation 5.6). This is achieved by:

$$K_{i,H,min} \leq K_H - K_s \leq K_{H,max} \qquad [5.3]$$

Where: $K_{i,H,min}$ is allowable minimum hydraulic head at *i* [L], $K_{i,H,max}$is allowable maximum hydraulic head at *i* [L], $K_{i,H}$ is hydraulic head at *i* [L], K_s is drawdown at *i* [L]. At the pumping wells, the drawdown must not exceed the desired values for all time steps. Using the transient functions, these constraints can be expressed as:

$$I_s = \sum_{i=1}^{n} \gamma_i Q_{g,i,m} \qquad [5.4]$$

Where: I_s is drawdown at cell *i*, γ_i is Objective weighting factor for groundwater yield from *i*. and $Q_{g,i,m}$ is pumped groundwater from cell *i* in command area m [L^3].

$$\sum_{r=1}^{m} \sum_{i=1}^{n} Q_{r,i,m} \leq \sum_{i=1}^{n} W_r \qquad [5.5]$$

Where: $Q_{r,i,m}$= surface water from source *r* to command area m, W_r= surface water reservoir capacity [L^3].

$$\sum_{r=1}^{m} \sum_{i=1}^{n} \mathrm{Q}_{g,i,m}^{j} + \sum_{i=1}^{n} Q_{g,i} \leq Q_{g,n} \qquad [5.6]$$

Where: $\mathrm{Q}_{g,i}^{j}$ groundwater pumped from aquifer *i* for user *j* in command area m [L^3].

$Q_{g,i}$ Groundwater pumped from cell *i* [L^3]

$Q_{g,n}$ Overall natural groundwater recharges in part [L^3]

5.6 MODEL APPLICATION

5.6.1 Study area water resources

Based on the available supplies from Water Treatment Works and permissible yield from the groundwater reservoir, the developed conjunctive use management tool is applied to determine the optimal water supplies in Sekhukhune District Municipality. The model application is demonstrated through a case study of existing reservoirs for Elias Motsoaledi Local Municipality as presented in Figure 5.3.

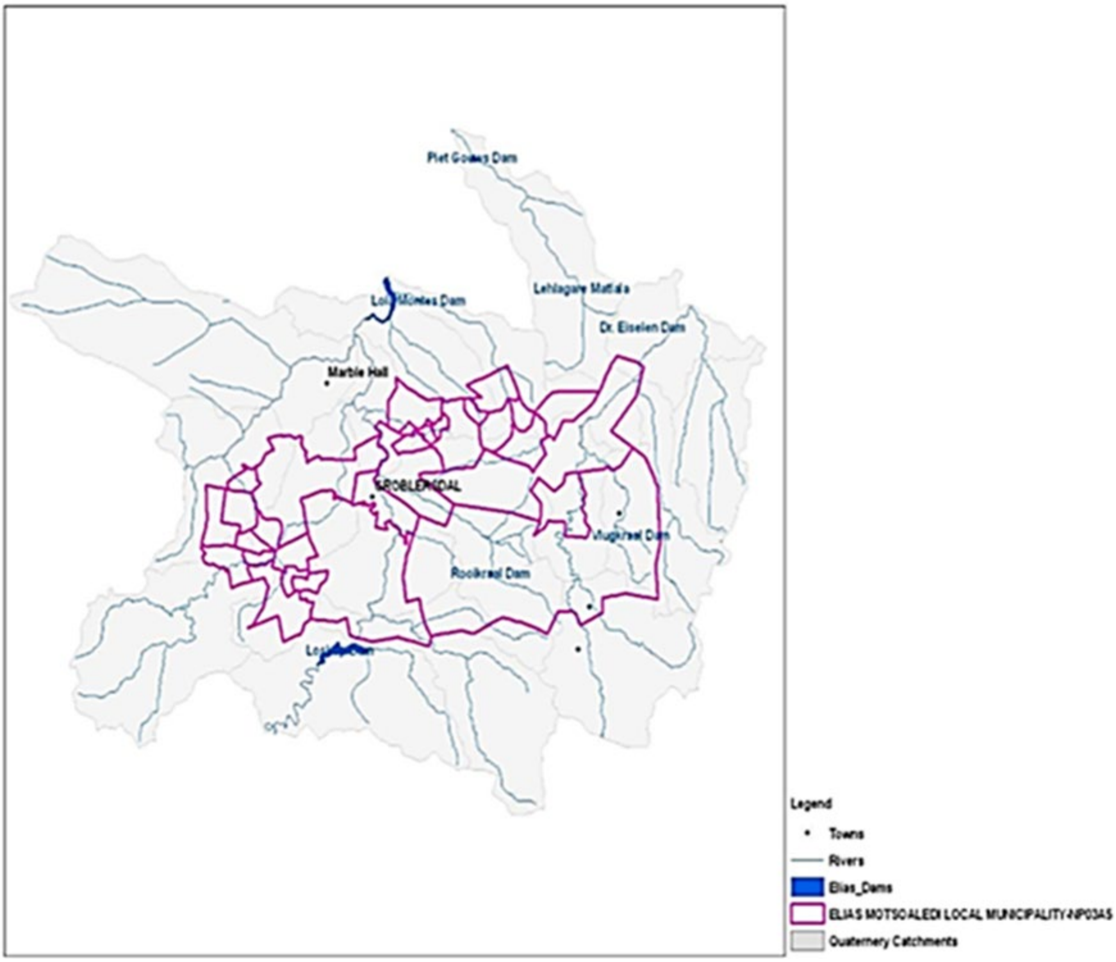


Figure 5.3 Location map of the reservoir

5.6.2 Elias Motsoaledi Local Municipality

Elias Motsoaledi Local Municipality is one of four local municipalities of Sekhukhune District Municipality with the reticulated network among the other local municipalities. The surface water resources in Elias Motsoaledi Local Municipality are comprised of Olifants and Tonteldoos rivers. Although no dams have been constructed within Elias Motsoaledi Local Municipality area of jurisdiction, however, the municipality makes use of a number of sources. The following is the listing of the sources with their associated problems:

1. Loskop Dam – The dam is approximately 30 km long with a full capacity of 348.1 million m^3 and supplies water to most irrigation schemes in the area of Loskop, 67 000 ha of Groblersdal and Mable Hall.
2. Mahlangu Dam – Water Treatment Works is currently not in operation due to vandalism.
3. Nkosisni weir – currently not working due to vandalism.
4. Spitzkop dam – dam is full to capacity but not in use.
5. Olifants River – supplying water to Groblersdal Water Treatment Works.
6. Tonteldoos River – supplying water to Roossenekal Water Treatment Works and
7. Rooikraal Dam – this is empty most of the time.

