A METHODOLOGY FOR ECONOMIC ASSESSMENT OF WASTEWATER INTRINSIC VALUE RECOVERY USING AN INDIRECT PRODUCTION FUNCTION APPROACH

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DECLARATION

I declare that this is my own unaided work. It is being submitted for the Degree of Doctor of Philosophy to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

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(Signature of Candidate)

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ABSTRACT

The efficient use of finite water resources and measures to extend the service value of these resources in water scarce countries is a pre-requisite for achieving sustainable development. There is constant pressure to explore new resources to meet the ever increasing demand posed by growth in population and that of industry in urban cities.

Introduction of unconventional resources such as wastewater and greywater reuse, allows access to a readily available valuable resource and intrinsic value recovery for the benefit of society. Not only does this assist with fresh water resource conservation and optimal use thereof and mitigation of negative impacts but also closing of urban nutrient loops and extraction of chemical energy for energy generation.

This research explores wastewater intrinsic value recovery at wastewater treatment plant and wastewater management system levels as part of the balancing equation of natural-unconventional resource use and environmental, social and economic constraints. A methodology for assessment of wastewater intrinsic value recovery was developed that derive a monetary equivalent of value recovery of reuse employing an econometric production function approach. Apart from a economic level life cycle analysis, the methodology developed include a holistic multi-criteria analysis (MCA) covering sustainability criteria related to the economic, technical, social and environmental domains. The methodology can be adopted to analyse the economic effects of choices between the different pathways of wastewater intrinsic value recovery or a combination thereof and performance differences between surface and ground water reclamation strategies. The methodology allows strategic level comparative analyses of wastewater management system options within the centralised-decentralised wastewater continuum and appropriate technology option choices, being demonstrated for sewered technology in the second case study of the research.

It is concluded that wastewater beneficiation or intrinsic value recovery consists of three different pathways of reclamation, reuse and recycle, each being location

specific with different social, environmental and economic repercussions. While reuse positively impact virtual water components and water footprints, modification to allow multiple water use is needed to apply the concept in wastewater management. By quantifying the impact of reuse on water availability for urban water supply systems the link between reuse level and resource conservation benefits is established.

The main recommendations made include the exploring of shadow prices and contaminant removed at treatment and management system levels over multiple time periods. In addition, sustainability of extended system scale and technology options over the centralised-decentralised wastewater continuum and returns to scale of urban sewered systems within a South African context require investigation. The adoption of the methodology is also proposed to analyse the economic impacts of wastewater beneficiation pathways or combinations thereof, additional benefits of multiple water use and ways of adjustment of the virtual water (VW) concept to be more amenable to wastewater management. Furthermore, impact of reuse on increased water availability for urban water supply systems by incorporating a network-specific and consumer-end related system losses differentiation as link to resource conservation benefits assessment is also recommended.

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PUBLICATIONS

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Reynders, C., Musiyarira, H. & Marjanovic, P. “Wastewater Treatment Technology Sustainability within a Centralised or Decentralised System Context in Smaller South African municipalities” Presented at the 10th WaterNet/WARFSA/GWP Symposium ‘Environmental sustainability, Climate change and Livelihoods’ Entebbe, Uganda, from 28-30 October 2009.

Reynders, C, Musiyarira, H. & Marjanovic, P (2010) “Wastewater Treatment Technology Sustainability within a Centralised or Decentralised System Context in Smaller South African municipalities” Presented at the 11th WaterNet/WARFSA/ GWP Symposium ‘IWRM for National and Regional Integration: Where Science, Policy and Practice Meet’ Victoria Falls, Zimbabwe, from 27–29 October 2010.

Musiyarira, H., **Reynders, C**. & Marjanovic, P. (2010) “Multi-criteria use in Wastewater Planning” Presented at the 11th WaterNet/WARFSA/GWP Symposium ‘Integrated water Resources Management: Where, Policy, Science and Practice meet’ Victoria Falls, Zimbabwe, from 27-29 October 2010.

Musiyarira, H., **Reynders, C.** & Marjanovic, P. “Decision Making Support in Wastewater Management: Comparative Analysis of Techniques and Tools used in Centralized and Decentralized System Layouts”. 1st Climate Change, Economic Development, Environmental and People Conference. Novi Sad, Serbia, from 14-16 September 2011.

Reynders, C., Musiyarira, H. & Marjanovic, P. (2011) “The Value of Decentralisation in Wastewater management: Gauteng Province Case Study, South Africa”. 1st Climate Change, Economic Development, Environmental and People Conference. Novi Sad, Serbia, 14-16 September 2011.

Marjanovic, P., Musiyarira, H. & **Reynders, C**. (2011). “Managing Water Resources in Developing Countries: South Africa as an Example for Policy and Regulation”. Journal of Serbian Water Pollution Control Society: Water Research and Management. (1) (3) (2011) ISSN 2217-5237.

Marjanovic, P. & **Reynders, C**. (2012). “Generalised Model and Framework of Analysis of Sanitation and Wastewater Management and Intrinsic Value Recovery from Wastewater”. Journal of Serbian Water Pollution Control Society: Water Research and Management. (2) (1) (2012) ISSN 2217-5547.

TECHNICAL REPORTS

Marjanovic, P., Musiyarira, H. & **Reynders C**. (2009). Project for the Gauteng Department of Local Government & Housing South Africa:

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LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

ANS	Anthropogenic Nutrient Solution
AUD	Australian dollar
AWU	Agricultural Water Use
B	Boron
BNR	Biological Nutrient Removal
BOD	Biological Oxygen Demand
Ca	Calcium
CBD	Central Business District
CDM	Criteria decision model
CEM	Choice Experiment method
COD	Chemical Oxygen demand
CPI	South African consumer price index
CRD	Capital Regional district
CSIR	Council for Science and Industrial Research
CUS	Centralised Urban wastewater System
CVM	Contingent Valuation
CWU	Crop Water Use
DEA	Data Envelopment Analysis
DESAR	Decentralised Sanitation and Reuse
DWW	Domestic Water Use
DNHPD	Department of National Health and Population Development
DSS	Decision support system
EB	Environmental Benefits

ECB	European Central Bank
EM	Electrical and mechanical equipment
EUAC	Equivalent Uniform Annual Cost
EWFP	External Water Footprint of a country
FC	Faecal Coliforms
FWR	Fresh Water Rate
FWT	Fresh Water Tariff
GAC	Granular Activated Carbon
IMQS	Infrastructure Management Query System
IWF	Internal Water Footprint
IWF	Internal Water Footprint
IWW	Industrial Water Use
K	Potassium
kg	Kilogram
kW/m^3	Kilowatt per cubic metre
LCC	Life cycle cost
LCCA	Life cycle cost analysis
MBR	Membrane Biological Reactor
MCA	Multi-criteria analysis
MDG	Millennium Development Goals
MEC(L)	Marginal Externality Cost of water resources borne Locally
MEC(L+G)	Marginal Externality Cost borne Locally and Globally
MF	Microfiltration
MFC	Microbial Fuel Cell
Mg	Magnesium

mg/L	Milligrams per litre
MLSS	Mixed Liquor Suspended Solids
MNPB	Marginal Net Private water use Benefits
MNPB(sub)	Marginal Net Private water use Benefits exacerbated by Subsidies
MOSTWATAR	Model for Optimum Selection of Technologies for Wastewater Treatment and Reuse
MWCO	Molecular Weight Cut Off
N	Nitrogen
Na	Sodium
NF	Nanofiltration
NOWAC	No water consumption
O & M	Operation and Maintenance
P	Phosphorus
PE	Person Equivalent
PV	Present value
RMI	Rocky Mountain Institute
RO	Reverse Osmosis
ROEC	Reed odourless earth closet
S	Sulphur
SCA	Strategic Choice Approach
SS	Suspended Solids
STP	Sewage Treatment Plant
SWITCH	Sustainable Water Management Improves Tomorrow's Cities Health project
TBL	Triple Bottom Line

TDS	Total Dissolved Solids
TEV	Total Economic Value
TOC	Total Organic Carbon
UD	Urine diversion
UF	Ultrafiltration
UK	United Kingdom
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organisation
IHE	Institute of Higher Education (Delft)
USA	United State of America
US EPA	United States Environmental Protection Agency
US NRC	United States National Research Council
UV	Ultraviolet
UWM	Urban Water Management
VIDP	Ventilated improved double pit latrine
VIP	Ventilated improved pit latrine
VVT	Ventilated vault toilet
VW	Virtual Water
VWC	Virtual Water
VWE_{dom}	Virtual Water Export domestic
$VWE_{re\text{-}export}$	Virtual Water Export related to re-export of imported goods
VWI	Virtual Water Import to a country
WA	Water resource Availability
WAWTTAR	Water and Wastewater Treatment Technologies Appropriate for Reuse

WCI	Water Crowding Index
WD	Water import Dependency
WF	Water Footprint
WF_{pc}	Water Footprint per capita
WFP	Water Footprint of a country
WHO	World Health Organisation
WISA	The Water Institute of Southern Africa
WRC	Water Research Commission
WS	Water Scarcity
WSM	Weighted sum method
WSP	Water services provider
WSS	Water Self-sufficiency
WTRNet	Water Treatment for Reuse with Network Distribution
WWTP	Wastewater Treatment Plant
ZAR	Republic of South African Rand
Zn	Zink

TABLE OF CONTENTS

PART I: WASTEWATER RECLAMATION AND REUSE

PART II: ECONOMIC CONSIDERATIONS IN WASTEWATER MANAGEMENT SYSTEMS

APPENDICES

CHAPTER 1

INTRODUCTION AND THE BACKGROUND TO THE STUDY

In a semi-arid water scarce country like South Africa, the efficient use of the limited water resources and measures to extend the service value of these resources is a pre-requisite for achieving sustainable development. Constant pressure exists to explore new resources to meet the ever increasing demand posed by growth in population and that of industry. Urban areas being centres of high economic activity not only attract new industries because of viable financial prospects and readily available resources, but also large numbers of people hoping to secure a better future.

1.1 BACKGROUND

Based on the United Nations population projections (2009), the world's urban population is expected to be around 3,5 billion in 2010 compared to a total world population of just below 7 billion. In Figure 1.1 the mentioned UN projections for urban and rural populations in both developing and developed countries are given.

It is evident from Figure 1.1 that the world urban population has moved beyond the 50% mark since 2007 (equal urban and rural populations) and is expected to reach nearly 60% by 2030. Furthermore, for developing countries, the urban population is expected to be around 45% in 2010 and reach 55% by 2030, while for developed countries the urban populations will approximately be 75% by 2010 and 80% by 2030. All cities of various size categories will experience growth in populations (smaller ones with inhabitants less than 100000 as well as the larger ones with inhabitants in excess of 1 million), and the population is expected to increase by around 25% by 2025 as shown in Figure 1.2.

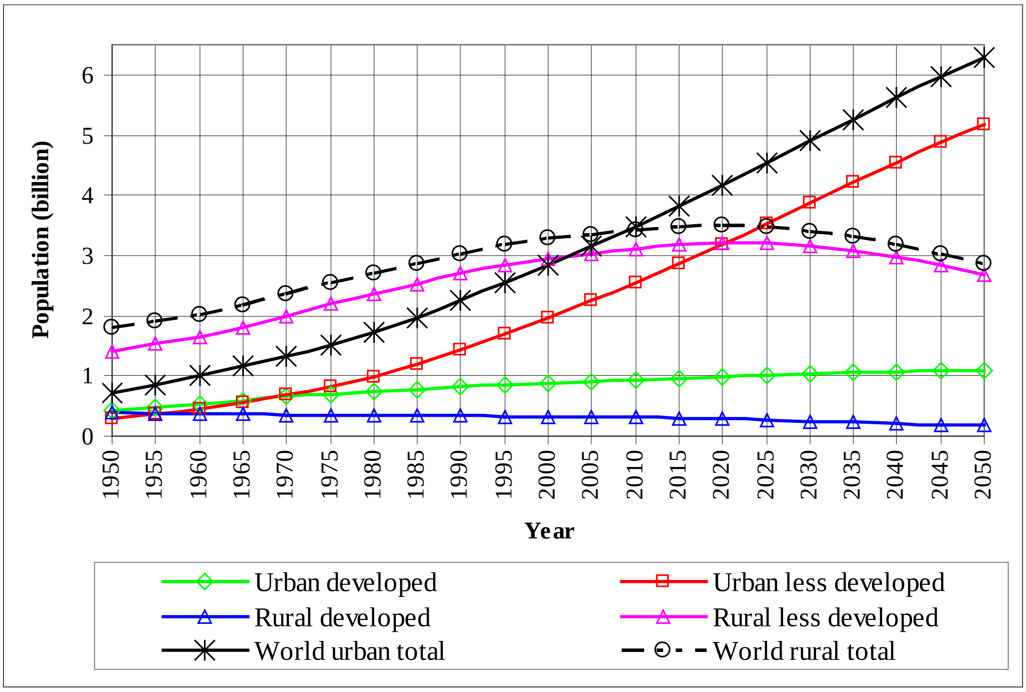


Figure 1.1 Contributions of urban and rural populations for developed and less developed (or developing countries) (derived from UN Department of Economic and Social Affairs, Population Division: World Urbanization Prospects, the 2009 Revision)

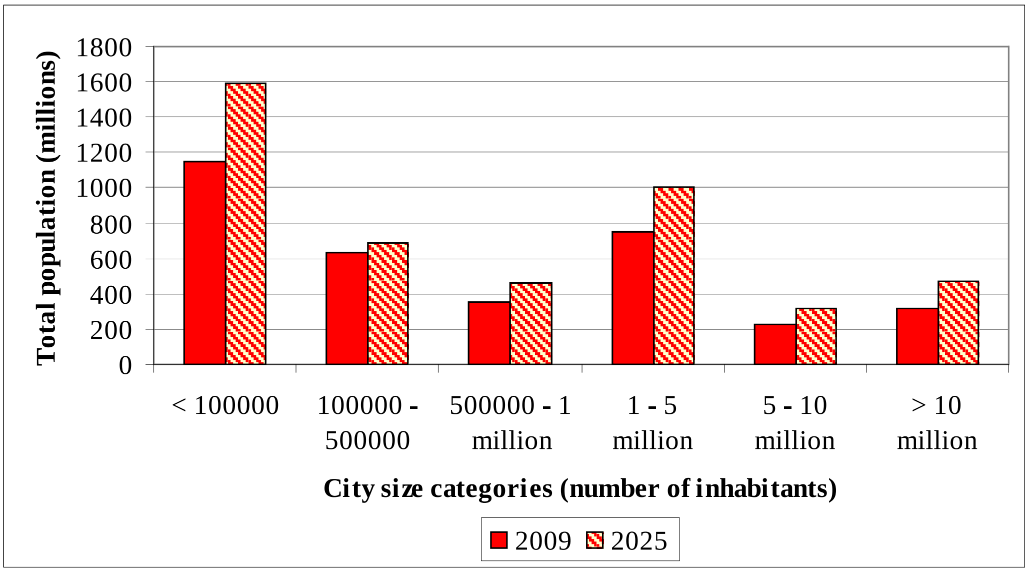


Figure 1.2 Total population by city size categories (in millions) (derived from UN Department of Economic and Social Affairs, Population Division: World Urbanization Prospects, the 2009 Revision)

Growth in populations applies to all urban areas but not necessarily so in parts of the world were demographic decline (i.e. Europe) is in progress.

Based on the population data mentioned, the rate of urbanisation in developing countries in the next decade or two is expected to be about twice that of developed countries. This surge of growth in city populations will result in urban areas becoming demand nodes where ever increasing water supply and wastewater management will become a major challenge. This will apply increased pressure, not only on infrastructure necessary for provision of water, but also on finite fresh water resources and the available natural resource flow relied on.

1.2 PROBLEM STATEMENT

The conventional supply-sided management approach to water supply causes increased wastewater generation with accompanied increased pollution loads requiring higher levels of mitigation of environmental pollution. Where disposal of wastewater treatment effluent takes place in rivers and natural water bodies, the lack of adequate natural compensating capacity of such water bodies typically result in severe ecological damage of the aquatic environment. With a shift of emphasis to a sustainable demand side management approach (as opposed to a supply side one), the avoided water wastage and reduction of high volumes of wastewater generation represents both resource conservation and an environmental protection friendly approach that contributes to overall sustainability. The integrated nature of water supply and wastewater management systems requires an approach that considers these systems holistically. In nature “water and sanitation” systems are linked and all by-products of any process are utilised with a “zero waste” objective. In other words, all elemental cycles are closed loop cycles within the given spatial and time frames. To ensure environmental sustainability of the corresponding man-made water and sanitation (wastewater) systems, it is essential that the pattern established in nature be copied as closely as possible by use of an “integrated water management” approach. This will require a transformation of the conventional segmented approach to water supply and sanitation planning and management. Through a different and innovative new way of thinking (i.e. wastewater considered as valuable resource opposed to waste product) and proper related public health and social educational programmes, the paradigm shift required could obtain momentum with due consideration in water resource planning and management in the future.

To summarise, population growth and, in particular, rapid urbanisation and industrialisation with increased water demand result in over-exploitation of available water resources. This in turn generates large waste stream loads via wastewater discharges that pollute the environment and as a consequence causes growing negative ecological impacts. The segmented approach of conventional water management with a mainly supply-side approach is under pressure. While having to meet growing need of water and sanitation services the conventional approach is not able to efficiently manage the reducing water resources and minimise both negative impacts on the environment and deterioration of the quality of life of urban inhabitants.

Apart from increased supply through mobilisation of the available fresh water resource (water storage, transport and treatment) a demand-sided management approach with resource conservation objective would reduce water demand through appropriate water saving measures at the consumer end and supply systems water loss prevention programmes. These measures could save around 30% in demand for water in larger supply systems and even more in smaller ones (van Rooyen and Versfeld, 2010).

Furthermore, other than renewable surface waters, groundwater would be an appropriate alternative conventional resource provided it is readily available and could be treated to a sufficient quality if required.