In terms of functionality, Olifants and Tonteldoos rivers are the main sources of surface water for Elias Motsoaledi Local Municipality. The surface water sources supply Groblersdal Water Treatment Works (GWTW) (Figure 5.4) and Roossenekal Water Treatment Works (RWTW) (Figure 5.5), which are then reticulated for Roossenekal Area and Groblersdal town/Motetema Area. Groblersdal Water Treatment Works and Roossenekal Water Treatment Works both have gross reservoir capacities of 20.4 ML. On one hand, Groblersdal Water Treatment Works with a design capacity of 23 ML/day abstracts water from Olifants River.

On the other, Roossenekal Water Treatment Works of 0.4 ML/day design capacity abstracts its water from Tonteldoos River having flow capacity between 500-700 kL/day. The estimated total of water demand for the whole areas is 3.4 ML/day, which is about 6.6% of total existing water use of Sekhukhune District Municipality.

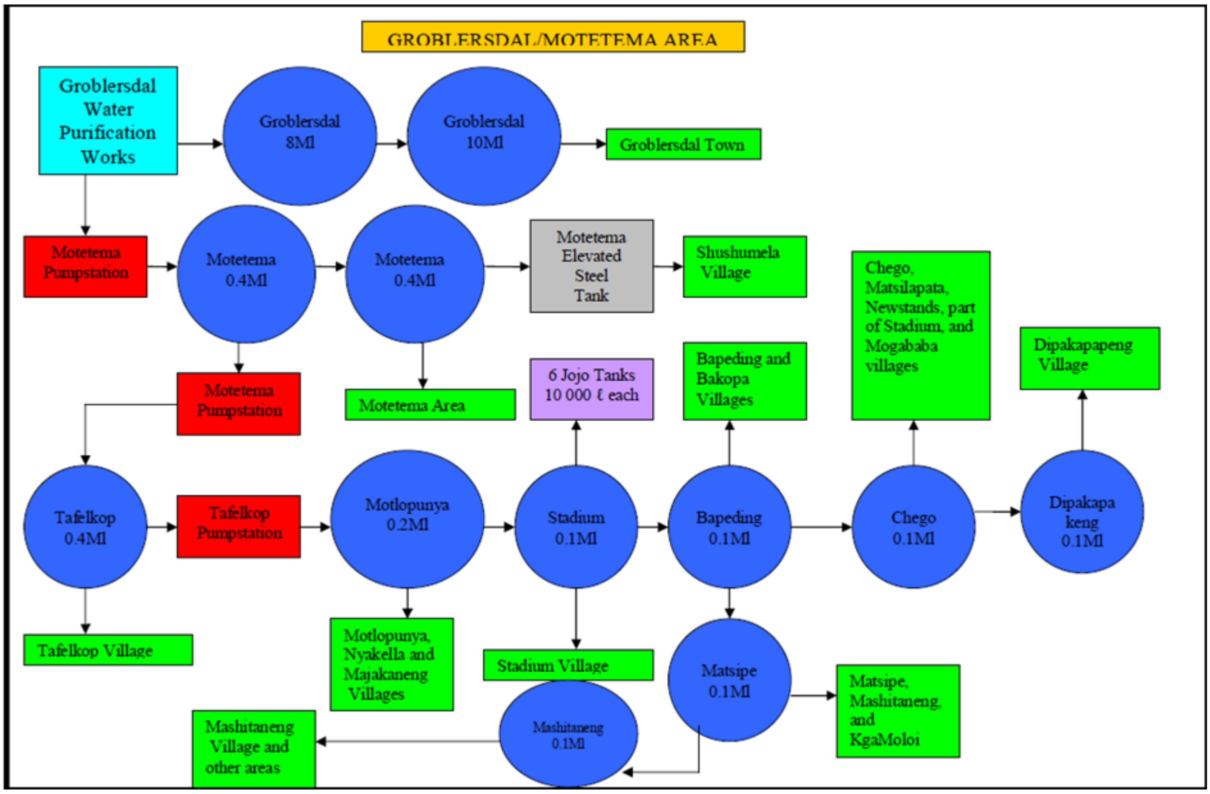


Figure 5.4 Groblersdal/ Motetema area reservoir distribution

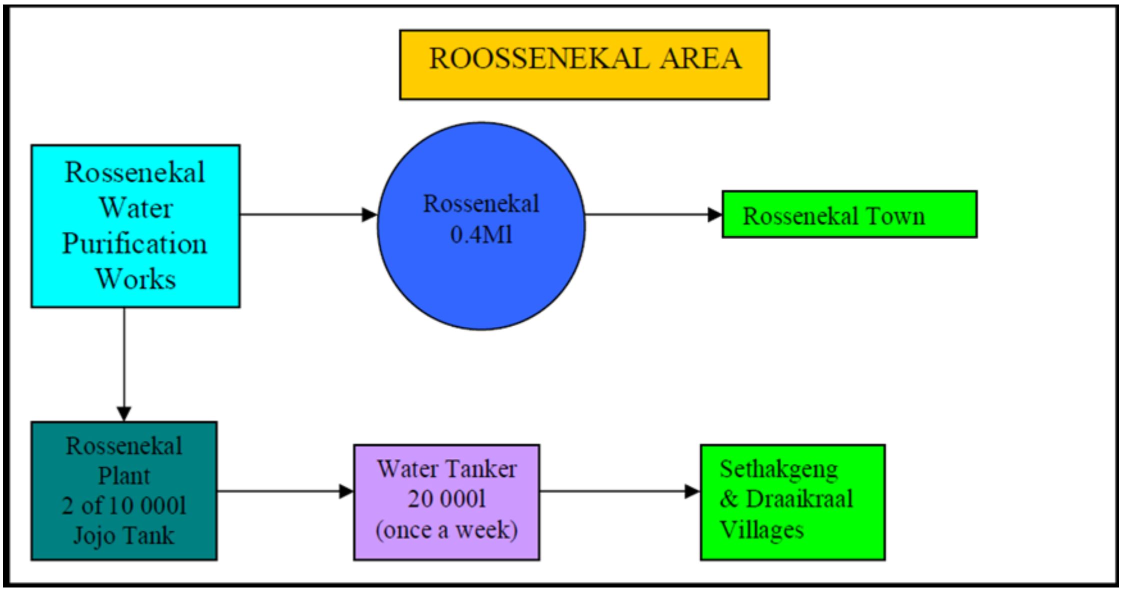


Figure 5.5 Roossenekal Area reservoir distribution

5.6.3 Surface water data

Considering the use, a decision interval spanning 30 days period is selected for the case study. In a year, twelve decisions are taken and the interval between each decision is a 30 days period in a wet year. A wet year is considered to begin from June 1 and ends May 31. The mean annual rainfall in the command area is 620 mm based on 10 years of historical records from January 2006-December 2016. Based on the Mean Annual Precipitation (MAP) in the surrounding area, assuming recharge being 2% of MAP, the rainfall recharge is approximately 702 m^3/a. Figure 5.6 presents a mapping feel of the hydrology of SDM while Table 5.2 gives the average inflow to the reservoir, pipeline loss, consumption and average rainfall in the command area for each of the 12 decision intervals for the whole year. The first period starting from June is taken as the beginning of the wet year.

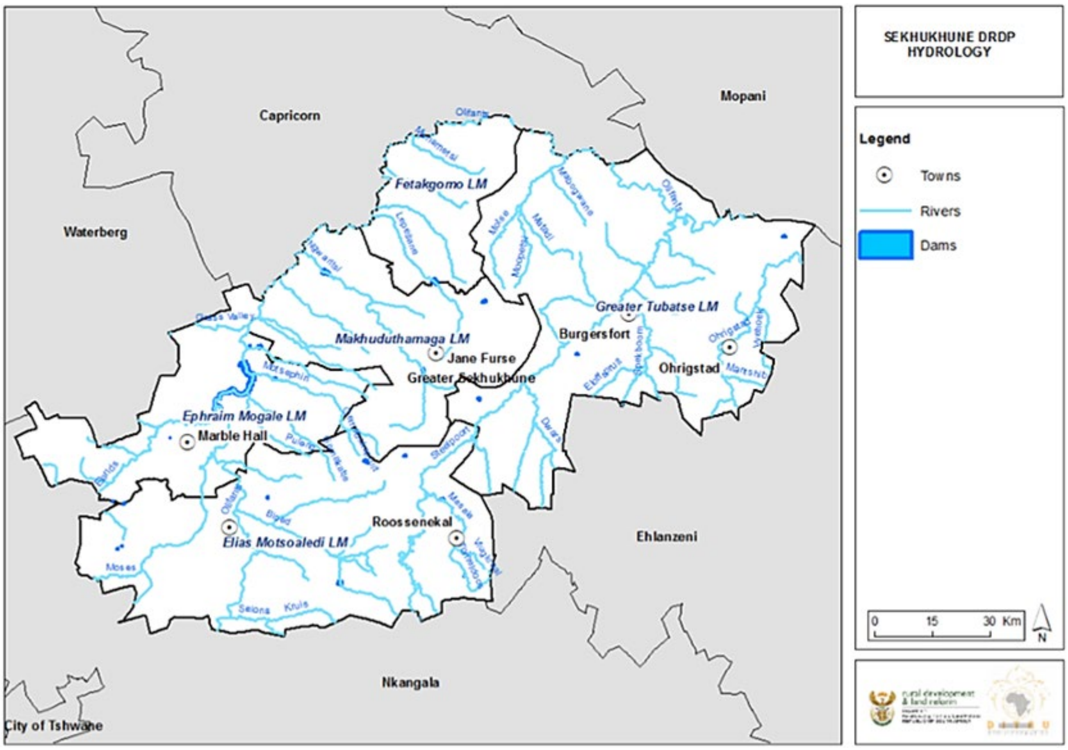


Figure 5.6 Sekhukhune District Municipality Hydrology

Table 5.2 Inflow from WTP, pipeline loss, consumption statistics

Decision interval	Inflow (m^3)	Pipeline loss (m^3)	Consumption (m^3)	Rainfall Ave (mm)
1	283.950	15.67	268.28	5.69
2	233.660	15.13	218.53	5.87
3	221.150	12.64	208.51	7.47
4	263.979	24.136	239.843	10.12
5	296.757	24.265	272.492	49.45
6	266.795	27.324	239.471	83.23
7	258.596	24.477	234.119	105.09
8	315.941	31.856	284.085	124.89
9	267.737	10.125	257.612	101.62
10	310.651	0.39	310.261	69.41
11	192.760	6.94	185.82	53.12
12	288.990	38.7	250.29	18.73

In addition, Table 5.2 shows the periodic consumption in the command area with pipeline losses incurred by the municipality that varies from 0.390 kL to 38.7 kL in decision period 10 and 12 respectively. The lowest pipeline loss period has a medium range rainfall record while the highest pipeline loss period has a low range rainfall record. Such observations need to be investigated as they do have significant influence on the operation rule of the conjunctive use model.

Groundwater plays a major role as a source of potable water for most of the Elias Motsoaledi communities. Elias Motsoaledi consists of Minor Aquifer Types, which can generally supply communities of 1 800 people from a single borehole at 30 L/c.d. However, there is no formal or regular groundwater monitoring and testing of water quality from the boreholes. Nearly 50% of the boreholes are not in operation and groundwater information is limited.

For this study, the limited local data is supplemented with information gleaned from DWS Water Services Assessment records for the study area. Table 5.3 presents the outcome of Water Services Assessment by DWS, a summary of the quaternary of Water Resources of Elias Motsoaledi. The outcome of the Water Services Assessment Model (WSAM) quaternary water resources indicates a total of 255.9 m^3/a surplus in and out. This demonstrates the potential of exporting and developing water resource.

Table 5.3 Elias Motsoaledi Local Municipality quaternary water resources

Summary of Water Resources			
Water Resources		Water Requirements	
million M^3/a		million M^3/a	
Surface	**545**	Irrigation	199.1
Groundwater	**54.6**	Urban	10.6
Return Flows	**18.2**	Rural	23.3
Transfer IN	**50.9**	Mining & Bulk Industrial	5.3
		Ecological Reserve	123.6
		Transfer OUT	50.9
TOTAL	**668.7**		412.8

5.6.4 Groundwater data

Monthly observations of groundwater level at 10 observation wells in the study area were taken. From historical rainfall data, the wet year with actual rainfall of 620 mm is taken as the normal hydrological year or a normal year. Monthly groundwater levels are determined for this normal rainfall year. The initial and boundary conditions at various cells in the study area are specified from these groundwater levels by interpolation.