Unconventional resources can be considered to supplement fresh water supplies such as rain water harvesting, desalination and wastewater reuse. The technologies required for these systems to provide water of adequate quality to match any application requirements are available, but its employment would be subject to social, political, economic, hydrological and geographical constraints. Rain water harvesting would not suffice in arid environments while it could be appropriate in semi-arid areas. Desalination would be more appropriate for coastal areas close to the source such as seawater, than inland regions due to costs related to conveyance of purified water. In addition, the high energy costs associated with desalination systems inhibit its employment generally, although energy requirements have been reduced substantially. For example in the case of reverse osmosis for seawater, energy requirements have been reduced from around 8 kWh per cubic metre purified water produced in the 1990s to nearly half of that currently.

Through wastewater effluent and household level greywater reuse, a potentially equivalent fresh water supply could be conserved. Moreover, the reduced or zero discharge of wastewater effluent to receiving waters mitigates negative environmental impacts.

Wastewater and greywater are linked to fresh water usage for human livelihood and are independent of climate and rainfall variations in time and space as is the case with fresh water. It is therefore a readily available resource compared to fresh water resources and dependent only on the level of fresh water usage (and quality). Apart from fresh water resource conservation, reuse will also present benefits of deferred fresh water mobilisation or supplementing existing resources due to a lack of sufficient fresh water resources.

A new paradigm for water management is needed to ensure that the issues of waste disposal and pollution are dealt with in a sustainable manner taking into account the emerging objectives of modern society for resource conservation and environmental protection. A balance therefore has to be found between the use of additional fresh water resources as a means of satisfying an ever increasing water demand on the one hand and alternative unconventional resource exploration and employment, without the risk of depletion of the natural available fresh water resource flow, irreversible harm to the environment and social and economic constraints.

1.3 RESEARCH OBJECTIVES

This research explores wastewater intrinsic value recovery at wastewater treatment plant and wastewater management system levels through reuse, as part of the balancing equation of natural-unconventional resource use and environmental, social and economic constraints. The objective is the development of a methodology for assessment of intrinsic value recovery economics, for technology choices and extended to both treatment and management system levels, by obtaining a monetary equivalent of value recovery and application thereof in feasibility analyses.

1.4 JUSTIFICATION OF THE RESEARCH

Wastewaters should be viewed as valuable resources and its intrinsic value for society can be recovered. Although sustainable wastewater management is a prerequisite for intrinsic value recovery, employment thereof in practise would only take place under conditions of recovery being economically justified. The objective of developing a methodology for assessment of the economics of intrinsic value recovery at treatment and management system levels as well as technology choices is the contribution of this thesis.

1.5 RESEARCH METHODOLOGY

A methodology for deriving monetary indicator values for wastewater reuse at both treatment plant and wastewater management system levels was developed. This was achieved by internalising negative environmental impacts and application of Lagrangian optimisation of individual treatment plant production functions (output distance functions) to derive marginal prices of contaminants removed and the environmental benefits as a result of the avoided pollution. Through a sensitivity analysis of plant economic viability and a comparison with the appropriate bulk fresh water tariff the required economic breakeven tariffs for water reuse were determined.

1.6 LIMITATIONS OF THE RESEARCH

Although the methodology developed for intrinsic value recovery applies to wastewater treatment plant and overall wastewater management system levels, the analysis for the latter required localised synthetic data generation due to extended system related data not being readily available. In addition, a single annual cost for plants was made available for the research which allowed a marginal cost evaluation for a single year period only. For a longer term approach associated with works of this nature, assessment of multiple annual cost cycles (that incorporate changes in costs and plant process performance over time) is necessary for obtaining more realistic longer term monetary equivalents for intrinsic value recovery feasibility analyses.

The methodology could also be modified to include additional benefits of multiple water use as well as benefits that could occur indirectly through a reduction of negative virtual water export streams (negative export streams refer to subsidised water included as virtual water in exported products) for which the real cost of water are not taken into account.

1.7 THESIS LAYOUT

This thesis consists of seven major parts or chapters as summarised in the following sections below:

Chapter 1 introduces the topic of research and outlines the background to the study. The growth in urban populations globally and the increased demand for and the concomitant pressure exerted on finite fresh water resources are highlighted. Unconventional water resources such as rain water harvesting, desalination and wastewater reuse are briefly mentioned. Wastewater reuse being the focus of this research is elaborated on further by highlighting on some core benefits thereof. The chapter is concluded with a thesis layout describing briefly the core content of the various sections of the thesis.

Chapter 2 discusses the importance of fresh water resource for sustaining life and the finite nature of this resource (2,5% of total water on the planet) being under pressure due to increased population growth. To fully understand and appreciate the value of wastewater reuse it is necessary to appreciate the global water cycle and understand the limited extent of fresh water resources available globally. Various water resource scarcity indicators are considered and commented on.

Chapter 3 discusses sustainability in wastewater management and the evolution of the concept over time. Starting initially as a simplistic quantitative measure of the balance between fresh water demand and supply, sustainability has developed into an inclusive concept catering for adequate quality, resource conservation and pollution protection with closing or recovery of nutrient flows in society. The Triple Bottom Line (TBL) concept which allows for sustainability decision-making by a framework for both quantifiable and non-quantifiable factors related to costs and benefits in a balanced way across social, environmental and economic goals and, objectives, is also briefly discussed. Furthermore, the integrated wastewater management approach requiring the application of “cleaner production” principles in tandem with the wastewater disposal options and the resulting so-called “3-Step approach” for wastewater management is introduced. The potential of a number of technologies currently available for nutrient recovery are discussed.

Chapter 4 introduces the two distinct wastewater management system options of centralisation and decentralisation and how sustainable water management is dependent on the system option employed. Problems associated with large-scale sewered centralised wastewater management systems are reviewed together with comparative benefits of decentralised systems being highlighted, resulting in decentralised systems being shown as beneficial compared to conventional centralised systems.

Chapter 5 expands on the argument given in other previous chapters that wastewaters should be seen as valuable resources and its intrinsic value for society can and must be recovered. The logic and drivers for wastewater reuse as a non-conventional resource to supplement finite fresh water resources under pressure globally is also alluded to. Although sustainable wastewater management is a prerequisite for intrinsic value recovery, employment thereof in practise would only take place under conditions of recovery being economically justified. A needed methodology for assessment of the economic evaluation of the intrinsic value recovery potential from wastewater is developed for application at both a wastewater treatment plant and wastewater management system level making use of an indirect production function (output distance function) valuing approach. The methodology developed includes a holistic multi-criteria analysis (MCA) together with formulation of sustainability criteria that cover the environmental, social, technical and economic domains. Use of a simplistic water balance model to quantify the impact of reuse on water availability for urban water supply systems was employed to link reuse and resource conservation benefits (being equivalent to the increased supply achieved) for inclusion into an integrated management system level analysis. This model was revised to differentiate between network-related and consumer-end related losses for assessing the impact of reuse closer aligned to the actual situation in practise.

Chapter 6 presents a first case study where the developed methodology for assessment of economic evaluation of intrinsic value recovery outlined in Chapter 5, is applied for evaluation of treated effluent reuse at nine wastewater treatment plants in Gauteng, South Africa. The results obtained from the evaluation exercise and conclusions reached are discussed in detail.

Chapter 7 presents a second case study where the methodology for assessment of wastewater intrinsic value recovery was applied for a sewered wastewater system within a urban centralised-decentralised continuum. Apart from an economic level life cycle analysis, a holistic multi-criteria analysis (MCA) of sewered sub-system component (treatment and collection) and mixed sewered system scale levels was done for sustainability covering the economic, technical, social and environmental domains. The assessment approach followed considered sewered system associated components individually (treatment and collection) with economic and flow throughput baseline aggregation for sub-system and mixed system scale comparisons.

Chapter 8 is the concluding chapter consisting of a brief summary of the thesis and conclusions made from the research done, the limitations of the study and aspects identified for future further research.

CHAPTER 2

WATER AS RESOURCE, AVAILABILITY AND SCARCITY

In order to fully understand and appreciate the value of wastewater reuse it is necessary to have an appreciation of the global water cycle and recognise the limited extent of fresh water resources. This chapter reviews the global water cycle and considers availability of renewable freshwater resources globally as well as various scarcity indices for the measure of resource availability. The concept of virtual water (VW) and water footprint (WF) are also considered as measures of water use of various nations.

2.1 WATER AS A RESOURCE

Water is essential for all life and has to be available on a regular basis for life to exist. Therefore water must be viewed as a resource with all the implications that such a view carries (e.g. all resources have a value, all resources can be used efficiently or inefficiently, etc.).

The fundamental law of hydrology determines that all water is present as part of the universal hydrologic cycle shown in Figure 2.1 (Falkenmark 1989). Figure 2.1a shows the global circulation system that brings water to continents, while Figure 2.1b shows precipitation and evapotranspiration taking place over continents. Figure 2.1c illustrate the net run-off as surface flow in rivers (renewable resource), the “short branch” accounting for the loss due to evapotranspiration (plant transpiration and surface evaporation) and the “long branch” responsible for the portion that did not run off land but percolated down into the soil and eventually into subterranean aquifers to recharge such aquifers and ultimately rivers.

However, a finite amount of water is available in any one phase of the hydrologic cycle at any one moment in time. Human interventions to alter the availability of fresh water resource at best retain portions thereof longer in spatial and temporal terms. Examples of human intervention of the natural cycle are dam construction and artificial aquifer recharge.

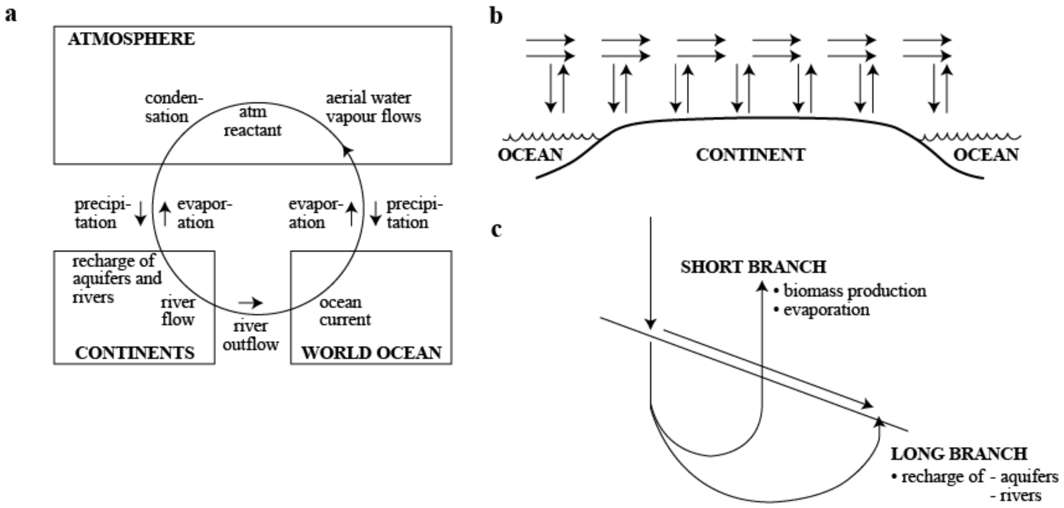


Figure 2.1 Global water cycle and system components at country and river basin level (after Falkenmark 1989)

The finite water resource, broadly speaking, is found in three main forms (Turton 1998):

1) atmospheric water found in the form of humidity that result in precipitation, of which rainfall is a particular type thereof
2) surface water, being largely water that has run off the land as a result of precipitation and is found mainly in rivers, lakes and other man-made impoundments
3) ground water, being precipitation that has not run off the land, but which has percolated down into the soil, through the root zones of plants and finally into subterranean aquifers

Water is a renewable resource and limited in the sense of flow available for use at a particular time and is neither created nor destroyed but converted from one form to another (Harremoës 1999, Anderson 2003).

The water available to any country is determined by the global water cycle. The water available for use at a country or river basin level after precipitation over its territory (endogenous) is basically twofold:

1) soil moisture available for rain-fed plant production
2) the annual recharge of terrestrial water systems (ground water aquifers and river flow)

In addition any surplus from an upstream country or countries by cross-border rivers and aquifers can enter as exogenous flow. The total amount provided by these two components is complementary and is what can be distributed or mobilised for use by the existing and future population. It is obvious that with growth of the population the per capita amount of available water will decrease (Falkenmark 1989).

The total amount of water in the earth's hydrosphere consists of the free water in liquid, solid, or gaseous states in the atmosphere, on the earth's surface, and in the crust down to the depth of 2 000 metres. According to Shiklomanov (2000), planet earth has in total approximately 1,386 billion cubic kilometres of water. This is the long term average amount of water simultaneously contained in the hydrosphere (also known as the natural static water). Over short intervals such as seasons and years this storage varies due to the dynamic nature of the global water cycle or hydrological cycle. Of the total water on earth the sea contains nearly 97,5%, while the balance of 2,5% is in the form of fresh water. This fresh water resource is found in three separate forms:

1) bound in glaciers and permanent snow caps in the Arctic and Antarctic and high altitude mountain peaks (68,9%)
2) groundwater, soil moisture, swamp land and permanent frost (30,8%)
3) water in bodies such as rivers and lakes and natural storage reservoirs (0,3%)

The fresh water from lakes, rivers and some groundwater is considered to be the most accessible according to Turton (2010) and Anderson (2003) and this useable fresh water is estimated to be less than 1% of total water on the planet and has to be shared with aquatic ecosystems.

2.2 GLOBAL WATER RESOURCE APPRAISAL AND ASSESSMENT

Several appraisal and assessments of the global water resources and their use were made over the past decades. According to Shiklomanov (2000) the most comprehensive studies were by Russian and German researchers that resulted in two monographs published in the mid and late 1970s. Shiklomanov (ibid) reveals that although data from these studies are generally considered as very reliable, data for different countries may vary up to 40% due to different approaches used for river flow calculations. Among institutions that published data cited by Shiklomanov (ibid) are the data of the USA World Resources Institute which were used by various researchers for analysis of global water resources and availability in the late 1980s and early 1990s.

In order to provide more future expected scenarios Shiklomanov (2000) embarked on a study of global water resources and use in 1995. Meteorological data and observations for over 2 500 hydrological sites together with hydrological models were used to assess renewable water resources globally. Although per capita resource availability was originally done by Shiklomanov (ibid), these were revised in this study to account for more recent United Nations (UN) world population projections (2008) being available. These revised per capita water availability values together with the Shiklomanov (ibid) average renewable water resource data are given in Table 2.1.

The UN world population data used for the calculation of availability is given in Appendix A1. Shiklomanov's renewable resource availability values for continents are based on mean river runoff without taking into account any variations thereof. Shiklomanov (ibid) points out that for minimum renewable resource values compared to the average, the factor would be a decrease of around 1,2 times to about twice the average value.

In the case of Europe the resource per capita availability virtually remains the same due to an expected near zero population growth over the next three decades.

Table 2.1 Renewable water resources and availability by continents

Continent	Average renewable water resources (km^3/year)*	Potential water availability (m^3/ca/yr) #			
		2000	**2010**	**2020**	**2030**
Europe	2 900[1]	3 991	3 958	3 957	4 009
North-America ©	7 890	16 021	14 421	13 178	12 290
South-America	12 030	34 628	30 594	27 963	26 263
Africa (North-Africa)	4 050 (111)	4 942 (618)	3 920 (521)	3 173 (448)	2 657 (400)
Asia	13 510	3 653	3 242	2 939	2 748
Oceana	2 400	77 022	66 968	59 511	53 845
The World	42 780	6 995	6 192	5 574	5 149

* after Shiklomanov (2000) also p28 Tab 9 FAO

\# Water availability is the value of average renewable water resources per capita, based on UN population data (2008)

© according to Shiklomanov consists of “North-”and “Central-America” + “Caribbean”

[1] Russian federation was split into Asia & Europe -FAO Tab 9 note 5

The water resource availability levels and corresponding issues of sustained human livelihood and agricultural and industrial development potential, according to Shiklomanov are as follows:

< 1 000m^3 per capita per year – catastrophically low
1 000 to 2 000 m^3 – very low
2 000 to 5 000 m^3 – low
5 000 to 10 000 m^3 – average
10 000 to 20 000 – high
> 20 000 m^3 – very high

To sustain human livelihood of a minimum survival diet (for food production and drinking water requirements) would require 1 m^3 of water per capita per day, while the more common needs are between 2,5 m^3 to 5 m^3 (for low animal and high animal diets respectively) and a high animal-product based diet as much as 10 m^3 per day (Renault 2003). Considering these basic life support water requirements, it is evident that availability per capita levels less than 1 000 to 2 000 m^3 per year would be able to barely sustain livelihoods, but inadequate for sustaining agriculture or industrial development. With these values of water availability, very serious problems arise unavoidably with population life-support and industry and agriculture development (Shiklomanov 2000). Therefore, for sustained agricultural and industry development to be possible higher levels of resource availability would be required.

Although resource availability per capita for the world as a whole would remain at an “average” level over the next two decades, for individual continents it varies from resource abundance for the America’s and Oceania and low availability levels for Europe, Africa and Asia, depending on various hydrological factors. The situation would be worse for arid regions within continents and regions thereof particularly with extreme drought conditions. As an example, the resource availability for North-Africa is also given in Table 2.1 to illustrate variation of a region within a continent and in particular that of an arid region.

Falkenmark (1989) undertook a study using traditional water-balances (based on the so-called L’vovich’s hydrological maps and generalised hydrological information), to arrive at a 1st approximation of water availability for countries of the world. The fresh water resource data was then used to determine a so-called “Water Competition Level” being indicative of the number of people dependent (for meeting food, household and industrial needs) on a unit flow of resource of a million m^3 per annum. The initial term of ‘Water Competition Level’ has subsequently changed to the “Water Crowding Index” (WCI) (Turton 2010).

For availability assessment purposes for sufficiency in meeting food production and various water-dependent societal needs, Falkenmark (ibid) identified five levels of the WCI. These WCI levels are as follows (with corresponding problems and constraints):

1) < 100 persons/flow unit (well watered)
2) 100 – 600 persons/flow unit (moderate problems)
3) 600 – 1 000 persons/flow unit (water stressed)
4) 1 000 – 2 000 p/flow unit (chronic water scarcity)
5) > 2 000 p/flow unit (beyond ‘water barrier’)

A brief description of management issues related to each of the above WCI levels according to Ashton (2002) are given in Table 2.4.

In terms of the categories identified, a level of 2000 persons/flow unit is considered as an absolute water barrier beyond which economic development is not possible based on technology available at the time. Falkenmark (ibid) further points out that the scarcity values have to be considered in the light of added complication scenarios, being:

1) for arid/semi-arid climates higher water demand would be required for crop yields
2) where river catchment basins are shared by several countries the impact of increased upstream use will result in decreased resource availability downstream
3) intermittent drought years aggravate conditions of having sufficient water resources available. Provided water demand remains relatively low, water scarcity problems could mainly be during such intermittent drought periods.

A summary of the regions of Africa (excluding South Africa as data were not made available for the study) is given in Table 2.2, illustrating the expected WCI status for the years 1982, 2000 and 2025 respectively. A detailed illustration for Africa by region and country is given in Appendix A2. Falkenmark (ibid) pointed out that even though the estimates have limited precision, it nevertheless are indicatory of whether more detailed national studies should be carried out and also serves as an early warning mechanism to countries heading towards “chronic water scarcity”.

Based on the 1989 projections made by Falkenmark (ibid), regions of Africa as a whole such as North- and East-Africa were expected to move into a “water stress” condition by the year 2000. Figure 2.2 shows that by the year 2000 only six countries in Africa (about 15%) were expected to be under either conditions of "water stress" or "chronic water stress", but by 2025 the number of countries is expected to increase to sixteen (nearly 40%). In addition, by 2000 no country were expected to be beyond the 'water barrier' level, but by 2025 about five countries (approximately 10%) would be experiencing wide scale water scarcity problems. The WCI level distributions of the number of countries per region and Africa as a whole are given in Appendix A3.

Table 2.2 WCIs for regions of Africa (derived from Falkenmark 1989)

Region	**Water Crowding Index (initially water competition level)** (no. of people/million m^3/year)		
	1982	**2000**	**2025**
Eastern Africa	312	593	1195
Middle/central Africa	22	37	69
Northern Africa	341	551	870
Southern Africa*	169	319	634
Western Africa	109	200	394
* South Africa excluded from study (data not made available at the time of study)			

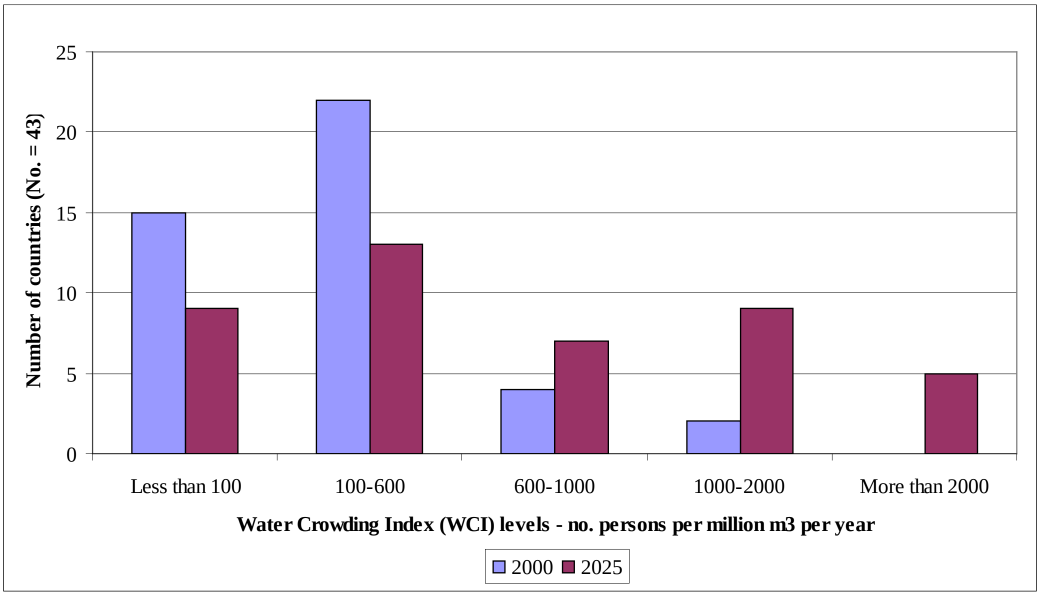


Figure 2.2 WCI levels of countries in Africa (derived from Falkenmark 1989)

An exercise along similar lines to that of Falkenmark (ibid), was done for South Africa by the Council of Science and Industrial Research (CSIR) (Turton 2010). The results for some of the river catchment basins are given in Table 2.3, that shows that all four river basins of South Africa listed are already at “chronic shortage” level and that the Limpopo-basin is already far beyond the “water barrier” level. By the next decade or so it is likely that all these basins will be beyond the “water barrier” level with a general water shortage and severe conditions during periods of drought.

Table 2.3 WCI for some river basins in South Africa (after Turton 2010)

River basins	**2000**			**2025**		
	Population (1 000s)	**Water resources** (million m^3/yr)	**WCI**	**Population** (1 000s)	**Water resources** (million m^3/yr)	**WCI**
Orange-Senqu	11 319	9 568	1 183	19 502	10 816	1 803
Limpopo	10 906	2 585	4 219	18 790	3 778	4 974
Incomati	1 122	723	1 552	1 934	837	2 310
Maputo	1 166	847	1 376	2 009	849	2 366

The Falkenmark (ibid) approach of managing water resources with emphasis on the demographic dimension required dealing with a more contentious issue of population growth and associated need of additional supplies. However, in order to have a more manageable issue to deal with, a switch to an approach of adequate water quantity per capita was made. For comparison both the original WCI levels and the Ashton modified WCI (inverse of WCI) are given in Table 2.4 (Ashton 2002). Ashton (ibid) points out that a switch of emphasis to adequate water supply per capita, not only presented a more manageable issue to deal with, but also established such measure as driver for a supply-based technology approach for mobilisation of additional resources.

In addition, developments of wastewater recycle and reuse technologies and demand management through water use reduction devices as well as the investigation of unconventional resources of water were initiated. Ashton (ibid) also noted that a deficiency of the initial WCI as formulated by Falkenmark, is the lack of information provided on the actual fraction of resources that could be mobilised for use by society. As mentioned before, population growth and the increased water supply demand will ultimately result in a decline of finite fresh water resource, even with suitable technology to make use of resources. The question of dealing with the continually changing levels of supply has to be dealt with in the social, economic and technological domains.

Table 2.4 WCI categories, Ashton's modified WCI and Shiklomanov scarcity indices (after Ashton 2002, Shiklomanov 2000)

Scarcity category and associated problems	**WCI** (no. people/ million m^3/year)	**Ashton index** (m^3/person/year)	**Shiklomanov Index** (m^3/person/year)
Well-watered: Very infrequent water supply and quality problems, except with extreme drought conditions.	< 100	> 10 000	10 000 – 20 000 (high)
Moderate: Occasional water supply and quality problems, with some adverse effects during severe droughts.	100 – 600	1670 – 10000	5000 – 10000 (average)
Water stressed: Frequent seasonal water supply and quality problems, accentuated by occasional droughts.	600 – 1 000	1 000 – 1 670	2 000 – 5 000 (low)
Chronic water scarcity: Continual water supply problems, worse during annual dry seasons and frequent severe droughts.	1 000 – 2 000	500 – 1 000	1 000 – 2 000 (very low)
Beyond "water barrier": Continual, wide-scale water supply problems, becoming catastrophic during droughts.	> 2 000	< 500	< 1 000 (catastrophic)

Comparing the Ashton and Shiklomanov water indices of resource availability per capita (Table 2.4), it is evident that the limits of the respective envelopes overlap substantially. For the "beyond water barrier" category Ashton's modified WCI is below 500m^3, while the corresponding Shiklomanov value is 1 000 m^3. The "well watered" category for both indices is relatively similar. For the intermediate categories the ranges of the two indices differ substantially and indicative of an arbitrary categorisation by the two researchers.

2.3 IMPACT OF CLIMATE CHANGE ON RESOURCE AVAILABILITY

The resource availability projections used by Shiklomanov (ibid) and Falkenmark (ibid) referred to previously, do not allow for any changes in water resource availability due to climate change. The global changes expected in precipitation due to climate change by the end of this century (compared to the beginning thereof), are illustrated Figure 2.3 (Meehl *et al*. 2007).

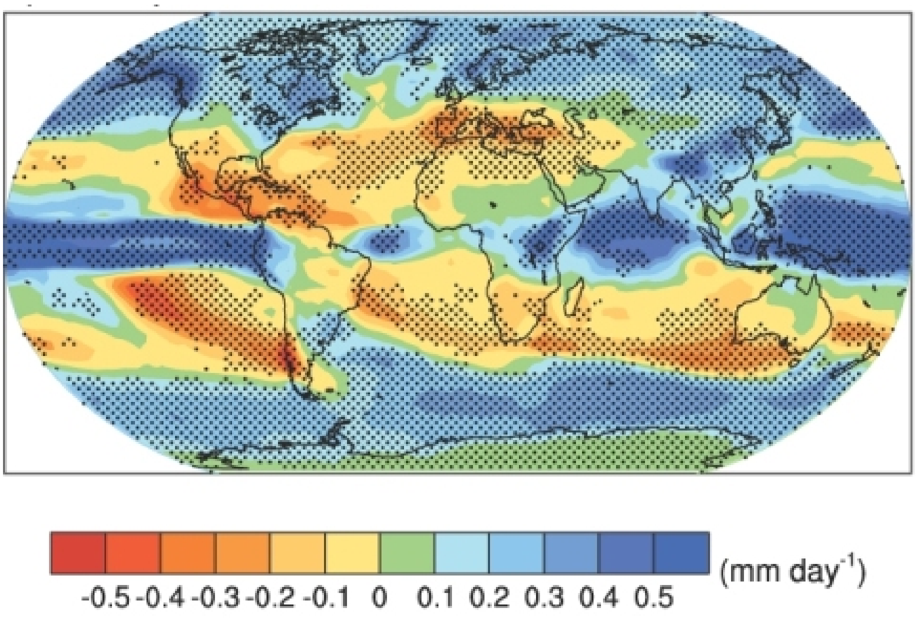


Figure 2.3 Global projection of expected changes in precipitation as a result of climate change (after Meehl *et al*. 2007)

As a result of climate change precipitation is likely to decrease in Europe as well as North and Southern Africa. This implies that for Europe the water resource availability is likely not to increase as suggested in Table 2.1, while in the case of North and Southern Africa scarcity will increase further than projected by both Shiklomanov (ibid) and Falkenmark (ibid).

The WCI of Falkenmark as well as the Ashton and Shiklomanov water availability indices does not take multiple use of water into account. Reuse will impact these indices positively due to a net increase in the water resource volume available. This will result in increases in the water supply indices of Ashton and Shiklomanov (increased available supply per person) and a decrease in the Falkenmark WCI values (less number of people per available resource flow unit).

2.4 VIRTUAL WATER (VW) AND WATER FOOTPRINT (WF)

According to Hoekstra (2003), the concept of ‘embedded water’ or ‘virtual water’ was first introduced by J.A. Allen in the early/mid 1990s. By international trade virtual water from more abundant soil water regions are conveyed to comparatively disadvantaged regions (Allan 1998). This scenario provides opportunity for the concept of virtual water through import (not real water, but that embedded in food products) to be a mechanism to release pressure on countries with high water scarcity levels. The extension of the virtual water concept termed the Water Footprint (WF) was introduced by Hoekstra and Hung (2002), to express the annual cumulative virtual fresh water content of all goods and services consumed by a single individual or all individuals of a country to sustain its population. The total water use of a country would generally be the sum total of the domestic, agricultural and industrial water sector databases kept for the economy. The WF however differs from this audit in that it also reflects the effect of import and export of goods of a country in terms of the embedded or virtual water requirement of such goods. In addition to being a production sector-based quantities indicator, it is also gives information of countries related to consumer patterns of water use through allowance for virtual water flows between nations (Chapagain and Hoekstra, 2004a). The WF can be expressed for a product or service, at different scales such as for an individual, community, and a nation or even as a global indicator of human appropriation of the available freshwater resources on planet earth as a whole. This requisitioning of water at the various levels mentioned has to be compared with the annually available freshwater resource to determine the level of resource usage.

Three components are distinguished in the determination of the WF, i.e. the green, blue and grey WFs. The green component is the volume of water evaporated from the global green water resources being rainwater stored in the soil as soil moisture. The blue component is the volume of freshwater that evaporated from the global blue water resources, being the surface water and ground water, to produce goods and services consumed by an individual, community or nation. The grey component is the volume of water that is polluted by the production processes of all goods and services mentioned and therefore represent the fresh water volume required to assimilate pollution. **However, the grey component (allowance for wastewater pollution impacts) does not account purified wastewater being reused as a replacement for use of green and blue water components**. A link between the footprint and wastewater intrinsic value recovery could therefore be made resulting in a reduction of the internal water footprint of a community or nation which is discussed in more detail later.

In a UNESCO-IHE study done in 2004 (Chapagain and Hoekstra, 2004a), resulted in the water footprint for most nations of the world being calculated for the period 1997–2001. This study compared to similar previous ones, used a more refined methodology and more accurate data which allowed a larger variety of products to be covered. Distinction was made between an internal and external WP. The internal WF covers water used from local water resources to produce the goods and services consumed by the inhabitants of a country. The external WF is water used in other countries to produce goods and services which are imported for consumption by the inhabitants of the said country.

The method followed for calculating the WF is illustrated in Figure 2.4.

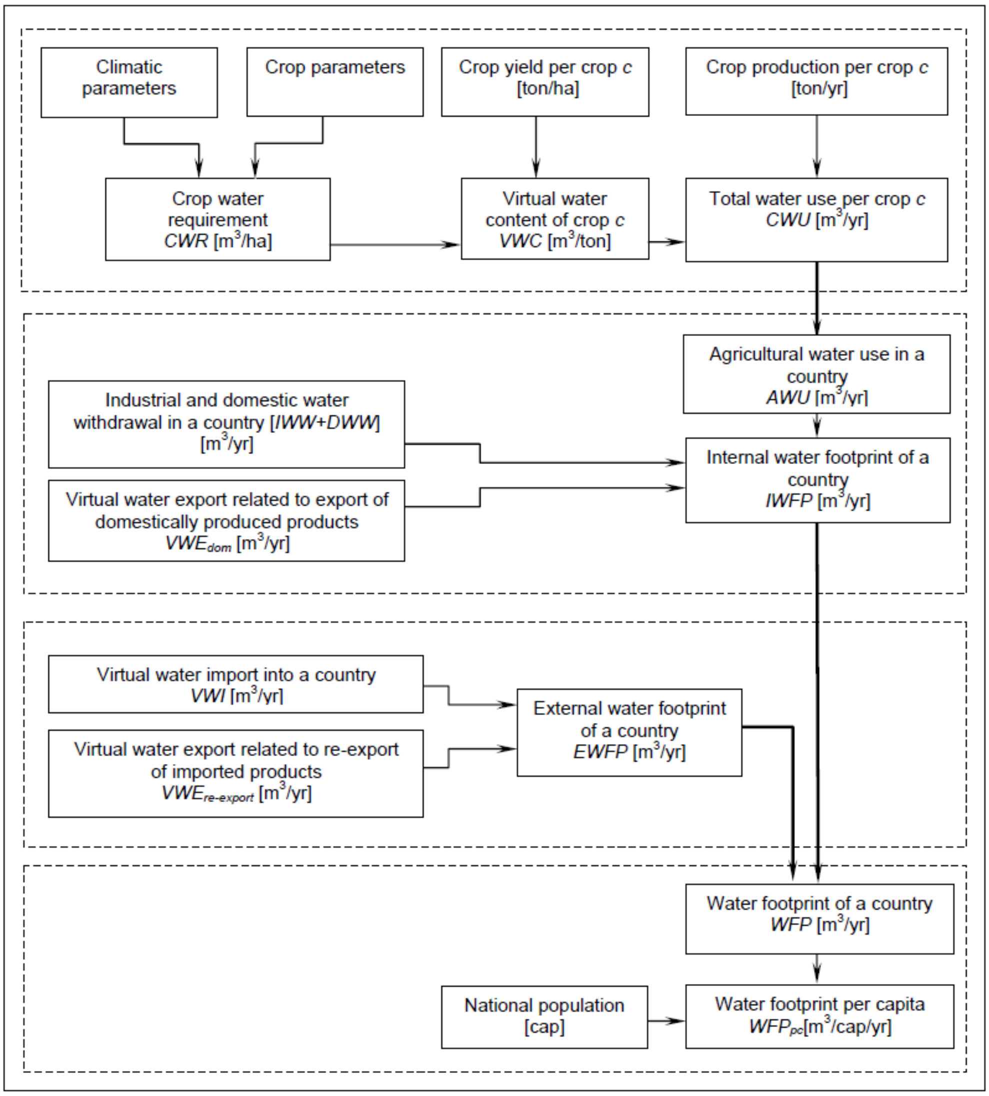


Figure 2.4 Water footprint of a nation – calculation methodology (after Chapagain and Hoekstra, 2004)

The method of deriving the WF in a qualitative sense is briefly described next. The internal WF covers water use in the agricultural, industrial and domestic sectors within the country concerned. For the agricultural sector the total volume of water is based on the total volume of crop produced and its corresponding virtual water content. The virtual water content (in cubic metre per ton) of primary crops in turn is calculated based on the crop water requirements and yields. The virtual water content of particular crop products is calculated based on product fractions (ton of crop product obtained per ton of primary crop) and value fractions (the market value of one crop product divided by the aggregated market value of all crop products derived from one primary crop). For livestock the virtual water content is calculated based on the virtual water content of their feed and the volumes of drinking and service water consumed during their lifetime. For livestock products the virtual water content is based on product fractions and value fractions.

When determining virtual water flows between nations the statistics on international product trade and the virtual water content per product in the exporting country is used.

The water footprint of a nation is calculated as the total use of water resources domestically, adding virtual water flows entering the country and deducting virtual water flows leaving the country.

The WF concept because of its composition allows for it to serve as an indicator of freshwater appropriation in relation to freshwater availability.