The aquifer parameters are taken for each cell in the command area as S_y =0.03 and T= 49 m^2/day based on existing technical information pertaining to the study area. Groundwater levels are restricted to 1 m to prevent over drafting.

5.7 RESULTS AND ANALYSIS

Table 5.4 depicts the results of the optimisation using the earlier linear programming model and the corresponding optimal distribution of hydraulic heads in both confined and phreatic aquifers in the area of study. From the model, optimal allocations of water resources, that is, optimal conjunctive use of surface water and groundwater resources between various users in the applied study area are presented. The solution of the optimisation problem gives the optimal water supplies of 205.214 m^3 and 4.7 m^3 for surface water and groundwater respectively for the command area with the lowest deficit (command area 9). The minimum water supplies deficient of 6.15 m^3 was achieved for the optimal water supplies, which is about 0.18% of total existing water use of the study area. The initial water demand ratio of surface water to groundwater in the study area benchmarked at 2:1 shows there is a better improvement at the current optimal ratio of 44:1, in that way lowering the risks associated with aquifers over abstraction. However, the results depict that dependence on surface water supplies to fulfil water requirements of the study communities will go right into the future under the status quo scenario. This could be different however with the expected future scenarios of growth and development in designated special economic zones and development/growth nodes in the SDM. While optimal water supplies of users' current water demand are, mostly satisfied, optimal water supplies cannot be satisfied in some instances if over abstraction control for groundwater system is not maintained. This can be attributed to the uneven spatial distribution of the water infrastructure in command areas.

Table 5.4 Optimal water allocation of water resources for consumers (Unit: m^3)

Command Area/water infrastructure	**Command Area Water Demand**	**Groundwater supply**			**Surface water supply**			**Deficient water supply**
		Phreatic consumers	Confined Aquifer consumers	Total	GWTW	RWTW	Total	
1	331.363	1.7	3.2	4.9	258.280	11.563	269.843	56.62
2	279.112	4.1	0.2	4.3	233.660	13.412	247.072	27.74
3	245.562	2.3	1.2	3.5	198.310	18.632	216.942	25.12
4	319.172	3.2	0.3	3.5	241.774	12.548	254.322	61.35
5	356.576	6.5	0.5	7.0	270.472	19.124	289.596	59.98
6	271.203	6.5	3.1	9.6	238.365	16.458	254.823	06.78
7	326.977	2.6	0.2	2.8	223.712	15.325	239.037	85.14
8	345.590	3.7	4.4	8.1	284.085	12.756	296.810	40.68
9	216.064	4.5	0.2	4.7	187.240	17.974	205.214	06.15
10	328.639	5.5	0.1	5.6	241.774	19.005	260.779	62.26
11	344.773	1.8	1.1	2.9	256.023	16.010	272.033	69.84
12	279.335	2.4	0.4	2.8	243.190	11.025	254.215	22.32
13	324.980	4.6	1.2	5.8	271.365	13.365	284.730	34.45

Note: GWTW = Groblersdal Water Treatment Works; RWTW = Roossenekal Water Treatment Works

CHAPTER 6: CONCLUSIONS & RECOMMENDATIONS

6.1 CONCLUSIONS

6.1.1 Scoping

A successful scoping of the study was completed through a comprehensive literature review on Hybrid Water Supply Systems and Conjunctive Water Use highlighting the Challenges and Opportunities. The literature review highlighted the following: current information on the global scale regarding the water situation expressly the urban water cycle; information on water supply systems from the conventional centralised systems to the decentralised systems, and additionally, information on the current paradigm shifts in municipal water supply that combines both centralised and alternative water supply systems that define the Hybrid Water Supply Systems with an outline of the advantages, disadvantages and challenges of the various systems; and general information on Conjunctive Use of Groundwater and Surface Water Resources.

6.1.2 Domestic rainwater harvesting frameworks

Based on previous studies, a framework for estimating domestic rainwater harvesting (DRWH) potential was deduced. However, as evidenced in the literature review, glaring gaps in the deduced framework were evident in that most of the hitherto proposed rainwater harvesting potential methodologies primarily concentrated on the quantity of the available rainwater. The flaw in this approach is in the focus on the rainfall element with little attention on other important elements of a rainwater harvesting system such as storage, the intensity of usage, economics (economic feasibility), as well as the environment (environmental impact of rainwater harvesting on the catchment hydrology) and socio-economic acceptability of the selected RWHS. In an attempt to address this gap, the authors developed and proposed a revised framework for estimating DRWH potential and selection of optimal RWHS(s). The presented revised framework addresses and incorporates other determinants such as economic potential (through a life cycle analysis – LCA), social acceptance surveys through the inclusion of the Socio-economic acceptance index (S-eI) and additional environmental indicators such as the energy use potential (EUP) and the Global Warming Potential (GWP) that address the ever-growing need of incorporation the water-energy nexus (WEN) as an integral part of the design of a water supply system. Other elements incorporated in the revised framework include the Environmental Risk Scores (ERS). ERS are derived through an analysis of the contribution of RWHS facilities or components such as HDPE tanks used for storage of harvested rainwater in the release of carcinogens and/or respiratory organics and Greenhouse gas emissions. The development of a revised framework for estimating DRWH potential and selection of optimal RWHS(s) is a major contribution of this study. Other major contributions include: the development of the following submodules of the main framework: a framework of rainwater energy nexus (RWEN) analysis for a rainwater harvesting system; and a global warming potential (GWP) analysis framework of a rainwater harvesting system.

6.1.3 Stormwater harvesting systems and monitoring frameworks

A framework for the harvesting and treatment of stormwater as well a monitoring framework were successfully developed. The stormwater harvesting and treatment framework outlines the requirements to identify, select and set up a combination of processes and procedures that translate to a stormwater treatment train. The treatment train being a combination of Best Management Practices (BMPs), either in parallel or in series, with different processes or a singular BMP that exhibits a combination of processes within its structure such as a constructed wetland. In this case, stormwater treatment entails the processes and procedures to remove or contain stormwater volumes from the point of its generation and reduce or eliminate stormwater pollution load. The framework for monitoring the progress of a stormwater treatment project was also developed. A key parameter in this monitoring framework is the Social Indicators (SI). Social indicators for Non-Point Source (NPS) management provide information about awareness, attitudes, constraints, capacity, and behaviours that are expected to lead to water quality improvement and protection. The inclusion of SIs as a submodule of the stormwater harvesting and treatment framework is also a major contribution of this study as it presents an integrated approach to developing sustainable stormwater harvesting systems through the aggregate LID-BMPs system with a monitoring component that sets parameters that monitor progress of stormwater harvesting projects.