2.4.1 Indices related to evaluation of availability of fresh water resources

The *water scarcity* (*WS, %*) of a nation is the ratio of the nation's water footprint (*WFP*) to the nation's water resources availability (*WA*). If a nation's water scarcity is more than 100%, it indicates that there is more water needed for producing the foods and services consumed by the people of a nation than what is available in the country. W*ater import dependency* (*WD in* %) of a nation is the ratio of the external water footprint (*EWFP in* m^3/yr) to the total national water footprint (*WFP in* m^3/yr). National *water self-sufficiency* (*WSS,* %) is defined as the ratio of the internal water footprint (*IWF*, m^3/yr) to the total national water footprint. The self-sufficiency is 100% if all the water needed is available and indeed taken from within the own nation's territory. A value of zero is approached if the demands of goods and services in a country are heavily met with gross virtual water imports, i.e. it has relatively large *external water footprint* in comparison to its *internal water footprint* (Chapagain and Hoekstra, 2004a).

Based on the Chapagain and Hoekstra study, the largest WF contributor globally is the agriculture sector at around 86 %, followed by the industrial sector and domestic consumption at around 9% and 5% respectively (Figure 2.5). Globally the total external WFs represents a contribution of 16%, with agriculture also being the largest at 13% (around 80% of external WF) and the industrial sector the balance of 3% (Figure 2.6). Thus agriculture dominates both internal and external WF impacts. Sufficient food production to satisfy an ever increasing population will require focus on more intense agriculture. This could result in less of the resource being made available for the domestic and industrial sectors within the limitations of a finite fresh water resource.

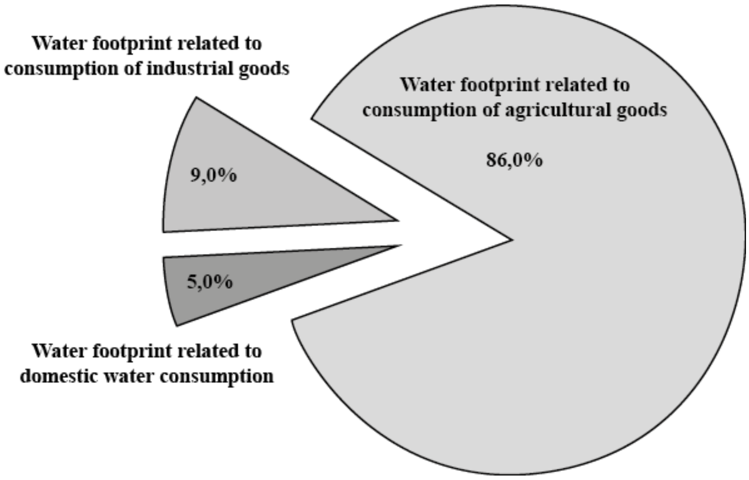


Figure 2.5 Global WF per consumption category (after Chapagain and Hoekstra, 2004)

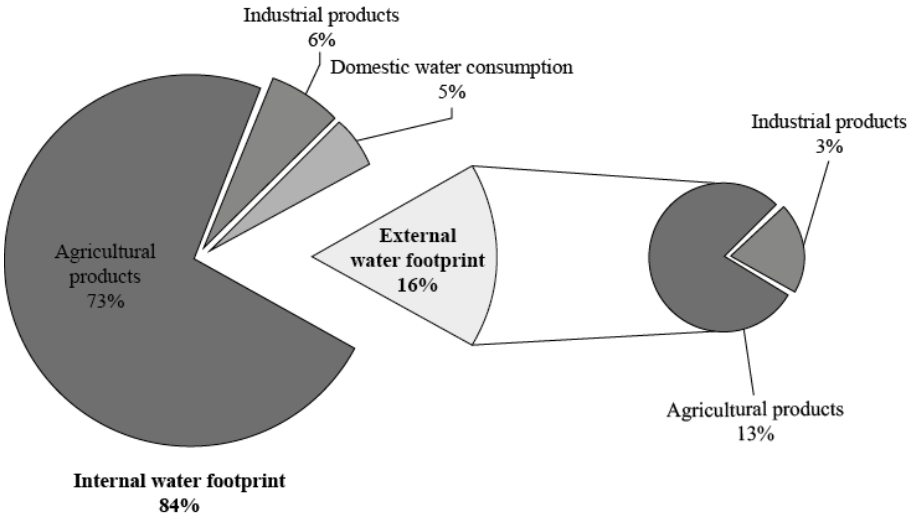


Figure 2.6 Global internal and external water footprint of consumption categories (after Chapagain and Hoekstra, 2004)

As mentioned before the contributions do not allow for any wastewater intrinsic value recovery through reuse which will result in reduction of water resource use and a net lower internal water footprint and also assist in mitigating possible reduced water allowances for strategic industrial demands.

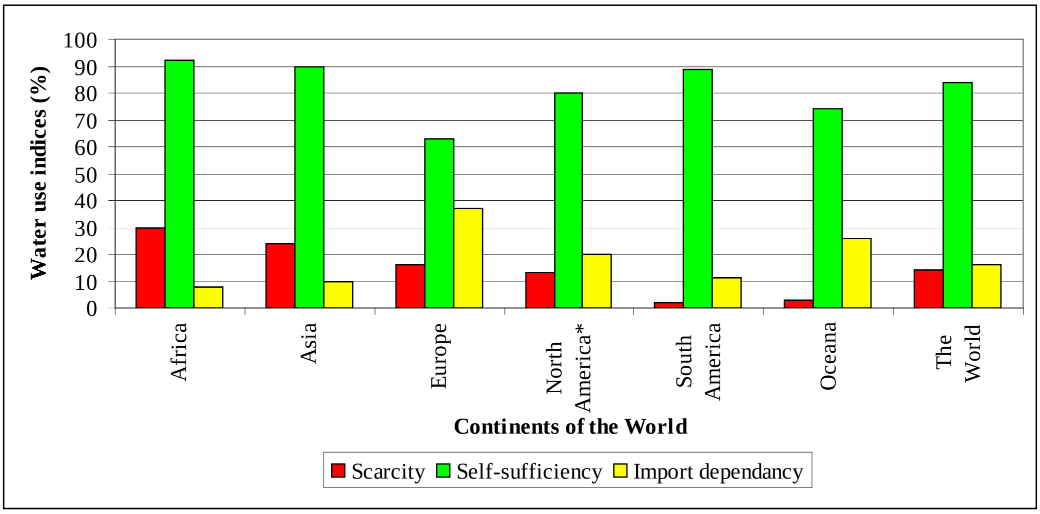


Figure 2.7 Water use indices – continents and the World as a whole (derived from Chapagain and Hoekstra, 2004)

According to the study of Chapagain and Hoekstra (2004), the continent with the highest ‘water scarcity’ (i.e. fraction of overall use of renewable water resources) at the start of the 21st century is Africa with around 30%, followed by Asia with about 25% (Figure 2.7).

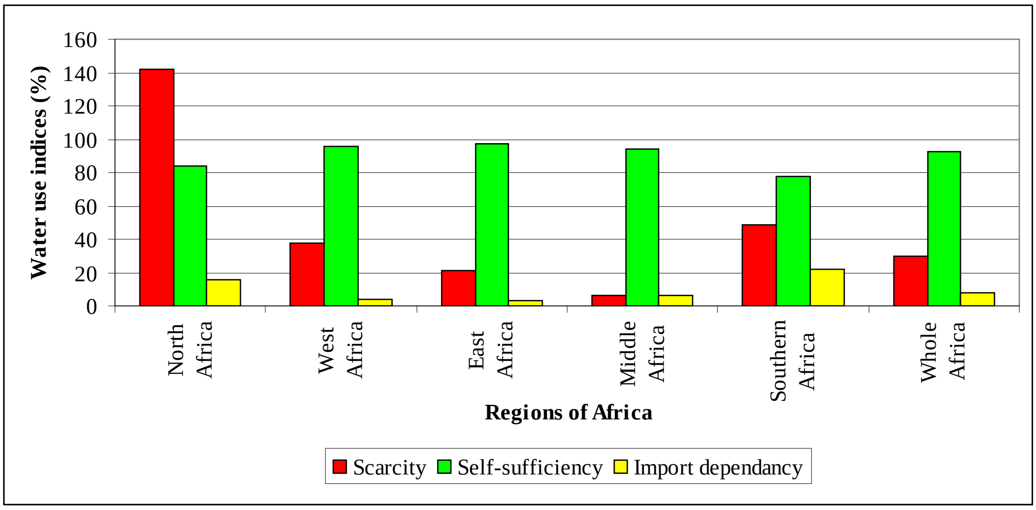


Figure 2.8 Water use indices for Africa (derived from Chapagain and Hoekstra, 2004)

For the continent of Africa the highest ‘water scarcity’ is in Northern Africa with just over 140%, followed by the southern region at nearly 50% and the western region at close to 40% (Figure 2.8). For Africa the self-sufficiency level (i.e. use of the available water resource within the region itself for meeting needs) varies from 80% to 97% with a virtual import dependency of between 3% and around 20%. The northern and southern regions are those with highest virtual import, while higher self-sufficiency occurs in the central and northern regions. The higher import dependence of the northern and southern regions of Africa could possibly be due to their close proximity to the Middle-Eastern or even European and South African economies respectively.

The Chapagain and Hoekstra study mentioned estimated the indices of “water scarcity”, “water self-sufficiency” and “water-import dependency” for South Africa, based on a total renewable water resource of 50 000 million m^3/annum, as 79%, 78% and 22% respectively. In the latest report of assessment of water resources of South Africa by the Water Research Commission of South Africa (Middleton and Bailey, 2008), completed in 2007, the previous extent of resource of approximately 51 100 million m^3/annum was revised and set at 49 210 million m^3 for the area inclusive of the countries of South Africa, Lesotho and Swaziland. Although the resource value used is considered reasonable compared to the latest WRC data, it appears that the WFs of the countries of Swaziland and Lesotho were not taken into account for comparison with the resources inclusive of that of all three countries. Should the WFs of all three countries be allowed for, the water use indices of “water scarcity” and “water self-dependency” for South Africa would be somewhat higher, while “import dependency” will decrease according to the increase in the self-dependency value depending on the change in WF values.

Furthermore, in addition to surface water resources, the WRC report also gives an estimated resource value of utilisable groundwater that may be extracted on a sustainable basis amounting to approximately 7 500 million m^3/annum. Should groundwater be taken into account together with surface water resources (total resource becomes 56 710 million m^3/annum) and WFs remain of the same order, then the ‘scarcity’ index for South Africa is expected to reduce potentially to about 70%, while both ‘self-dependency’ and ‘import dependency’ values will remain similar.

2.5 INTERVENTION POINTS IDENTIFIED TO DECREASE THE WATER FOOTPRINT

By exploring other unconventional resources (i.e. wastewater reuse, seawater desalination, etc.) to either supplement or substitute finite natural resources would not only contribute to avoiding depletion of such resources, but also the marginalisation of other use sectors such as industry which are strategic for economic development in any country.

If one considers the virtual water concept impacts on the Water Footprint, five distinct intervention points can be identified where the water footprint of a country can be reduced. For clarity these positive impacts (“+”) are indicated on the WF calculation methodology diagram as shown in Figure 2.9 and details of each point is discussed below:

1. *Crop parameters*

   Specific crop parameters determine the water demand of a particular crop. The overall water footprint can be reduced by a reduction of the crop water demand. This could be achieved by crop substitution with less water intensive crops or a genetic selection and modification to low water demand crops. This aspect is beyond the scope of the thesis and would not be discussed further.

2. *Industrial and domestic water withdrawal*

   The uses of water for industrial and domestic purposes increase the impact on the water footprint (the higher the withdrawal the higher the footprint) and any reduction of water withdrawals will reduce the water footprint accordingly. It follows therefore that any improvement in the efficiency of water use will reduce the water footprint or management of a water footprint of a nation starts with water withdrawal. By multiple use of the water withdrawn, a significant reduction of total water withdrawals can be achieved. The concept of multiple use of water withdrawn establishes a link for wastewater reuse and reuse being positioned as a principal tool in reducing the total water footprint.

3. *Virtual water export related to export of domestically produced goods*

   Export from a country of domestically produced goods result in increase of the water footprint. The implication is that with reduction of exports (especially the exports of high VW products), the water footprint would be reduced. While this is a viable way to reduce ones water footprint, such action is contrary to the interests of the economy and is not usually considered as a viable option for reducing the water footprint.

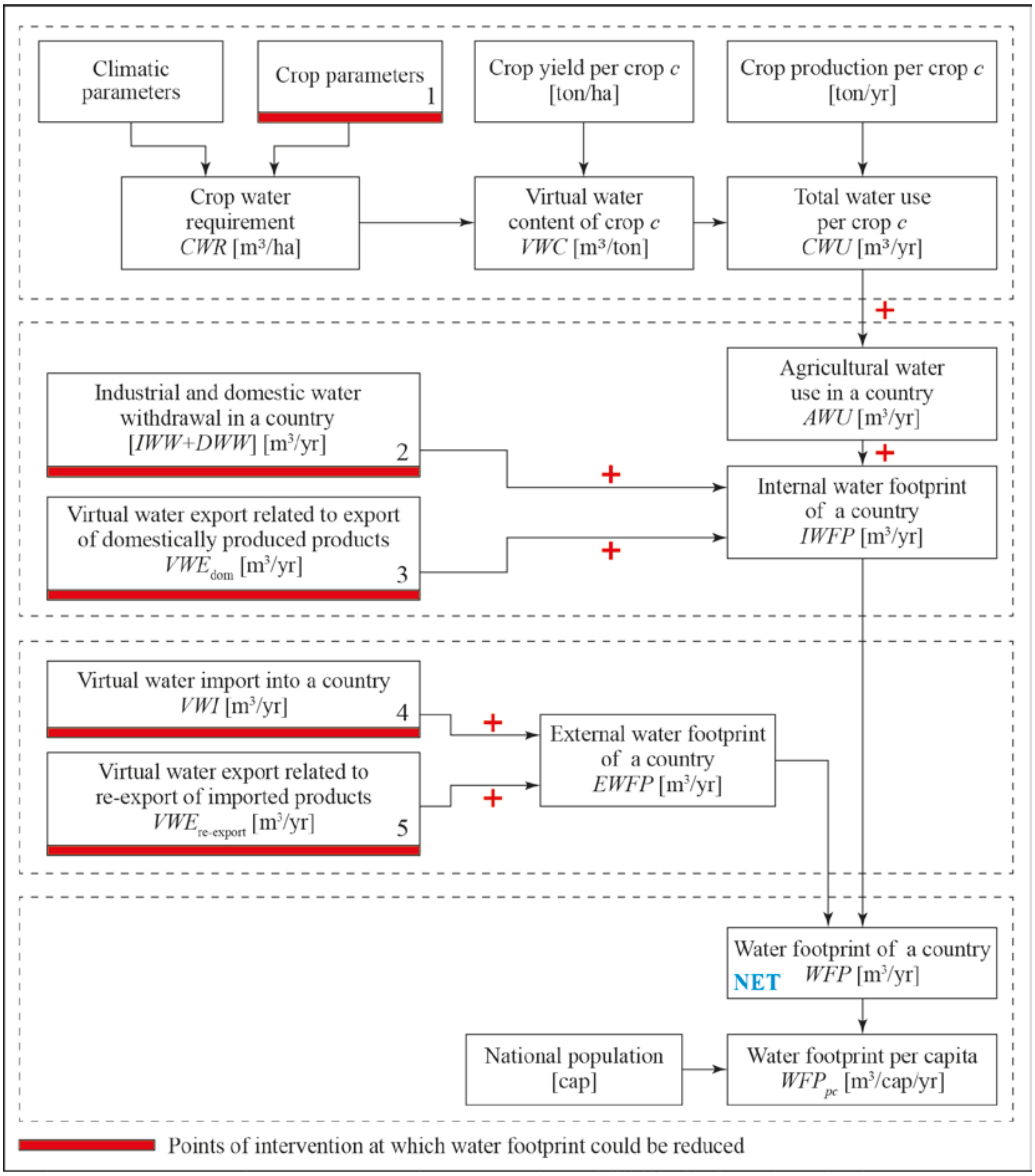


Figure 2.9 Intervention points for reducing the water footprint of countries by reuse

However, what this implies is that export of products with high VW content, (especially when export prices do not account for full cost of the VW contained within the exported products and/or crops), should be avoided as much as is possible as it is in effect subsidising consumers elsewhere in the world. More detailed analysis of this are beyond the scope of this thesis.

4. *Virtual water (VW) import into a country*

Import of products into a country also results in an increase of a water footprint. Again as the case with exports, reduction of imports to reduce the water footprint is contrary to the interests of the economy and is not usually considered as a viable option. However, what this implies is that import of products with high VW content (especially when import prices do not account for full cost of the VV contained within the imported products and/or crops) should be stimulated as much as possible as it is in effect subsidising domestic consumers despite the fact that it is increasing the countries water footprint. More detailed analysis of this are beyond the scope of this thesis.

5. *Virtual water export related to re-export of imported products*

   Discussion given under intervention points 3 and 4 above also applies here.

The above discussion implies that reduction of water footprint is dependent on the extent of water withdrawal reduction and this could be enhanced through encouragement and implementation of multiple water use through reuse. In this research an attempt is made to address multiple water use through reuse.

CHAPTER 3

SUSTAINABILITY IN WATER MANAGEMENT

3.1 SUSTAINABILITY CONCEPTS

Since the early 1970s environmental issues have become basic reference points of the performance of society with respect to efficient use of resources, sustainable economic performance, social well-being and concern for future generations (Fricker 1998).

Hermanowicz (2005) points out that the concept of sustainability has its roots far back in human history and was developed from an initially very simplistic concept requiring self-sufficiency that has changed in meaning over time to take cognisance of the redefinition of “self” to mean humanity self-sufficiency over the long term. Originally, meeting human needs by available natural resources implied the sustainable use of such resources. From a water resources perspective, increased water demand for human, agricultural and industrial use over time resulted in additional resources being mobilised and the underlying simplified concept of sustainability being that of supply at least matching demand. With continued growth in water demand and associated larger wastewater discharges, water sources became more polluted and the concept of sustainability changed. The quality of water supply became prevalent and water treatment a necessity. Sustainability became more comprehensive in that the available resource had to match the demand with respect to both quantity and quality and advanced technical solutions had to be implemented to achieve this. However, the linear approach of water supply being abstracted at source and then used and returned in the form of wastewater back to the environment (with inferior quality) remained and resulted in a linear chain as illustrated in Figure 3.1.

The introduction of alternatives to meet demand by direct reuse (or water reclamation) as opposed to the mobilisation of additional fresh water sources resulted in the concept of sustainability having to account for such an alternative. Reuse makes used water available as a substitute to fresh water sources and result in the said linear water system being potentially reduced to a closed loop of the urban hydrologic cycle (Hermanowicz and Asano, 1999).

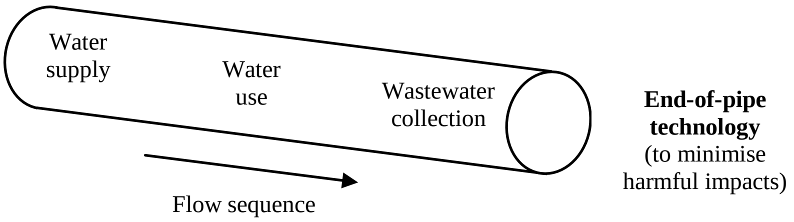


Figure 3.1 Linear end-of-pipe water systems (derived from Wilderer 2001)

Direct water reuse closes the linear open ended system and allows for mitigation of negative impacts of the natural environment. This however has a potential of conflicting with societal perceptions and corresponding psychological barriers of acceptability.

Furthermore, reuse systems do have some disadvantages. The more advanced treatment required to alleviate health concerns as well as the additional distribution systems and quality monitoring and management thereof occur at a cost premium.

The new paradigm of sustainability requires the assessment of all water resource supply systems that include water reuse as an option. Within the technical and economic constraints of such systems, the evaluation of the broader environmental and social impacts must be made.

The World Commission's Brundtland report (1987) states that "*sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs*". Although generally considered to be the expression of today's standard for sustainable development it is not specific at all, nor does it give a clear directive on the practical application thereof and could be interpreted in different ways (Fricker 1998). Beck *et al*. (1994) refers to a research background document of the Netherlands Organisation for Scientific Research (NOW, 1992) which distinguishes between sustainability and environmental quality concepts and clarify this as follows:

"*Sustainability is a way in which society utilizes the environment. The environmental load that follows from social activities should be 'ecologically suitable*". This means that the functioning of regeneration systems, absorption capacities and other parts of the ecosystems is guaranteed, both quantitatively and qualitatively. The environment is seen as a set of resources for society. Sustainability therefore refers to the continued existence of the socially functional components of ecosystems, but sustainability implies the use that is made of these components is limited. The concept of environmental quality serves to place the interactions of society and the environment in a broader perspective than that of a basis or condition. From this perspective, the environment and its components contribute to the quality of life and the well-being of people. In addition, it serves to focus on the intrinsic (non-instrumental) qualities of the environment and its components.

Environmental quality becomes one of the goals of social processes if it is considered from the perspective of human health and quality of life; at least once the 'sustainability condition' has been established. From this vantage point, individual elements of the environment may need to remain less polluted than required for their sustainability. Quality also pertains to environmental values based on ethical, aesthetic, or cultural and historical grounds. This also applies to the intrinsic values of biological diversity, and the conditions under which these values can develop."

The above authors in essence emphasises that environmental quality is a goal to be strived for once sustainability in use of the environment is guaranteed. They further conclude that within an inclusive sustainability strategy, the goal of environmental quality, amongst others, must involve refinement of particular environmental elements that will contribute to human health as well as quality of life. Harremoës (1997), also emphasis that by confusing quality of life issues with sustainability will result in sustainable development in future to be wrongly perceived causing future development to take the wrong path. The cited authors also give a clearer demarcation of the sustainability concept which allows for the formulation of clearer societal objectives within the water management domain.

Distinguishing between resources and ecosystems as two broad environmental concerns and bearing in mind the context of the Brundtland report mentioned earlier, the following objectives for sustainability are given by Harremoës (1997, 1999):

1. *Concern for resources*

   Resources must not be exhausted and society must make use of them in such fashion that such a catastrophe is avoided. Within the water management domain the resource of interest is water and the focus here is therefore water conservation and resource protection.

2. *Concern for ecosystems*

   Society should take measures to protect the environment against irreversible functional damage including protection of unique species and habitats and their functional roles.

If sustainability is defined as the use of the environment by society at an ecologically suitable level, the quantification of sustainability or its assessment presents a challenge. A reasonable quantitative definition is required of sustainability to incorporate and allow consideration of the concept in normal business and societal activities. Hermanowicz (2005), suggests the use of a descriptor, similar to a currency unit (as in the case of economic analysis), which is developed per activity and aggregated for whole systems. This descriptor is used as a tag for meaningful comparison of the sustainability of alternatives and not the assessment of individual activities as such and is used in the context of a framework together with a monetary metric. As the least expensive product is not necessarily considered as being the desirable one from the economics perspective each “sustainable” activity is not necessarily considered better irrespective of environmental impact standards that apply.

The Triple Bottom line (TBL) approach articulated by Spreckley in 1981 and often attributed to John Elkington (Brown *et al*. 2006), has the objective of achieving the necessary equilibrium through the establishment of a delicate balance between economic, social and environmental factors for a community, nation and the Earth so that sustainability is achieved (Fricker 1998). TBL provides a framework incorporating both quantifiable and non-quantifiable factors related to costs and benefits across the spectrum of social, environmental and economic goals and objectives. In turn TBL ensures a balanced representation and acts as the basis for the tool for decision-making in evaluation of multiple alternative management options/solutions that cast a wider net in identifying important issues during decision-making (Ilemobade *et al*. 2009). The interlinking of TBL elements of importance for sustainability within the water sector are illustrated in Figure 3.2.

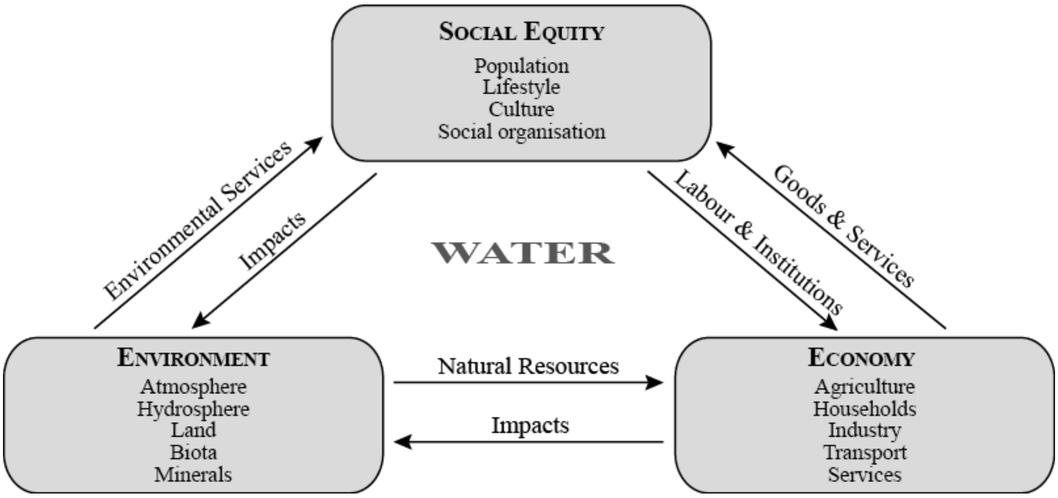


Figure 3.2 Triple Bottom Line sustainability elements linkage in water sector (after llemobade *et al*. 2009)

The TBL analysis indicate the relative extent to which the goals set for the economic, social and environmental domains are achieved by considered options.

Through a sensitivity analyses of the various criteria used to evaluate sustainability with their respective weighting (allocation of differential importance to different criteria), the most critical criteria could be indentified and mitigation measures taken for reduced impacts within the three domains of sustainability (Capital Regional District (CRD) 2007).

There is therefore a need for a paradigm shift in wastewater management consisting of an integrated approach that requires the entire urban water Management concept be reconsidered.

3.2 A PARADIGM SHIFT TOWARDS SUSTAINABILITY FOR WASTEWATER MANAGEMENT

The United Nations (2008) population projections estimate the world's population in 2010 to be around 7 billion and to rise to approximately 8 billion by 2025 (Figure 3.3).

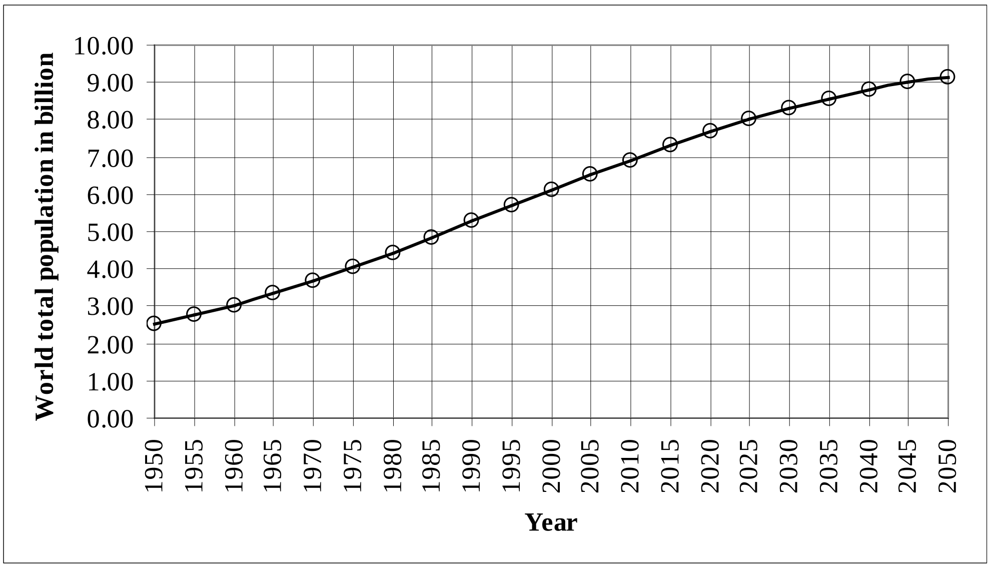


Figure 3.3 Population of the World (in billions) (derived from UN Department of Economic and Social Affairs, Population Division: World Population Prospects, the 2008 Revision)

The UN (2009) further estimated that the proportion of the population in Africa that will reside in urban areas will reach 50% by 2030. The UN (ibid) also claims that 1,3 billion people living in cities with population in excess of one million in 2009 will grow to 1,8 billion by 2025. This implies that by 2025 approximately 25% of all the earth's population will be living in such larger cities. Furthermore, not only will the increased population place a large burden on resources, but the high rate of urbanisation and accompanying population growth would result in increased urban sprawl and slum development phenomena which make the provision of water and sanitary services extremely difficult and costly. The United Nations MDG progress report (2010), emphasises that since 2000 the portion of urban inhabitants of the developing world living in slums have declined from 39 to 33% in 2010. Even though some 200 million slum dwellers gained by obtaining access to a reasonable level of services and improved housing, in absolute terms the population living in slums has actually increased due to eradication measures being insufficient to offset the growth of more slum settlements. It is estimated that in 2010 slum inhabitants accounted for 830 million people compared to 760 million in the year 2000.

Furthermore, the slum sections of urban communities in need of infrastructure will grow unless the provision of services and housing is either heavily subsidised by with grants obtained from the international community and organisations. It is clear that the financial burden of the growing cities to render adequate essential services to all would simply become much more difficult. Under conditions of ever dwindling financial resources available to cities for the purpose of achieving the United Nations MDG and specifically the Goal 7 of a 50% reduction in people without safe water and appropriate sanitation by 2015, would become very difficult if not unlikely to achieve. This further emphasises the urgency for a new water management approach and innovate ideas of options of technology to meet such goals. In essence what is needed is a paradigm shift from the conventional approach. In order to establish what the required paradigm shift would entail it is first necessary to discuss the conventional urban water management (UWM).

3.3 CONVENTIONAL URBAN WATER MANAGEMENT (UWM)

Conventional urban water management of developed countries consist of bulk piped water supplies into cities and the use of extended sewer networks to convey combined waste streams to centralised wastewater treatment plants outside cities (UNESCO-IHE (SWITCH) 2006). Large quantities of potable water, used as waste carrier in these sewered systems, are being facilitated by the seemingly unlimited bulk water supply available.

In the developed world the foundations for these present day technologies for water supply and wastewater treatment were established due to rapid expansion of cities in combination with outbreak of waterborne diseases in the past. The effects on public health with these end-of-pipe systems have been very good, but the sustainability of this approach continues to be questioned (Gijzen 1998). The use of large quantities of high quality water to convey concentrated human waste to centralised treatment facilities located on the outlying borders of cities and beyond makes resource management very difficult and limit fresh water resource conservation. For water-scarce countries this state of affairs is particularly not desirable nor feasible from a sustainability point of view.

How a rapidly growing city short of finances and water and limited institutional capabilities can achieve safe, non-polluting sanitation for all its inhabitants has become the main question that must be answered if the MDGs of the United Nations are to be achieved and the expectations of people be met. According to (Lettinga *et al*. 2001), the high cost of current conventional centralised systems is beyond the economic means of most developing countries. Countries with an average per capita GNP less than US $ 1000 (1994 cost base), lack the resources to construct centralised systems and also cannot afford to maintain them. Lettinga *et al*. also pointed out the fact that such systems have to be rebuilt after 50 to 70 years at increased expense and this makes such systems even more unaffordable for developing countries.

Conveniences like flush toilets are totally dependent on a constant water supply. Supply of clean water, delivery and collection of sewage and the treatment thereof require sophisticated systems whose costs put strain on the financial resources even in most developed countries of the world. The conventional approach therefore needs to be urgently reconsidered to ensure that service delivery is not hampered.

3.4 INTEGRATED WATER MANAGEMENT APPROACH (SUSTAINABLE WATER MANAGEMENT)

Integrated or sustainable water management (water supply, sanitation and wastewater collection and treatment) requires that the entire urban water management concept be reconsidered. Sustainable water management will only be realised if both the waste minimisation (reduced water consumption) and wastewater reuse concept are applied in an integrated way (Gijzen 1998). To effectively manage the challenges, a sustainability driven integrated approach, as opposed to the traditional problem/incident driven one, is required. The need for a new approach is a result of the need to further protect the environment from pollution and to ensure that a high ecological diversity is maintained while at the same time natural resources are conserved by optimal use (Lettinga *et al*. 2001).

Furthermore , the application of cleaner production concepts, defined as the approach in which production processes and activities are carried out in such a manner that the impact thereof on the environment is kept to the lowest level possible, is also seen as a prerequisite for sustainable water management according to Gijzen (1998).

Cleaner production interventions have been successful in the industrial sector to bring about innovative environmental thinking in terms of waste avoidance and reduction. Gijzen (2001) introduced the "cleaner production" concept into wastewater management, by combining of two approaches:

1) pollution prevention
2) wastewater reuses

Although "cleaner production" was developed for industry applications and has a different meaning in the context of urban water, the following essential principles of "cleaner production" compared to corresponding current practice in urban water management highlight the areas of concern (Gijzen and Siebel, 2002).

- *Principle 1 – Use minimum input of resources per unit of product*

  Water use (130 to 500 litre/capita/day) is far in excess of that essential for livelihood to avoid dehydration under normal conditions for an adult is around 2 litre/capita/day (WHO 2003). The largest use occurs in the case of waterborne systems that require high level of technologies to treat the resulting highly diluted waste at great expense. Water supply and sanitation from an ecologically sustainable management approach must be viewed as a single interconnected system with the objective to achieve minimum withdrawal from the resource and reduced discharge to the environment.

  Questions needing consideration are: 1) can waste flows be reduced by appropriate water use interventions, and; 2) can the waste flow itself be reused? Both water demand management interventions and reuse will contribute to water resource conservation.

- *Principle 2 – Do not use input materials of a higher quality than strictly necessary*

  The highest quality purified water is used for flushing toilets, cleaning floors, vehicle washing and garden watering. As early as 1958 the United Nations (Economic and Social Council) stated that "*A no higher quality of water, unless there is a surplus of it, should be used for purposes that can tolerate a lower grade*". Supplying various quality of water into residences would be costly in term of the infrastructure needed. Providing the highest quality for all purposes is equally unsuitable. There is therefore scope for a different water management approach that is water demand driven oppose to the conventional supply driven one that sustain high water consumption and is not contributing to water resource conservation.

- *Principle 3 – Do not mix different waste flows*

  Various wastewater flows are combined at household level (urine and faecal matter, grey water and black water). Often industrial waste and urban storm water run-off also enter the sewage system contributing to an extensive mixed waste flow. The mixing of potentially useful resources with large waste flows result in high dilution and make reuse of specific components less feasible.

- *Principle 4 – Evaluate other functions of by-products before considering treatment and disposal – treatment with reuse objective*

  Waste production is inherent to material and energy conversion processes. Once wastewater flow is reduced to the minimum attainable, then possible uses thereof have to be considered. The vast useful components present in the form of nutrients and organics have both agricultural and food production possibilities. Generally treated effluent rich in nutrients are discharged into open water bodies without any effluent or effluent component reuse. Apart from discarding a potential resource, this action causes pollution of such water bodies.

The application of "cleaner production" principles in tandem with the wastewater disposal options, as defined by Harremoës (1999), resulted in the formulation of the so-called "3-Step approach" for wastewater management which is illustrated in Figure 3.4 (Nhapi and Gijzen, 2005).