6.1.4 Conjunctive water uses modelling of surface water and groundwater resources

A generic simulation-optimisation conjunctive water use model was successfully developed and applied to the EMLM. In the application, optimal solutions to supplies of scarce water resources of Sekhukhune District Municipality have been achieved through the application of the simulation-optimisation approach. The developed conjunctive use management tool has been used to appropriate the allocation of surface and groundwater resources of the study area. The findings illustrate that daily demand can be reasonably met without leading to over-abstraction of groundwater resources by minimum deficient of water supplies of 6150 litres. From the data used, this deficiency is less than 1 percent of total water demand. The performance of the model shows a marked improvement over current experience in a region where water scarcity has peaked to crisis level. The current reliance on surface water is envisaged to linger into the future as optimal water supplies show more improvement in surface water resources over groundwater at a ratio 43:1, which result in healthy aquifer conditions. However, failure to implement the water supply infrastructure maintenance will result in a water crisis, having a severely negative impact on groundwater resources and water services delivery in the Sekhukhune District Municipality. Generally, the developed conjunctive use management tool can be applied to other local municipals in Sekhukhune District Municipality.

6.2 RECOMMENDATIONS

6.2.1 Scoping

In spite of a successful collation of a scoping of the study through a comprehensive literature review on Hybrid Water Supply Systems and Conjunctive Water Use highlighting the Challenges and Opportunities, it should be noted that literature, being a constantly changing element of a document, implies that the contents provided in this document is subject to change as and when new or divergent information is available, verified, justified and authenticated.

6.2.2 Domestic rainwater harvesting frameworks

The proposed revised framework for estimating DRWH potential and selection of optimal RWHS(s) is considered a great improvement of the previously deduced framework. It is however not a panacea framework but subject to further improvements even though in its current form it addresses and incorporates critical elements of a comprehensive design of a RWHS. Elements such as the WEN analysis, GWP, EUP, and S-eI that were hitherto treated in isolation, have now been enlisted as key parameters of design and selection of a RWHS. At this stage of the report, it was difficult to obtain the requisite data in form, quantity and quality to evaluate the rainwater harvesting potential in quantity as a case study to verify the implementation of the framework. However, the tenets of the framework are based on sound literature review, desktop study and anchored on verifiable solid theoretical background. It is recommended that case studies in conjunction with a set of comparative studies should be conducted to evaluate the robustness of the proposed revised framework. The results obtained thereof should then be used as a verifiable yardstick to endorse and/or improve the proposed revised framework. An envisaged challenge is to obtain the requisite data in form, quantity and quality to evaluate the rainwater harvesting potential in quantity.

6.2.3 Stormwater harvesting systems and monitoring frameworks

For the aggregate LID-BMPs system developments, studies on cost effectiveness of stormwater treatment trains need to be conducted as there is currently a dearth of information in this regard. The current practice in costing estimation is based on estimation of OPEX and CAPEX of individual BMP practices and processes within a given stormwater management treatment train. However, a system that interrogates multiple stakeholder priorities needs to be put in place. There is need to develop multi-objective-multi-criterion decision-making aid tools for the implementation of SWH systems. Suggested costing comparison studies should consider a holistic approach in which the following are addressed:

- the cost through the life cycle of the BMPs;
- the cost through comparisons of the economy of scale;
- the cost through a comparative analysis of the cost of retrofit versus installation of BMPs in new construction projects; and
- the full cost of the project considering CAPEX, OPEX, cost of land, design, permitting, and contingency in terms of climate action (global change versus climate change).

There is need for conducting case studies to develop a critical body of knowledge that enhance the application of the suggested framework as a stormwater management tool at the watershed scale as well as make improvements on the parameters identified in the framework.

Singular application of conventional stormwater management systems for environmental protection in a treatment train has a higher probability for failure if the resource managers and system designers do not analyse and address all the alterations to flow regimes resulting from storm conventional stormwater drainage systems.

6.2.4 Conjunctive water uses modelling of surface water and groundwater resources

The developed conjunctive use management tool can be applied to other local municipals in Sekhukhune District Municipality. However, reliable and continuous data may be an impediment in many of the local municipalities due to a lack of funding and technical skills for implementation of efficient groundwater and surface water monitoring networks. Future planning and budget allocation should therefore make provision for this risk. The current model is developed for conjunctive use of surface water and groundwater only. However, with the availability of “new tap” water sources such as rainwater harvesting, stormwater harvesting, water conservation and demand management, etc., the appropriation rules will definitely change and new modules will need to be added to the model to accommodate the “new tap” water sources.

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APPENDIX A: COUNTRY/REGION SPECIFIC HARMONISED IFI DEFAULT GRID EMISSION FACTORS

APPENDIX B: PROCEDURES ON HOW TO APPLY THE HARMONISED IFI DEFAULT GRID EMISSION FACTORS

APPENDIX C: METHODOLOGIES USED TO DETERMINE THE COUNTRY/REGION SPECIFIC HARMONISED IFI DEFAULT GRID EMISSION FACTORS

The IFI Dataset of Default Grid Factors
v.3.2

The IFI Dataset version 3.x

- The IFI Dataset (Version 3.x) will be used by IFIs as the default basis of their GHG emissions accounting.
- The IFI Dataset (version 3.0) was published in December 2021.
- The IFI Dataset (version 3.1) was published in January 2022 with a minor change. The methodology and sources used to derive the default emission factors are detailed under "AHG-001: Methodological Approach for the Common Default Grid Emission Factor Dataset". As noted in AHG-001, WEM projections of CO2 emissions from new electricity generation cover 13 large countries and 13 regions that cover the remaining countries. In version 3.0, regression method was applied to all countries, whereas in version 3.1 emission factors provided by the WEO Model are directly used for the 13 countries and regression method was applied to the remaining countries to estimate the Build Margin (BM).
- The IFI Dataset (version 3.2) was published in April 2022 with minor changes. The errors identified for the emission factors for “EU27” were corrected. Also, the values for "World" were added.

The IFI Dataset version 2.x

In the IFI Dataset (version 2.1), one column each for energy efficiency and electricity consumption were added.

In the IFI Dataset (version 2.2), a column for Operating Margin (OM) values was added.