The three steps of the "3-Step approach" have the following objectives:

1) to rationalise water use
2) to consider treatment with a reuse objective
3) to augment the self-purification capacities of natural system processes used for wastewater treatment

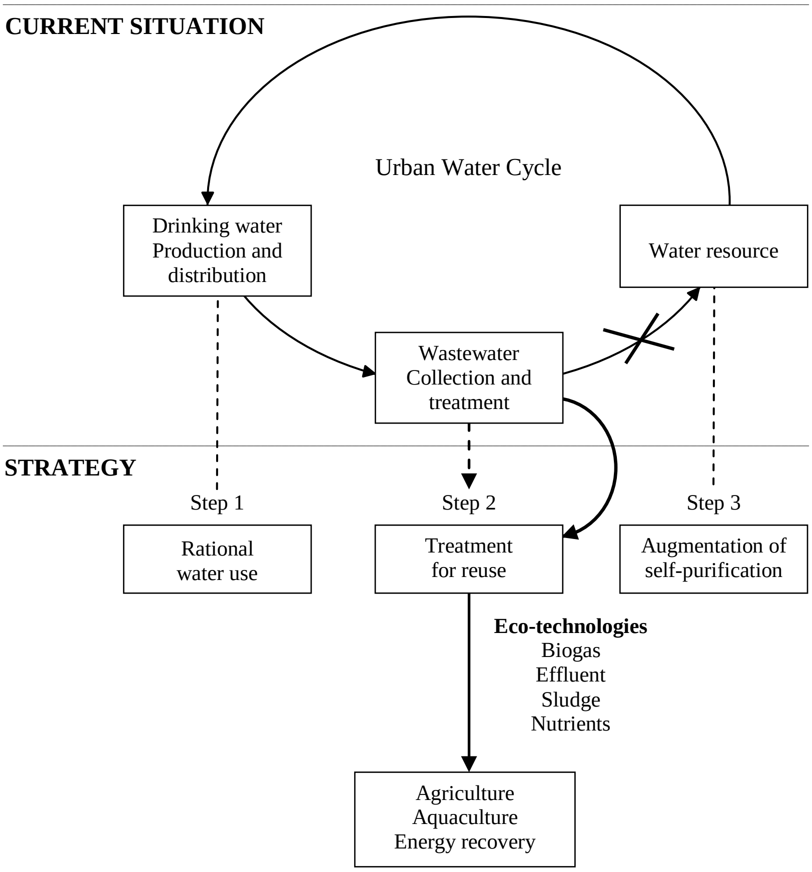


Figure 3.4 The 3-Step approach for intervention in conventional urban water management (after UNESCO-IHE (SWITCH) 2006)

The individual steps of the "3-Step approach" are briefly elaborated on as follows:

- ***Step 1:*** *Rationalise water use – pollution prevention and minimisation*

  This is done through interventions for reduction of water use through the introduction of water saving technologies, low water use or dry sanitation, grey water reuse and banning of the use of undesirable compounds that have a negative impact on the environment.

A household would require highest quality water for drinking, cooking and personal hygiene purposes. In the absence of reuse, the remaining household water use also relies on the highest quality water, while a lesser quality would suffice. The larger fraction of high quality water used ends up as wastewater and without any reuse applied it is “wasted” water. In contrast to the use of highest water quality for all household purposes, a reuse system balances the quantity of high quality water needs with that lesser quality water to meet some household water needs. This system requires storage of different secondary waters intended for reuse while any deficit in the system is supplemented from the potable supply. Potable water use could also be reduced by considering alternative sources such as rainwater harvesting where this is viable.

- ***Step 2:*** *Treatment towards a reuse objective*

  The main objective here is to select treatment processes that best utilise wastewater as resource. The process chosen must convert waste to a useful product such as biogas, fertiliser, etc. In this manner negative impact on the environment is reduced and effluent reuse can be optimised.

- ***Step 3:*** *Augmentation of self-purification*

  The use of natural systems’ self-purifying capacity is maximised to allow for minimum energy inputs as well as by introduction of innovative means for augmentation of the self-purification capacity of natural systems.

The “3-Step approach” is well aligned with The Bellagio Principles (WHO/NEP 2006), which is also given in Appendix A4. Statement 4 of these principles reads: “*The domain in which environmental sanitation problems are resolved should be kept to the minimum practical size (household, community, town, district, catchment, and city) and wastes diluted as little as possible*”. This emphasises that nature’s compensating capacity is limited and negative environmental impacts have to be in relation thereto.

It is noted that a decentralised wastewater management approach results in environmental impacts which are more distributed and smaller in scale than those of centralised systems. Decentralised systems not only allow improved reconciliation with natural system self-purification and compensating capacity, but also allow for improved access to reusable water by desirable users being in close proximity.

Bearing the above in mind the sustainability of the conventional urban water management approach is even more questionable and issues that can be raised are:

1) Whether it is rational to drastically dilute waste if biological treatment could be energy efficient with concentrated waste as for example in the case of anaerobic treatment.

2) Optimal use of the inherent energy contained in organics present in wastewater by using technologies that can achieve a net energy yield (i.e. anaerobic) would be more logical than utilising energy demanding processes for organic load removal which are being practised.

3) Employing expensive high technology tertiary treatment processes for the removal of nutrients from wastewater rather than retaining such nutrients and the reuse as natural fertiliser and also thereby reduces demand for artificial fertiliser at extremely high energy expense and depletion of very scarce natural phosphorus resources.

The issues raised amount to a three-fold requirement, this being:

1) technologies implemented have to be applicable to wastes being as concentrated as possible
2) a net energy gain of the process train used
3) a nutrient rich effluent must preferably be made available for agricultural reuse

These requirements correspond in principle with more extended criteria given by Lettinga *et al*. (2001) for sustainable sanitation being:

1) little, if any, dilution of high strength domestic (and industrial) residues with clean water

2) application of efficient, robust and reliable wastewater collection and transport systems and treatment technologies, which require few resources (e.g. fossil resources for energy) and long lifetime
3) maximisation of recovery and reuse of treated water and by-products, e.g. irrigation, fertilisation and soil conditioning

It is evident from the above that for minimum environmental impact and appropriate treatment technology choice an optimum balance between minimum energy use (or, if possible, a net energy gain) has to be found and the provision of a nutrient rich effluent and solids residue useful for agricultural purposes. If treated wastewater is to be reused for purposes other than agriculture further treatment to archive compliance with standards for intended use would be necessary.

Reuse of treated effluent for agricultural purposes is also a function of the proximity of the effluent source to the intended point use. This further complicates the analysis as additional economic and technical considerations may be required to account for potential need of conveyance systems from the source to the user.

The determining factor of viable reuse would be its comparative cost to that of bulk fresh water supply. However, it must be borne in mind that potable water systems are highly subsidised and the actual cost of fresh water provision is not fully recovered from the consumer.

It is emphasised that the comparison of alternative supply paths (fresh versus reused water) must consider the timeframe of interest which in this case is always long term implying that any comparisons should be made on the basis of the marginal costs of providing the equivalent additional fresh resource that would be replaced by reuse.

3.5 SUSTAINABILITY REQUIREMENTS AND WASTEWATER TREATMENT TECHNOLOGY CHOICES

The application of integrated or sustainable water management principles brings to the forefront the selection of wastewater treatment technologies that one would choose for a particular situation. That this is the case is well documented in the literature and the debate between pro-aerobic and pro-anaerobic professional constituencies (Gijzen 2001).

According to van Lier and Lettinga (1999) anaerobic technology has various advantages over aerobic ones (Table 3.1).

Table 3.1 Advantages of anaerobic treatment compared to aerobic treatment (after Van Lier and Lettinga, 1999)

Advantages of anaerobic treatment compared to aerobic treatment
• Low investment cost and low space requirements
• Applicable to small and large scale
• Low production of excess sludge (approx. 10 times less), well stabilised
• Low nitrogen, phosphorus requirement
• No or very low energy demand
• Production of valuable energy in the form of methane
• High loading capacity (approx. 5–10 times more)
• High treatment efficiency
• Effluent contain valuable fertilisers (ammonium salts)

In parallel to the choice between aerobic and anaerobic technologies a similar debate exists with respect to the technologies for nutrient removal and/or recovery or even regarding the need to remove the nutrients from wastewater at all if one is to opt for effluent reuse in agriculture.

A number of technologies are currently available for nutrient recovery:

1. *Biological, physical and chemical recovery methods*
2. *Transfer by plants and aquaculture*
3. *Urine separation technology*
4. *Decentralised eco-sanitation at household level*

The biological, physical and chemical recovery methods are seen as particularly suitable for the recovery of soluble phosphate. Such a practise has been widespread during the last five decades but usually not for nutrient recovery purposes since the recovered nutrients typically end up being disposed of at a landfill. The application of such methods can result in a mineral solid-enriched bio-sludge and a phosphorus (P) content of about 3–4% by dry weight (Larsen and Boller, 2001). Similarly Cornel and Schaum (2009), estimate that 39% of the incoming P load is removed by primary settled sludge and conventional biological wastewater treatment through incorporation into the excess sludge. To comply with effluent P discharge requirements of around 1 to 2 mg/l, approximately another 50% of the incoming P load has to be removed by either enhanced biological treatment or chemical-physical processes, resulting in a total treatment plant removal of approximately 90% of the incoming P load. All the removed P ends up as sludge (which is not necessarily reused) which requires a significant energy and chemical input. In comparison to sludge recovery of P, wastewater irrigation would surpass the 90 % P recovery and do so typically without any significant energy or other inputs while at the same time accomplishing the reuse of the water itself. (Cornel *et al*. 1991).

Cornel and Schaum (2009) emphasises that up to 2009, recovery of phosphorus appeared to be more expensive than mined phosphorus but this is largely the side effect of the energy intensive mining recovery technologies typically employed. None the less, this does not contribute positively to the promotion of phosphorus recovery as an alternative to mining extraction and the corresponding high energy demands nor does it give any positive stimulus to the promotion of sustainability in wastewater management. Were the appropriate technologies chosen for P recovery the findings of Cornel and Schaum (2009) would certainly been different.

Phosphorous and other micronutrients recovery can also be accomplished by the transfer of P from the wastewater into biomass by plants and aquaculture systems. However, reed beds and wetlands mass balances for nitrogen (N) and phosphorus (P) show that the level of nutrient taken up is relatively low. Larsen and Boller (2001) reported that in conventional reed beds in Japan, only about 9% and 7% of N and P respectively were removed by plants and that the majority nutrient removal was by soil adsorption of P and denitrification of N or loss via effluent from such systems. The fact that majority of phosphorous is adsorbed to soil particles not being considered to represent recovery as suggested by Larsen and Boller (2001), defies common sense if one looks at the P enriched soil as a resource for further plant biomass production.

Similarly aquaculture for the production of aquatic plants and fish farming represents large reuse potential of nutrient-rich wastewater effluent. Larsen and Boller (2001) also mentioned a viable option of aquaculture being the production of protein-rich duckweed which is harvested and in turn used either for fish farming or after drying used for animal feed. The duckweed protein production per m^2 compared to soya bean is estimated to be about 10 times higher. From a nitrogen balance point of view for a duckweed-algae pond system, it was found that a major fraction of nitrogen (approximately 73%) is lost to the atmosphere by volatilisation of ammonia, while approximately 18% and 6% was taken up by duckweed and related to sedimentation respectively. With conventional biological nutrient removal processes the main objective is to convert all of the nitrogen present in wastewater to nitrogen gas and in turn discharged to the atmosphere. Compared to an extremely high energy input to achieve the latter, duckweed-algae pond systems with an 18% recovery is actually a reasonable result considering it to be at zero energy input. On the other hand it is true that both wetland and pond systems require large areas of land which limit the use of such technologies to appropriate areas where there are no land availability limitations.

Application of the “3-Step approach” to achieve sustainable wastewater management suggests that source control and pollution prevention should receive the highest order of priority. In the case of nutrient recovery the value of the above approach becomes particularly visible.

Table 3.2 shows the typical chemical composition of urine and shows that a substantial fraction of nutrients from our daily diet is taken up in urine, in particular nitrogen (N), phosphorus (P), sulphur (S), sodium (Na) and potassium (K) and to a lesser degree calcium (Ca) and magnesium (Mg). Table 3.3 gives the nutrient content in daily person equivalent (PE) of the various domestic sewage components. Although urine (anthropogenic nutrient solution or ANS) is low in carbon (about 14%), it contains the major fraction of nitrogen and phosphorus (about 88% and 57% respectively). Separation of urine from domestic wastewater at source would allow a concentrated nutrient source to be available for reuse. If a urine separation strategy were to be employed it is clear that treatment of the remaining wastewater would change substantially and effect the sustainability of the resulting wastewater management practice.

Table 3.2 Typical production and composition of human urine (Anthropogenic nutrient solution) (after Larsen and Gujer, 1996)

Parameter	**Mean value** (average adult)	**Average variance, s**	**Typical concentration** (g/m^3)	**Fraction of uptake***
Flow	1,25 litre/day	2,7 (max)	–	–
pH	6,2	0,5	–	–
COD	15 g/day	–	12 000	–
Nitrogen	11,5 g N/day	2,3	9 200	85–90%
Urea N	9,6 g N/day	1,9	7 700	–
Total Phosphorus	1,2 g P/day	2,0 (max)	1 000	50–80%
$H_2PO_4^-$	1,1 g P/day	–	–	–
HCO_3^-	≈ 0 Mol/day	–	< 5 mol/m^3	–
Total sulphur	1,3 g S/day	1,5 (max)	1 000	≈ 100%
SO_4^{2-}	1,2 g S/day	–	–	–
Ca^{2+}	210 mg Ca/day	70	170	20–30%
Mg^{2+}	120 mg Mg/day	35	100	25–50%
Na^+	5,2 g Na/day	2,2	4 200	> 95%
K^+	2,7 g K/day	3,9 (max)	2 200	80–90%
Cl^-	4,8 g Cl/day	9,6 (max)	3 800	≈ 100%
* Uptake: 100% of a component included in human daily diet				

Table 3.3 Domestic wastewater carbon and nutrient content (after Larsen, Gujer 1996)

Sewage component	**Total organic carbon**		**Total Kjeldahl nitrogen**		**Total phosphorus**	
	g/PE/day	%	g/PE/day	%	g/PE/day	%
Kitchen, bathroom, cleaning	15	41	0,2	1	*	*
Faeces	17	46	1,5	11	0,6	43
ANS/Urine	5	14	12,2	88	0,8	57
Total	37	100	13,9	100	1,4	100
* Depends on detergent phosphorus content						

The impact of urine separation on the treatment of a typical European wastewater at a centralised wastewater plant is illustrated in Table 3.4. The impact is considered using a nitrogen and phosphorus mass balance of the incoming wastewater (influent) and process assimilation into biomass and effluent release (Larsen and Gujer, 1996). Table 3.4 assumes an idealised near 100% urine recovery which in practise would be very difficult to achieve due to other limitations. Nonetheless it demonstrates the trend of the impact that urine separation could have on centralised biological nutrient removal (BNR) plants. From the mass balance it is clear that by employing urine separation, nutrient removal would be no longer be required. The nitrogen effluent load would be less than without urine separation, while the effluent phosphorus load would be similar but with the advantage that enhanced phosphorus removal biologically and/or chemical precipitation would no longer be required.

Table 3.4 Impact of ANS on centralised BNR treatment by considering a nutrient mass balance (derived from Larsen and Gujer, 1996)

Fractional content of nutrients of influent wastewater	**BNR treatment process*: Assimilation in biomass + release in effluent**
Remainder of nitrogen = 25%	Nitrogen removal by denitrification = 50%
ANS fraction of total nitrogen = 75%	Nitrogen in biomass = 25%
	Nitrogen in effluent = 25%
Remainder of phosphorus = 50%	Enhanced phosphorus removal (biological/chemical) = 50%
ANS fraction of total phosphorus = 50%	Phosphorus in biomass = 25%
	Phosphorus in effluent = 25%

* BNR = biological nutrient removal (nitrification + denitrification + enhanced phosphorus removal)

The urine separation principle is also applied in eco-sanitation for nutrient recovery and reuse at a household level. In principle, if the different waste streams could be kept separate, a different set of possibilities for wastewater reuse do exist. If flush waterborne water is taken out of the equation (dry sanitation) and urine and faeces is kept separate, then the extent of polluted, unpleasant human excreta becomes manageable (faeces = 50 litres/ca/annum; urine = 500 litres/ca/annum)(Austin *et al*. 2005). Human urine is considered as a “free” fertiliser and can totally replace synthetic fertilisers. It is considered sterile and can be added to soil directly in tropical climates without a health risk. Human faeces can also be used as fertiliser provided it is composted to remove any health risk (Heinonen-Tanski and van Wijk-Sijbesma, 2005).

With the use of human excreta (through eco-sanitation) physical handling of the human waste products produced are necessary. For the successful implementation of eco-sanitation appropriate social interventions in the form of promotion, education, support and training are pre-requisites (Austin *et al*. 2005).

CHAPTER 4

CENTRALISED AND DECENTRALISED SYSTEMS IN SUSTAINABLE WASTEWATER MANAGEMENT

The problem of sanitation and wastewater management is under the influence of a diverse set of drivers that need to be fully understood in the process of development of an appropriate sanitation and wastewater management strategy. In decision making for finding suitable and appropriate system and technical solutions in wastewater management these drivers have to thoroughly defined and assessed for the service area under consideration. The general framework for the selection process is presented in Figure 4.1.

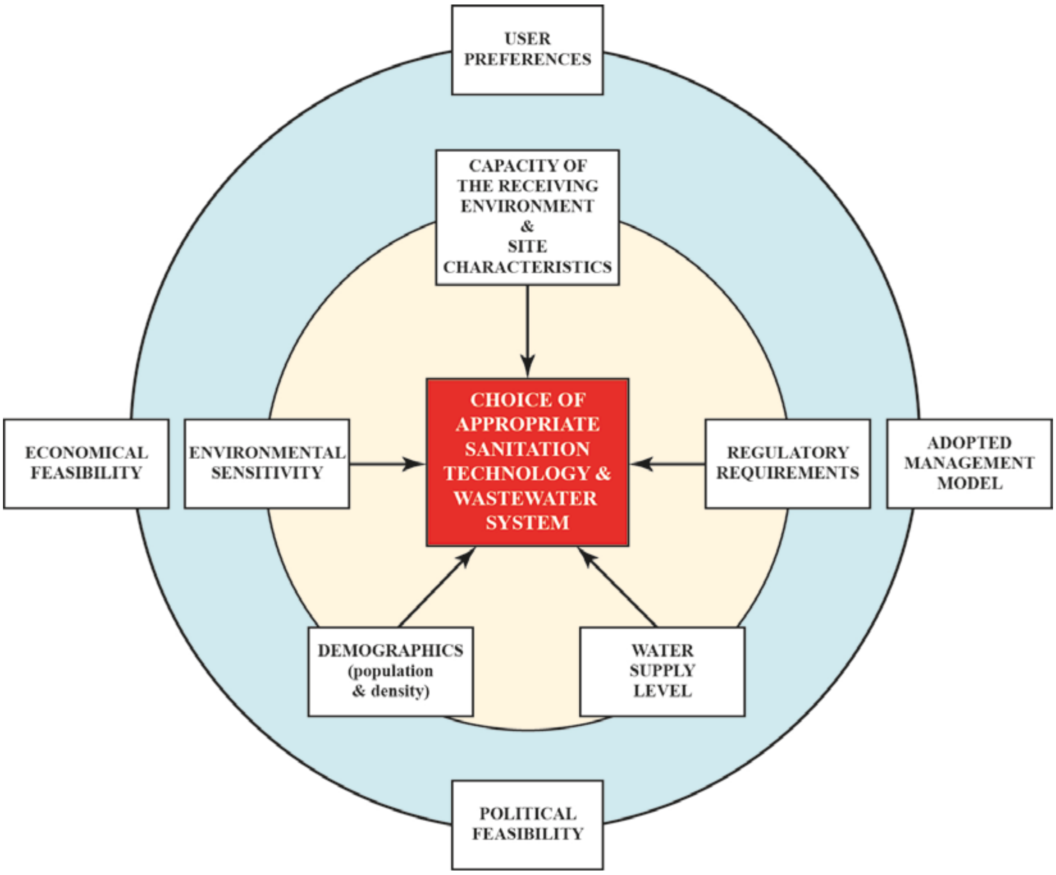


Figure 4.1 Generalised framework of appropriate system and technology option choices for wastewater management (adapted from Marjanovic *et al*. 2009)

The generalised framework presented in Figure 1 allows for establishing the relationship and interaction between different aspects of water and sanitation systems contributing to the required wastewater management strategy. As illustrated in Figure 4.2, the choice of technology is driven by the user needs and socio-political and legal environment and constrained by the physical and economic environments in which the systems are located and being implemented (Balkema *et al*. 2002). This implies that user needs as articulated through the socio-political and legal system may or may not be met in a manner that is sustainable or economically and environmentally feasible necessarily.

Figure 4.2 Wastewater management and sanitation technology drivers and constraints (after Balkema *et al*. 2002)

Sustainable water management is especially dependent on the system employed for management within the wastewater and sanitation continuum. In this context two distinct types of wastewater management systems can be distinguished, namely centralised and decentralised wastewater management systems.

The relevant question currently concerning system sustainability is whether it is possible to attain more sustainable urban water management through improving the existing conventional centralised systems. Alternatively, is it necessary to switch to new decentralised systems altogether or can a mixture of decentralised and centralised treatment combine the advantages of both system scales?

In this research (Chapter 5.15) the latter important question is addressed by developing a methodology for sustainable wastewater management system level decision making employing the multi-criteria analysis approach.

4.1 CENTRALISED WASTEWATER MANAGEMENT SYSTEMS

In a centralised wastewater management system all wastewaters collected from an urban or peri-urban community is treated at central wastewater treatment plants within feasible distance from the community and typically within the topographic constraints imposed upon the wastewater collection system.

Centralised systems for wastewater treatment are considered by many in the water sector as the best practice for most communities because of the high level of reliability, established management framework and economies of scale giving an apparent (but not necessarily real) advantage of least cost per capita. These systems became the norm for management of wastewater in cities in the mid-1930s in both Europe and the United States of America. The centralised approach was implemented to prevent nuisances and health hazards caused by indiscriminate waste disposal in and around neighbourhoods and the negative impacts of wastewater disposal in the environment. It furthermore enabled the solution of the problem of overloaded onsite systems in cities and the removal of infectious wastes out of cities. Such systems proved to be successful in breaking the faecal-disease transmission cycle and ensuring acceptable public health and improved hygienic living conditions in cities. The treatment of wastewater also evolved over time to prevent the pollution of wastewater receiving water bodies. Initial aeration treatment using soil filters and improvements thereon ultimately resulted in the activated sludge treatment process becoming the favourite technology for carbonaceous waste treatment. Since its introduction, various activated sludge process configurations were developed over time, resulting in a high technology process that incorporated nutrient removal (ammonia and nitrogen by nitrification and denitrification) followed by chemical/biological removal of phosphates in more recent times. Although different zones are distinguished in activated sludge treatment (i.e. anaerobic, anoxic and aerobic), the largest fraction of the process is aerobic in nature and requires high energy inputs for required oxygenation of the mixed liquor (mixture of biologically active media and waste) for carbonaceous breakdown. In addition to return flows and recycles requiring pump energy, constant energy inputs are required to keep suspended matter of the mixed liquor in suspension (Burian *et al*. 2000).

This approach, also known as the centralised urban wastewater system (CUS), are basically extended waterborne conduit conveyance systems for wastewater transport to centralised treatment facilities and subsequent treatment of the resulting large volumes of highly diluted wastewaters. The high dilution factor not only imposes a highly complex technology for wastewater treatment, but causes high operational cost per unit volume treated. Within the context of material flows, the centralised wastewater management system is an open ended loop system and is nowadays considered as being unsustainable in light of the high resource intensity (energy, inefficient use of water) and very little if any useful by-products recovery contained in wastewaters (Lettinga *et al*. 2001).

In a report on sanitation and disease in the developing world to the World Bank by Feachem *et al*. (1983), it is pointed out that **centralised systems of developed countries are not the result of a logical and rational design process, but rather a product of history that started about 100 years ago when the related fundamental physics and chemistry knowledge base were limited and the microbiology virtually undiscovered**.

Mainstream technologies used in centralised systems (activated sludge and its tertiary nutrient removal) do not allow for recovery of valuable energy and nutrients contained in wastewater.

Apart from the mentioned public health benefits achieved with centralised systems the approach also allows for reliable management and process control which benefits both consumers and the environment. In the case of the environment the benefits are achieved at a premium cost as the systems employed do not utilise the full potential of the environment itself to handle controlled amounts of wastes. Furthermore the overall environmental effect is not as beneficial as it seems at first if one considers the life cycle impacts on all environmental media rather than just the impacts on the receiving aquatic environment which is most often the case. It should also be noted that the large conveyance networks servicing the wastewater catchments have various disadvantages and problems.

Table 4.1 summarises the major disadvantages and problems associated with centralised wastewater systems, being a combination of those according to Van Lier and Lettinga (1999) and Wilderer (2001).

4.2 DECENTRALISED WASTEWATER MANAGEMENT SYSTEMS

Decentralised wastewater management is not a new concept. According to Burian *et al*. (2000), sanitation at the start of the modern era (seventeenth century) consisted of decentralised on site systems (wet privy vault-cesspools and dry pail or bucket systems). Due to the uncontrolled drainage of wastewater from privy vaults and cesspools contaminated soils and groundwater that caused contaminated drinking water and disease outbreaks, a public health protection intervention in the form of piped-in water supplies had to be introduced. With water freely available on demand, together with population growth and associated increased wastewater generation, overloading resulted of onsite wet systems then in use. Inadequate attention was paid to redesigning onsite wastewater systems and as a result the nuisance level to society and pollution of surface water bodies increased.

Table 4.1 Disadvantages and problems associated with centralised wastewater management systems (after Van Lier and Lettinga, 1999, Wilderer 2001)

Item	Disadvantages of large scale sewered systems
1	Relatively high fresh water flush volumes required in order to prevent sewer conduit clogging, resulting in large amounts of water being polluted.
2	Relatively high risk of spreading contaminants across the environment with stormwater ingress and overloading and leaking of sewers.
3	Relatively high risk of hazardous compounds, heavy metals, pharmaceuticals, etc. being discharged into sewers by residents and industries ('out of sight, out of mind') which could result in treatment excess waste sludges becoming unsuitable for agriculture reuse.
4	More expensive treatment technologies suited for highly diluted wastewaters have to be employed due to high volumetric rates of influent wastewater received resulting in higher unit costs to ratepayers.
5	Due to possible rainwater ingress into sewers occurring, an undesirable drop in groundwater levels can occur as well as the hydraulic overloading of treatment facilities being detrimental to treatment process efficiency.
6	Diseconomies of scale result due to the large extent of collection networks and pump stations and the associated high construction and maintenance cost thereof to convey waste flow to the centralised treatment facilities. In addition, downstream larger outfall sewers are normally sized to serve the sewage catchment needs as a whole, resulting in the increased cost for future reserved capacity being carried by existing contributors of flow. In addition the replacements of such infrastructure at end of its economic life in 50-60 years will be at a further even higher escalated cost.
7	Robustness of centralised systems is highly dependent on efficient asset management and adequate costly preventative routine maintenance. The dependence on electrical power supplies for general treatment operational functions also makes it highly vulnerable should such support services be unreliable.
8	For reuse, a dual pipe system with accompanying additional cost as well as precautionary measures must be implemented to deal adequately with related health issues.
9	Recovery potential of phosphorus present in wastewater to substitute mining of phosphorus rock not viable due to high dilution of waste.

To avoid the problems mentioned a gradual shift to centralise wastewater management for cities resulted towards the mid-19th century and its establishment as preferred wastewater management option for urban cities.

Traditional decentralised on-site systems consisting of pits, aqua privies as well as low technology multiple chamber systems, ponds and constructed wetlands remained in use for peri-urban and rural areas. However, some high technology package plants were gradually introduced as smaller scale technology developed for those utilised successfully in large centralised plants such as trickling filters, rotating biological contactors and sequential batch reactors (activated sludge) (Wilderer 2001).

At the time the main concerns to those in the water sector were the lack of control by regulating authorities, insufficient operation and maintenance and low quality effluents generally produced by traditional decentralised systems. The fact nevertheless remains that it was a lack of proper management and design that made decentralised systems unacceptable at the time rather than their inherent technological inability to meet the required performance levels. In addition, wastewater was not seen as a resource at the time compared to now and these systems did not take cognisance of the potential of wastewater reuse.

More recently the decentralised wastewater management approach is receiving renewed interest as it now has a prevention focus aimed at both resource protection and recovery (Lettinga *et al*. 2001). This is achieved by:

- little, if any, potable water use for conveyance
- separation of concentrated and diluted domestic wastewater streams at source and separate treatment thereof
- treatment at or near the community by low cost sustainable technologies
- recovery and reuse of valuable by-products at or near the waste source (water and nutrients for agriculture and energy from biogas for domestic use)

As for large centralised systems, the new decentralised systems approach must ensure achievement of the same degree of treatment as centralised larger plants.

Decentralised systems are not small systems per say, but its purposed redirection of water and nutrient cycles could be at a varying scale, such as from household to cluster or community levels. According to the Rocky Mountain Institute (2004), decentralised wastewater systems may be defined as:

"*the collection, treatment, and disposal/reuse of wastewater from individual homes, clusters of homes, isolated communities, industries, or institutional facilities, as well as from portions of existing communities at or near the point of waste generation.*"

Figure 4.3 shows a comparison between a decentralised and centralised system for the same user area and relative degrees of centralisation or decentralisation or system scale possible.

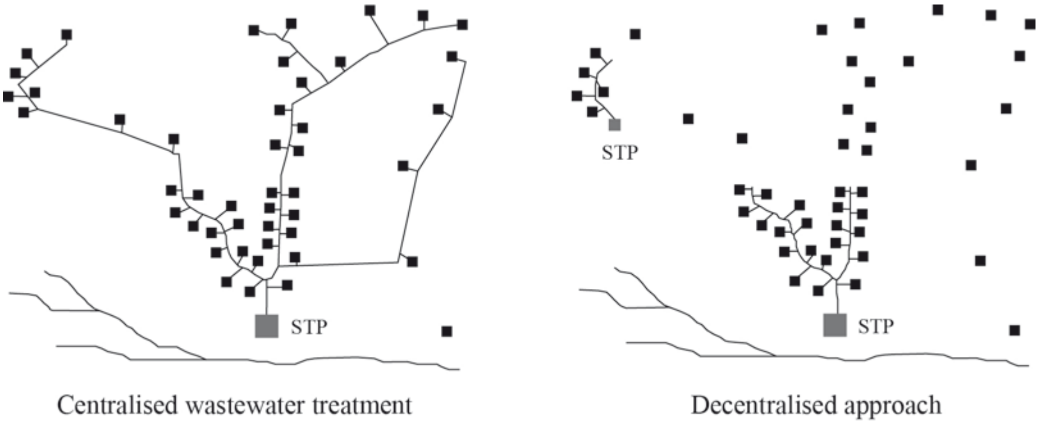


Figure 4.3 Comparison of Centralised and Decentralised Approaches to Wastewater Management (after Rocky Mountain Institute 2004)

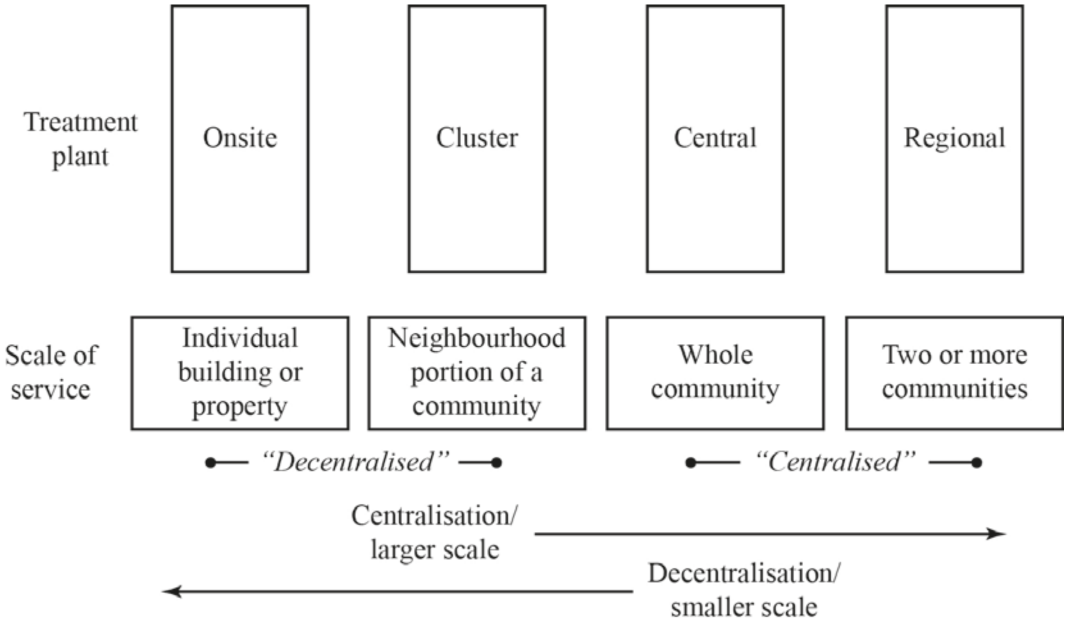


Figure 4.4 Scale of service within the wastewater system continuum (after Rocky Mountain Institute 2004)

Considering Figure 4.3 together with Figure 4.4 it becomes clear that with centralisation a single sewage treatment plant (STP) serves an area via a system of connection sewers, while in the case of decentralisation the management consists of a combination of one or more clustered/neighbourhood systems which are separately serviced by a smaller STP and a group of individual property non-sewered onsite systems.

The high costs of conventional centralised systems have sparked renewed interest of possible alternative approaches towards finding more affordable wastewater management solutions. While conventional centralised end-of-pipe systems are generally accepted as the preferred viable way of managing wastewater in cities, decentralised systems could be a more appropriate alternative to provide for tendency of sprawl development in cities towards the outer city fringes (Reynders *et al*. 2010). They could also, under specific conditions, become a viable alternative in highly urbanised communities in need of complete wastewater management system refurbishment. The Bellagio Principles (Appendix A4) is of primary interest here and read as follows:

> *"The domain in which environmental sanitation problems are resolved should be kept to the minimum practicable size"*.

This clearly emphasised that nature has a limited compensating capacity for pollution effects and that negative environmental impacts have to be in relation to this inherent constraint. For the same treatment effluent, the environmental impacts through a decentralisation systems approach are more distributed and smaller in scale compared to that of the less diffuse centralised system impacts. According to the Rocky Mountain Institute (2004), the more broadly distributed pattern of waste load release to receiving water is more numerous but much less severely impacts in the case of decentralised systems. In the case of discharges to land, substantial additional treatment will have occurred in the soil before the effluent reaches surface water lessening the severity of impacts further. Decentralisation not only makes natural systems more appropriate but also allow for local communities to participate more directly and benefit from any reuse options.

The benefits of decentralised systems, cost premiums produced by centralised systems and other considerations also shows decentralised systems to be beneficial compared to centralised systems. These were first identified by the Rocky Mountain Institute (2004), and are outlined in detail in Appendix A5. The issues compared to centralised systems not mentioned already under centralised systems, are briefly summarised as follows:

- **Financial planning and risk**

  Closer matching of capacity and growth in demand is possible with smaller decentralised systems allowing for a smaller increment allowance for spare capacity. This allows for spreading capital expenses compared to large up-front capital layouts associated with centralised systems. This result in a lesser debt burden to communities and facilitates flexibility in adjustment for changed growth patterns as well as improved treatment technology adjustments as they develop.

- **Community and watershed impacts**

  Decentralised systems allow for more scope for growth management strategies, as it allows for cluster-style development. It also may result in a more distributed pattern of negative impacts on the water environment as well as public health than centralised systems.

- **Onsite and neighbourhood impacts**

  While centralised systems are mostly considered ‘out of sight out of mind’, the case of decentralised systems being in closer proximity to communities require greater awareness and participation by contributing communities.

- **Capital and O & M costs**

  Smaller decentralised systems loose the advantages of economy of scale related to plant capital and operational and maintenance costs under certain conditions. Although high effluent standards would favour centralised systems, it is possible to achieve equally high effluent standards with appropriate technology choices.

- **Integration with other infrastructure**

  Decentralised systems being in closer proximity to wastewater sources provide cost-effective opportunity for water reuse at site and neighbourhood scale. It might be restrictive for large consumers of wastewater reuse as it may not be able to provide sufficient volumes required opposed to centralised systems.

- **Management**

  By a centralised management approach economy of scale for management may be possible compared to that of centralised systems.

- **Reliability, vulnerability and resilience**

  Although reliability and vulnerability to natural hazards and inadvertent disruptions may vary or be independent to system scale, the risks and costs of system failure would on average be less for decentralised systems due widely distributed impacts being limited compared to a large centralised failure.