In the IFI Dataset (version 2.3), the column for OM values was revised to read ‘Operating Margin Grid Emission Factor, gCO2/kWh (including for use in PCAF GHG accounting)'.

In the IFI Dataset (version 2.4), errors identified in GDP/capita or the grid mix for 5 countries from the non-IEA reporting group were corrected.

The IFI Dataset version 1.x

The IFI (Interim) Dataset of Grid Factors (Version 1.0) was released in July 2016 on the basis of the methodological approaches to GHG Accounting for Emissions from grid-connected RE and EE projects, that were announced by the IFIs at the 21st Conference of the Parties in Paris in December 2015.

For queries, please write to IFITWG-Coordinator <IFITWG-Coordinator@unfccc.int>.

INTERNATIONAL FINANCIAL INSTITUTIONS TECHNICAL WORKING GROUP ON GREENHOUSE GAS ACCOUNTING

IFI TWG - AHSA-004

Default Energy Intensity Factors for Water Supply Systems

Version 01.0

Date: October 2020

TABLE OF CONTENTS **Page**

1. Introduction

1. *This is a living document maintained by the IFI TWG. Its purpose is to provide default energy intensity and other relevant data to IFIs whom are carrying out a GHG analysis for water supply systems.*

2. Default Energy Intensity Factors for Water Supply Systems

2. There are several ways to approach a GHG analysis for water supply projects depending on what data is available. One common occurrence is that the expected project and baseline scenarios' total volume of water is known, but the energy intensity or total amount of energy demand is not known before carrying out the GHG analysis. For such cases, the factors below are available to use as default energy intensity factors for sourcing, conveyance, various treatment technologies, and distribution. They should only be used when reliable and accurate local data are not currently available. Please note that the energy intensity of each of the equipment for each of the steps outlined below in the potable water production chain may change over time, especially due to improvements in energy efficiency of new pumps and treatment equipment.

3. When using the default energy intensity values below (kWh/m^3), the given figure should be multiplied by the average volume of water produced in a given period of time (such as m3/day or Million L/year converted to equivalent m^3/year) to determine the total average annual energy consumption necessary to deliver that service. This average volume of water should be inclusive of non-revenue water (NRW)[1]. The energy consumption figure should then be applied to either 1) the default IFI TWG grid emission factor for the given country/region[2] or 2) emission intensity of the electricity based on the local project-specific energy mix.

4. The primary sources of the figures below are from global averages derived from Cooley and Wilkinson (2012)[3] and from the World Bank experience of carrying out GHG analyses for water supply investment projects from FY17-FY19. When a range of values are available in Cooley and Wilkinson, the median value is given below.

5. Default energy intensity figures for wastewater reuse treatment and distribution will be added to this document once the IFI TWG guidance on wastewater has been finalized and approved to avoid creating conflicts with that process at this stage.

[1] NRW is defined as the difference between the volume of water put into a system and the amount of water billed and collected. NRW broadly consists of 1) unbilled, but authorized, consumption; 2) commercial losses; and 3) physical losses (leakages). For the purposes of GHG accounting, water-supply energy efficiency improvement projects should be inclusive of all three forms of NRW relevant to particular project or program design.

[2] Harmonized Grid Emission factor data set available here.

[3] Cooley, H., Wilkinson, R., Heberger, M., and L. Allen. 2012. *Implications of Future Water Supply Sources for Energy Demands.* WateReuse Research Foundation, Alexandria, VA. Technical Report. http://pacinst.org/publication/wesim/.

2.1. Sourcing

6. Source pumping can have a highly variable energy intensity depending on the heights required to lift water, particularly for groundwater extraction. In such cases, the site-specific average pumping heights will be required instead of using a default energy intensity factor. The default efficiency rating of pumping equipment is 70% when energy is used for sourcing. This has been the most common estimated efficiency rating encountered for World Bank groundwater projects across the expected economic lifetime of such projects from FY2017-FY2019.

7. For water supply systems that use surface water as the sole source and use 100% gravity for sourcing, the energy intensity is 0 kWh/m3.

2.2. Conveyance

8. Conveyance can vary greatly due to the distance between the source and the treatment plant or end users.

Table 1. Default energy intensity for different types Conveyance Systems

Conveyance System Type	Energy Intensity (kWh/m^3)	Source	Notes
Pumped Local Conveyance	0.029	Cooley and Wilkinson (2012)	
Pumped Long Distance Conveyance	0.79		Long distance here is defined as a minimum of 200 km for systems requiring pumping over the length of conveyance with little gravity usage. Expert judgment should be used when deciding if a system should be assessed as a local system or a long-distance system.
100% Gravity-Based System	0		Assuming no energy use required. For systems that use a combination of gravity and pumping for conveyance, the energy use for the pumping portion should still be estimated.

2.3. Treatment

9. A water treatment plant or water supply system may use only one treatment technology (if any) or multiple technologies. For projects that use multiple treatment technologies, all of the relevant default energy intensity factors should be used in conjunction with the volume of water treated using each individual technology (inclusive of NRW).

Table 2. Default energy intensity for Treatment Technologies

<table>
<tr><th>Treatment Technology</th><th>Energy Intensity (kWh/m³)</th><th>Source</th><th>Notes</th></tr>
<tr><td>Conventional Standard Treatment</td><td>0.198</td><td rowspan="2">Cooley and Wilkinson (2012)</td><td></td></tr>
<tr><td>Chlorine Treatment (Mechanized)</td><td>0.0025</td><td></td></tr>
<tr><td>Chlorine Treatment (Muscle Power)</td><td>0</td><td></td><td>To be applied only when no electricity is required for chlorine injection</td></tr>
<tr><td>Ozone Disinfection</td><td>0.042</td><td rowspan="4">Cooley and Wilkinson (2012)</td><td></td></tr>
<tr><td>UV Disinfection (Low-Pressure Lamps)</td><td>0.017</td><td></td></tr>
<tr><td>UV Disinfection (Medium-Pressure Lamps)</td><td>0.04</td><td></td></tr>
<tr><td>Low-Pressure Membrane Treatment</td><td>0.13</td><td></td></tr>
</table>

2.4. Desalination

10. The default energy intensity **of brackish water desalination** depends on the pre-treatment salinity level. The chart below provides default energy intensity values for a range of salinity levels from 1,000 – 10,000 mg/L. Desalination in general tends to be highly energy-intensive.

Table 3. Default energy intensity for brackish water desalination

Brackish Water Salinity Level (mg/L)	Energy Intensity (kWh/m^3)	Source
1,000-3,000	0.951	Cooley and Wilkinson (2012)
3,000-5,000	1.255	
5,000-7,000	1.545	
7,000-10,000	1.942	

11. The default energy intensity of **seawater desalination using reverse osmosis** is 4.0 kWh/m^3.

Table 4. Default energy intensity Seawater Desalination Technology

Seawater Desalination Technology	Energy Intensity (kWh/m^3)	Source
Reverse Osmosis	4.0	Cooley and Wilkinson (2012)

2.5. Distribution

Table 5. Default energy intensity for Water Distribution Systems

Distribution System Type	Energy Intensity (kWh/m^3)	Source	Notes
Pumped Distribution	0.14	Cooley and Wilkinson (2012)	
100% Gravity-Based System	0		Assuming no energy use required. For systems that use a combination of gravity and pumping for distribution, the energy use for the pumping portion should still be estimated.

2.6. Note on Estimating the Energy Intensity for a Complete Municipal System

12. The data points above are separated out into different parts of the service chain to allow for fine-grained analysis of changes in energy intensity. For brownfield energy efficiency improvements, the potential energy efficiency savings may not be distributed equally between sourcing, conveyance, treatment, and distribution. In such cases, care should be taken to assess each of these steps separately to ensure accuracy in the analysis. For some projects, only municipal-wide or utility-wide energy intensity data may be available. This is acceptable data to use as long as the analysis is limited to the portion of the utility relevant to the investment.

2.7. Country-specific Local Data (World Bank projects)

13. The data below is a sample of local data that has been derived from World Bank water supply projects that were approved since FY18. The client either directly provided the data points below or World Bank staff derived the data from client-provided data points (except where noted). It is available for members of the IFI TWG to apply to their own analyses when local data is not available.

14. This table will be expanded covering other countries by the IFI TWG, when latest information becomes available.

Table 6. Country-specific local data from World Bank projects

Location	Activity	Energy Intensity (kWh/m^3)	Notes
Luanda, Angola	Treatment and Distribution (combined)	1.15	Baseline Data
Karachi, Pakistan	Conveyance	0.232	Baseline Data
Karachi, Pakistan	Conveyance	0.197	Project Data
Karachi, Pakistan	Conventional Treatment	0.117	Baseline Data
Karachi, Pakistan	Conventional Treatment	0.1	Project Data
Karachi, Pakistan	Distribution	0.132	Baseline Data
Karachi, Pakistan	Distribution	0.083	Project Data
Tegucigalpa, Honduras	Conventional Treatment	0.01134	Project Data

Location	Activity	Energy Intensity (kWh/m^3)	Notes
Baghdad, Iraq	Household Pumping (coping with baseline low-pressure situations)	0.5115	Baseline Data
Cambodia (Rural)	Home Boiling	1.274 tCO_2-eq per household per year	Baseline Data from existing CDM application

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Document information

Version	*Date*	*Description*
01.0	7 October 2020	Initial adoption.

INTERNATIONAL FINANCIAL INSTITUTIONS TECHNICAL WORKING GROUP ON GREENHOUSE GAS ACCOUNTING

IFI TWG - AHG-001

Methodological Approach for the Common Default Grid Emission Factor Dataset

Version 01.1

Date: 20 January 2022

TABLE OF CONTENTS **Page**

1. Overview

1. For the purpose of promoting greater harmonization, the IFI Technical Working Group (IFI TWG) on GHG accounting maintains a common dataset containing Default Emissions Factor (DEF) of the country's electricity grid including in-country interconnected grids. The DEFs apply to electricity generation in a country and currently do not consider the impact of interconnections with neighbouring countries.[1] The common dataset containing DEFs is constructed using a Combined Margin (CM) for the grid that is comprised of an Operating Margin (OM) and a Build Margin (BM). The OM and BM are terms defined under the clean development mechanism (CDM)[2] for grid connected electricity generation from renewable sources:

   (a) The OM represents the cohort of existing power plants whose operation will be most affected (reduced) by the project;

   (b) The BM represents the cohort of the prospective/future power plants whose construction and operation could be affected by the renewable energy project, based on an assessment of planned and expected new generation capacity.

2. Calculation of the OM

2. The International Energy Agency's (IEA) energy statistics database[3] provides country specific information on electricity generation from gas, oil, coal and "other" fuels and related CO_2 emissions that are used to calculate the OM emissions factor of most of the countries in the common dataset.[4]

3. In principle, the OM consists of generation from the power plants with the highest variable operating costs in the economic merit order dispatch of the electricity system. Natural gas and oil-based power plants have the highest variable operating costs, followed by coal. Nuclear power, hydropower, co-generation plants and other sources of power including waste to energy and other renewables are typically "must run" or low cost and therefore contribute to the OM only under special circumstances.

4. For the purposes of the common dataset, the default OM is defined as the plants producing the most-costly generation of the fossil fuel generation mix. Fossil fuel power plants in many countries provide firm power generation in base load or are must run and typically provide low cost power. To avoid including these power plants in the OM, only the top 50% or most costly half of the total fossil fuel generation mix is used. Gas and oil generation

[1] IFI TWG is undertaking further work to develop harmonized approaches for interconnection with neighbouring countries.

[2] ACM0002: Grid connected electricity generation from renewable sources available here.

[3] IEA CO_2 Emissions from Fuel Combustion Statistics provide information on fuel combustion and CO_2 emissions by sector, including gross electricity generation, for 142 countries and territories. A 3-year rolling average of the most recent statistics is used to smooth annual variations, and a correction factor for electricity consumed by the auxiliaries of thermal power plants is applied.

[4] As and when country specific data becomes available to the IFIs, e.g. through their detail country studies, such information can be used to replace IEA data to calculate operating margin emission factor but applying the same principle and methodology stipulated in this document.

are the most-costly and are the first to enter the OM. Due to fluctuations in oil and gas fuel prices, these sources are not differentiated and are assumed to contribute equally to the OM on a pro-rata basis.[5] Coal-based power plants contribute to the OM only when coal generation exceeds 50% of the total fossil fuel generation mix.[6]

5. “Other” power plants enter the operating margin when non-fossil fuel generation exceeds 50% of the total generation mix.[7] An adjustment factor based on CDM methodology[8] is used to determine the contribution of “other” fuels in the OM.

6. For countries not represented in the IEA energy statistics, research from publicly available sources is used to identify the mix of gas, oil, coal and other fuels used for electricity generation and default emissions factors for each fuel type are applied to define the OM according to the methodology described above.

3. Calculation of the BM

7. The IEA maintains a world energy model (WEM) that is the principal tool used to generate detailed sector-by-sector and region-by-region projections for the publication of the World Energy Outlook (WEO). Through the WEM, it is possible to project the CO_2 emissions of “new” electricity generation under various scenarios. New electricity generation comes from the cohort of power plants commissioned from the start of the projection period. The common dataset uses an average of the annual emission intensities of new electricity generation projected over the next 8 years under the Stated Policy Scenario (STEPS) of the most recent WEO as an estimate of the BM.[9] The STEPS assumes a continuation of the energy policies already adopted by governments and implementation of current and proposed commitments and plans and incorporates assumptions on fuel prices, technology costs and technological progress.

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[5] For example, if a country fuel mix comprises 40% gas, 20% oil, 20% coal and 20% hydropower, fossil fuels contribute 80% of the generation mix. According to the methodology, the most-costly half of the fossil fuels within the total fossil fuel-mix contributes to the OM, i.e. 40% of the total generation (half of 80%). Gas & oil generation have the highest variable costs and together exceed half of the fossil fuel mix (40/80+20/80= 60/80). Therefore, the OM consists of gas and oil generation only, as a pro-rata mixture of two-thirds gas (40/60=2/3) and one-third oil (20/60=1/3).

[6] For example, if a country fuel mix comprises 20% gas, 10% oil, 50% coal and 20% hydropower, fossil fuels contribute 80% of the generation mix. According to the methodology, the most-costly half of the fossil fuels within the total fossil fuel-mix contributes to the OM i.e. 40% of the total generation (half of 80%). Gas and oil generation have the highest variable costs but are less than half of the fossil fuel mix. Therefore, gas, oil and coal generation contribute to the OM. All of the gas and oil contribute as a pro-rata mixture (20/40+ 10/40 =30/40) and rest of the OM is coal generation (1-30/40= 10/40). The OM is a mixture of one-half of gas, one-fourth of oil, and one-fourth of coal.

[7] The power plants represented in the IEA statistics as “other” fuels generally use low cost or low carbon fuels that are likely to be “must-run” resources in most countries. The CDM Tool 07 (see footnote below) defines must-run resources as “power plants with low marginal generation costs or dispatched independently of the daily or seasonal load of the grid. They include hydro, geothermal, wind, biomass and waste combustion, nuclear and solar generation.”

[8] Clean Development Mechanism Methodological Tool (Tool 07): “Tool to calculate the emission factor for an electricity system” (v.7) available here.

[9] To offset the annual fluctuations of emission intensity from new power plants dispatched or operated a bit more or bit less in one year than in a previous one, the estimate of the BM uses an average of the 8 years of annual emission intensities.

8. WEM projections of CO_2 emissions from new electricity generation cover 26 large countries and regions. To create a common dataset that is consistent with the projections of the STEPS with granularity at the country level for all countries, a mathematical relationship to estimate the BM is used for the countries represented by a region.[10] The calculation of the BM is based on a regression analysis of the projected emission intensities of the WEM and two proxy variables – the most recent 3-year average emissions factor of the country's electricity grid (the "grid factor")[11] and the country's GDP per capita.[12] The regression analysis demonstrates a high correlation between these proxy variables and the emission intensities projected by the WEM.[13]

9. The grid factors for most countries are based on the IEA's energy statistics. GDP/capita[14] is obtained from the World Bank's World Development Indicators (WDI) and the UN Database.

10. For countries not represented in the IEA energy statistics, WDI or UN databases, research from publicly available sources is used to identify the mix of gas, oil, coal and other fuels used for electricity generation and default emissions factors, as well as recent data on GDP/capita, are applied to define the BM according to the methodology described above.

4. Combining the OM and BM to construct the CM EF

11. When combining the OM and BM to calculate the CM EF, generally the weighting ratio provided in the sector-specific approaches should be followed[15], for example:

    (a) For renewable energy projects, follow the guidance contained in "AHSA-001: IFI Approach to GHG Accounting for Renewable Energy Projects" (available here);

    (b) For energy efficiency projects, follow the guidance contained in "AHSA-002: IFI Approach to GHG Accounting for Energy Efficiency Projects" (available here);

    (c) For grid electricity consumption, follow the guidance contained in "AHG-002: Methodology/approach to account project emissions associated with grid electricity consumption" (available here).

[10] For the following 13 countries, the 8-year average of the annual projections of emissions intensities of new electricity generation are used directly: United Kingdom, USA, Canada, Mexico, Brazil, Chile, Russia, China, Japan, South Korea, Indonesia, India and South Africa.

[11] The "grid factor" represents a proxy for the influence of domestic fuel resources, existing fuel import infrastructure and technical experience with fuels and technologies – all of which contribute to the current emissions intensity and are likely to influence the BM.

[12] "GDP/capita" represents a proxy for the influence of a country's economic development on the potential rate of decarbonisation. Countries with higher levels of economic development are generally more capable of implementing effective decarbonisation policies, accommodating the technical challenges of a higher penetration of renewables, and have the capacity and experience to commission the more advanced technologies associated with low carbon and high efficiency power plants.

[13] A high correlation between these proxy variables and the projected emissions intensities, as demonstrated by the adjusted R2 of the linear regression and the normal distribution of the residuals.

[14] GDP is on real term (constant USD).

[15] Until more definitive guidance is available, the IFI should transparently document and share with the TWG any alternative weighting or other correction proposal for a specific country or region.

5. Process and timeline for the update

12. The common DEF dataset will be updated at least once in two years under the responsibility of the TWG.

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Document information

Version	*Date*	*Description*
01.1	20 January 2022	Minor revision. • To reflect the latest nomenclature used by IEA in its projections, i.e. New Policies Scenario (NPS) is changed to Stated Policy Scenario (STEPS). • Update of footnote 10 to list the 13 countries instead of earlier 12 countries for which WEM projections are now provided. • Addition of AHG-002.
01.0	18 May 2020	Initial adoption. Information on “IFI TWG Methodological Approach for the Common Default Grid Emission Factor Dataset” was extracted from “AHSA-001: IFI Approach to GHG Accounting for Renewable Energy Projects” and placed as a separate document for ease of reference in accordance with the decision of 3rd IFI TWG virtual meeting (6 May 2020).