4.3 SUSTAINABILITY ALONG THE CENTRALISED-DECENTRALISED WASTEWATER MANAGEMENT CONTINUUM

The necessary technologies for treatment of wastewater to any existing regulatory standard (even to drinking water quality if needed) are available for the complete wastewater continuum system scale (Rocky Mountain Institute 2004). These cover suitable plants for individual homes up to units serving single or multiple communities or even regional areas. Technology is therefore not the constraint for seeking an optimal solution, but rather the needs of society and the water resources availability. This however is not the case where one considers the implications of technological choices upon the financial sustainability of the chosen systems. Despite the fact that the technology may be available if it is unaffordable it cannot be considered to be sustainable.

Tornqvist *et al*. (2008) propagate a so-called Strategic Choice Approach (SCA). This is about ensuring communication and collaboration with stakeholders in the decision-making process when dealing with complex problems. Its core perspective is that urban infrastructure systems are dynamic in nature over time with many uncertainties when assessing and selecting a technology and/or a system. The approach divides the planning process into four modes: 1) shaping; 2) designing; 3) comparing, and; 4) choosing. Tornqvist *et al*. emphasises the process as being iterative and a return to any former mode in order to reduce essential uncertainties.

The implication of the Tornqvist *et al*. (2008) findings are that a solution which is flexible and easily adoptable to rapidly changing conditions should be favoured over other possible solutions and this in effect shifts our attention to more decentralised systems on the average. This becomes of even bigger importance when one attempt to apply the wastewater reuse ideas as included in the '3-Step Approach' suggested by Nhapi and Gijzen (2005).

As the centralised approach to wastewater management has become an established paradigm for wastewater disposal and treatment, the changes necessary in order to meet sustainability requirements, amongst others, could be divided into three options (Beck and Cummings 1996):

- Incremental adaptation of the conventional centralised system (according to Prof. P.Marjanovic, interviewed on 10 January 2011, this is possible but not likely in light of the expected future trends);
- Focus on optimal solids product recovery and the reuse of the water carrier opposed to that of a high quality liquid product returned to receiving surface waters
- Complete evolution of the wastewater paradigm with a decentralised approach with localised infrastructure cited as close as possible to heads of systems and the utilisation of soil as a receiving medium for treated effluent as most common solution.

The first option is feasible as some performance gains would be possible by integrated management of all sub-systems (personal communication: Prof. P. Marjanovic; 10 January 2011). The second option would be a more desirable approach for the environment and would result in a major benefit for the global nutrient cycles. The return of nitrogen from land to the atmosphere as opposed to via the aquatic environment would avoid the associated consequences of accelerated eutrophication. As the objective is nutrient recovery and incorporation thereof into the solid product, the biological processes of nitrification and denitrification employed in wastewater treatment with high energy demands of nitrification could be avoided. The third option has the focus of avoiding, as far as possible, the conventional approach of mixing different household waste streams and water addition for conveyance to an end-of-pipe treatment facility. With clean technology of confinement at source for industry already largely established, the systematic migration of centralised end-of-pipe solutions towards the control of residues at source will result in households forming part of an integrated clean wastewater management entity. This will ultimately result in a complete shift towards fully decentralised wastewater management in human settlements and a fully decentralised infrastructure provision.

Decisive factors of a new paradigm would be reliability of service and minimisation of impact of failure. Planning for sustainable urban water management must cover the full range of land-uses encountered (high and low density residential areas, CBDs, office parks, industrial areas, agricultural holdings, etc.). A differentiated approach and even combination of the optional approaches mentioned would have to be followed to ensure that the various scenarios could optimally contribute towards sustainable management (Reynders *et al*. 2010). With centralised treatment plants the combination of secondary treatment with nutrient reuse incorporating aquaculture, agricultural crop irrigation or even greening of sports fields and golf courses will move a long way towards more sustainable systems. In addition, a water management approach of decreased water-use initiatives would result in less dilution of wastes and greater potential for more energy efficient biological treatment technologies.

CHAPTER 5

METHODOLOGY OF INTRINSIC VALUE RECOVERY IN WASTEWATER MANAGEMENT

In Chapter 2 an argument was made that the best way of effectively reducing the water footprint of any given nation is by reduction of water withdrawals through implementation of reuse and multiple water use. This is especially true for water scarce countries such as the case in South Africa. The similar arguments can be made for other reusable resources contained in wastewater such as nutrients.

Also in Chapter 2 and subsequent chapters it was argued that wastewaters should be seen as valuable resources which have intrinsic value for society and such value can and should be recovered. While issues of sustainability of wastewater management act as a main driver for intrinsic value recovery, this will only happen in practice if economic value of such recovery is possible and the conditions under which such recovery will be justifiable are clearly outlined, not only from a sustainability point of view but also in terms of economic parameters. **What in fact is needed is a methodology for assessment of the economic evaluation of the intrinsic value recovery potential from wastewater.**

This chapter reviews wastewater reclamation, reuse and recycle in the above context and establishes a foundation for the development of a methodology for economic evaluation of the intrinsic value recovery from wastewater management in practice.

Wastewater reclamation, reuse and recycle quality standards have been established and are available worldwide, but will not be discussed here since they are not the focus of this research.

PART I: WASTEWATER RECLAMATION AND REUSE

Water reclamation and reuse make available a non-conventional resource that could offset freshwater demand and augment water supplies, while simultaneously avoiding negative environmental impacts caused by the discharge of nutrient rich wastewater to water bodies. Apart from the water content, wastewater contains primary nutrients such as nitrogen, phosphorus and potassium which are valuable plant nutrients. In addition, chemical energy is present in wastewater in the form of carbonaceous matter and the decomposition thereof has an inherent potential for energy generation.

5.1 WASTEWATER STREAMS, FLOWS, CHARACTERISTICS AND COMPOSITION

Wastewater flows would vary depending mainly on the level of water supply and lifestyle level. According to Tchobanoglous (1981), the typical per capita domestic household wastewater flows of particular devices in the average USA dwelling are as shown in Table 5.1.

Table 5.1 Wastewater flows from conventional domestic devices (average USA dwelling) (after Tchobanoglous 1981)

Household device	**Wastewater flows**	
	Litre/ca/d	**% of total**
1. Bathtub	30,3	12
2. Clothes washing machine	34,1	14
3. Kitchen sink	26,5	11
4. Water closet	11,4	5
5. Shower	45,4	19
6. Toilet	94,6	39
Total	**242,3**	**100**

Five possible waste streams could be distinguished for normal domestic wastewater (Wilderer 2001):

1. Brown water consisting of faeces, with or without flush water.
2. Black water, being combined faeces and urine, with or without flush water.
3. Yellow water consisting of urine, with or without flush water.
4. Grey water resulting from water use in bathrooms, laundries and kitchens.
5. Domestic solid waste from the kitchen (built-in grinders in kitchen sinks).

Streams 1, 2 and 3 represent the physiological or anthropogenic waste fractions while the rest are wastewater generated by human daily life and personal hygiene activities.

Household wastewater sources and their accompanying organic and nutrient components are given in Table 5.2.

Table 5.2 Household wastewater sources and organic and nutrient composition (after Henze and Ledin, 2001)

Components	**Unit**	**Household wastewater sources**				
		Faeces + urine	**Urine**	**Kitchen**	**Bath/ laundry**	**Total**
Total wastewater	m^3/yr	19	11	18	18	55
BOD	kg/yr	9,1	1,8	11	1,8	21,9
COD	kg/yr	27,5	5,5	16	3,7	47,2
Nitrogen	kg/yr	4,4	4,0	0,3	0,4	5,1
Phosphorus	kg/yr	0,7	0,5	0,07	0,1	0,87
Potassium	kg/yr	1,3	0,9	0,15	0,15	1,6

5.2 MANAGING WATER FLOWS IN SOCIETY

With finite fresh water resources having to meet the demand for water which is constantly increasing due to population growth, the resulting decrease in water availability per capita is becoming a real challenge in water management as has been discussed in Chapter 2. To make allowance for sufficient resource for economic growth of all sectors, an appropriate water management approach to ensure sustained growth with sufficient resource base is essential.

Consideration of having to remain with the conventional supply-sided approach and simply mobilising more of the renewable resource would eventually result in the inevitable of having to face water poverty. Alternatively approaches are necessary that integrate the social behaviour aspect of water use in a more demand-sided approach. This involves curbing water use through water saving technology introduction and also reusing water where ever possible.

The question of water reuse, although generally supported and implemented in the industrial sector, has had difficulty gaining acceptance in the domestic sector because of social perceptions of the value of water often caused by water pricing structures that do not reflect its actual economic value.

When considering resources both the quantitative “availability” and qualitative “applicability” issues have to be considered. According to Harremoës (1997, 1999, 2002), there are five intervention options when dealing with flows of material and of water in society and to manage water quality:

1. No-use
2. Reuse and recycle
3. Convert
4. Containment
5. Dispersion

These interventions briefly involve the following:

1. **No-use:** An unwanted substance could be avoided by prohibiting its use. This then would require finding substitutes which are environmentally friendly and applying “cleaner production” principles and demand control approaches.

2. **Reuse and recycle:** Through an internal system return and making repeated use (multiple use) of water withdrawn such that the quantity of substance reaching the environment could be reduced.

3. **Convert:** This involve tracing a substance along its route of flow and the treatment thereof (converting it from being obnoxious) by treatment and purification through “end-of-pipe” solutions to an environmentally acceptable form.

4. **Containment:** The ultimate containment of a hazardous substance in suitably engineered cells in landfills without risk of any contamination of the environment.
5. **Dispersion:** Freely dispersing a residue into the environment (air, water and onto soil), with or without treatment prior to disposal depending on environmental acceptability.

For a particular substance used by society, the ultimate fate thereof would be determined by the intervention applied. Dispersion and containment was applied till about the 1960s, but as the level of the awareness of environmental issues in society increased, a shift in focus followed and conversion of harmful substances were effected by "end-of-pipe" intervention solutions until the 1980s. Since then no-use and reuse approaches have systematically became more established. Harremoës (2002) furthermore points out that all the water quality control options mentioned as part of an integrated approach must be considered to achieve appropriate solutions.

In the urban setting, water is used as a means of transport for waste products, resulting in pollution of such water and leads to the greater part of water withdrawal of cities with effective water supply and wastewater drainage networks being returned to the aquatic system as wastewater. Considering that on a global scale urban water use represents some 30% of resource withdrawal (Harremoës 2002), water scarcity indicators such as WCI and WF (which include urban demand) then effectively have a capacity buffer equivalent to the wastewater flow fraction, provided the wastewater is adequately treated before discharge to the aquatic environment.

In a water consumption and return flow study done for urban areas in South Africa (van Zyl *et al*. 2007), it was found that return flows were a function of living area affluence. For highly affluent areas return flows were over 60% of water used, while for middle income areas and sub-economic townships (low income areas) the return flows were higher than 80 and 90% of water use respectively. In quantitative terms however higher volumes are returned from affluent areas due to their higher water consumption.

5.2.1 Wastewater as non-conventional resource and drivers thereof

Water recovery and resource enhancement

What is the logic and drivers for wastewater reuse as a non-conventional resource to supplement finite fresh water resources under pressure globally?

UNEP/GEC (2004) lists the following rationale and drivers for wastewater reuse:

- Optimal use – Fresh water is a finite resource and society can no longer afford the luxury of using water only once, putting emphasis on multiple use of water withdrawn.
- Matching application and quality – Not only is fresh water conservation required for resource sustainability, but more effective and efficient use of fresh water resources that require appropriate matching of applications of use with resource quality, which becomes attainable with reuse.
- Proximity – In the vicinity of urban environments where water resources are most needed, reuse of wastewater makes a non-conventional resource readily available.
- Dependability – Even under conditions of drought, urban wastewater remains virtually constant ensuring a reliable non-conventional water resource.
- Versatility – Technology has been proven and tested that can treat wastewater to required levels for non-potable and even potable reuse.
- Safety – Nearly four decades of operation of non-potable reuse systems with no adverse health impacts allows for limited risk through appropriate quality monitoring to be employed.
- Water resource competing demands – Increased pressure as a result of population growth and food security requiring increased agricultural demand exert pressure on the available water resources.
- Fiscal responsibility – Recognition by the water sector of economic and environmental benefits of wastewater reuse.

- Public interest – Enthusiasm with communities for willingness of acceptance of reuse due to an increasing awareness of negative environmental impacts of overuse of available fresh water resources.
- Environmental and economic impacts of traditional resource approaches – Recognition by the water sector of the negative environmental and economic impacts of reservoir facilities and dams.
- Proven success track record – Growth in number of reuse projects successfully achieved all over the world.
- Real cost of fresh water supplies – Introduction of charging systems for supplies that reflects actual cost of water delivery (such as full cost pricing) and the growing implementation of such pricing structures.
- More stringent water quality standards – Higher quality requirements of effluent disposal and the associated increased costs, makes direct reuse an economically viable alternative by avoiding effluent disposal.
- Necessity and opportunity – Droughts, water shortages, sea water intrusion prevention, wastewater effluent discharge restrictions and economic, political and technical conditions, are providing a favourable environment contribute to motivating reuse projects.

The water used for transport of waste together with valuable organics and nutrients contained in the wastewater makes it a valuable resource for multiple applications and reuse. Considering the fact that in the case of waterborne sewage the water component makes up as much as 99, 9 percent it has major potential as an unconventional water resource (McGhee 1991). Wastewater effluent adequately treated could be used for urban uses (landscape, fire fighting, etc.) groundwater recharge, environmental enhancement, industrial and agricultural purposes. Potable urban use could be considered provided more advanced tertiary treatment processes are introduced. The latter option of potable use would also require extensive quality monitoring and precautionary multiple barrier treatment measures to cover instances of any process efficiency breakdown (Haarhoff and van der Merwe, 1996).

Reuse not only has a resource conservation benefit, but by making more of the freshwater resource available for higher quality uses such as for drinking and personal hygiene, it also contributes to more sustainable fresh water resource utilisation. Through resource conservation further infrastructure requirements of additional fresh water supplies and the additional financial burden could be deferred or possibly abandoned altogether.

The increased wastewater flows generated in direct relation to population growth, particularly in the case of centralised urban city systems serving high density areas, represents a consistent and increasing non-conventional water resource base. As wastewater flows tend to remain relatively constant even under drought conditions the wastewater as non-conventional resource would be minimally impacted by such conditions.

Nutrient recovery

Some important nutrients for agriculture such as nitrogen (N), phosphorus (P), potassium (K), zinc (Zn), boron (B) and sulphur (S) are present in wastewater (UNEP/GEC 2004). Figure 5.1 reflects the different nutrient content of human metabolism ending up in wastewater.

The main nutrients for agriculture and horticulture are nitrogen (N), phosphorus (P) and potassium (K) with the former two nutrients being the most critical (Heinonen-Tanski and van Wijk-Sijbesma, 2005). For plant growth the need of nitrogen is highest with vigorous growth occurs. Although essential, N has to be applied at the right time as surplus application can leach out and pollute the aquatic environment. The need for P in plant growth is approximately one tenth of that of N but is a limiting nutrient for plant growth.

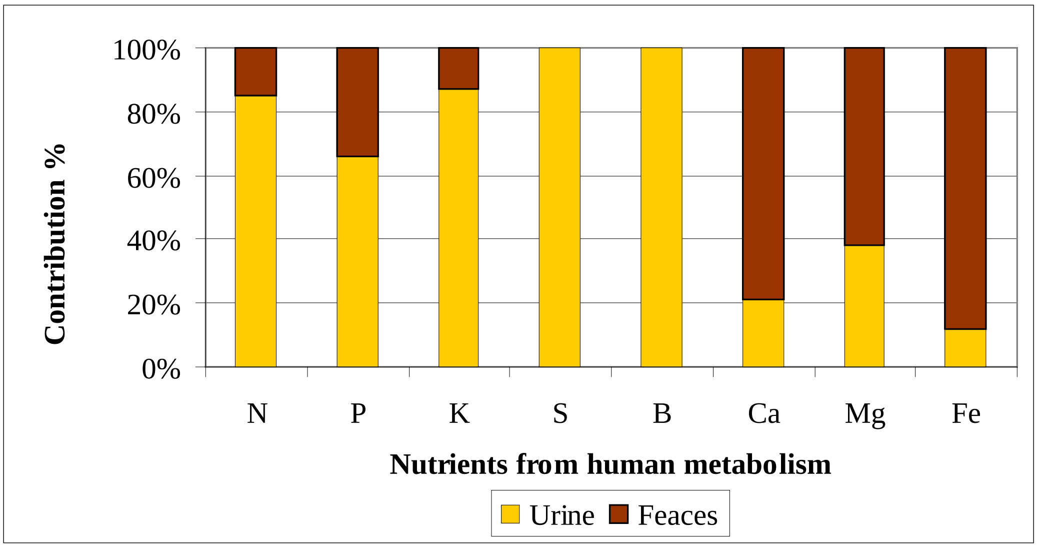


Figure 5.1 Nutrients from human metabolism (after Larsen and Boller, 2001)

Wastewater may therefore be used for agricultural purposes as well as for irrigation of parks and recreational landscaping, not only for watering as such, but also as a means of applying a natural fertiliser that would reduce or eliminate artificial fertiliser needs. The use of nutrients contained in wastewater would reduce the exploitation of a scarce phosphorus mineral resource as well as the high energy use for its mining and the nitrogen fixation process required for artificial fertiliser production and a vast array of negative environmental impacts of such production processes could also be avoided (Gijzen 2001). From an environmental point of view the reduced energy use for artificial fertiliser production would also contribute to climate change mitigation. The decrease in energy required will result in less dependence on fossil fuel based energy generation and reduced greenhouse gas emissions. By not discharging nutrient rich wastewater effluent to the aquatic environment the negative environmental impact of eutrophication would also be alleviated.

Energy recovery

Chemical energy is present in wastewater in the form of carbonaceous matter and the decomposition thereof has an inherent potential for energy generation. Burton *et al*. (2009) outlined three appropriate technologies (Figure 5.2) for extracting energy from wastewater and their basic operation:

1. Anaerobic digestion
2. Biofixation (plants, algae)
3. Microbial fuel cells

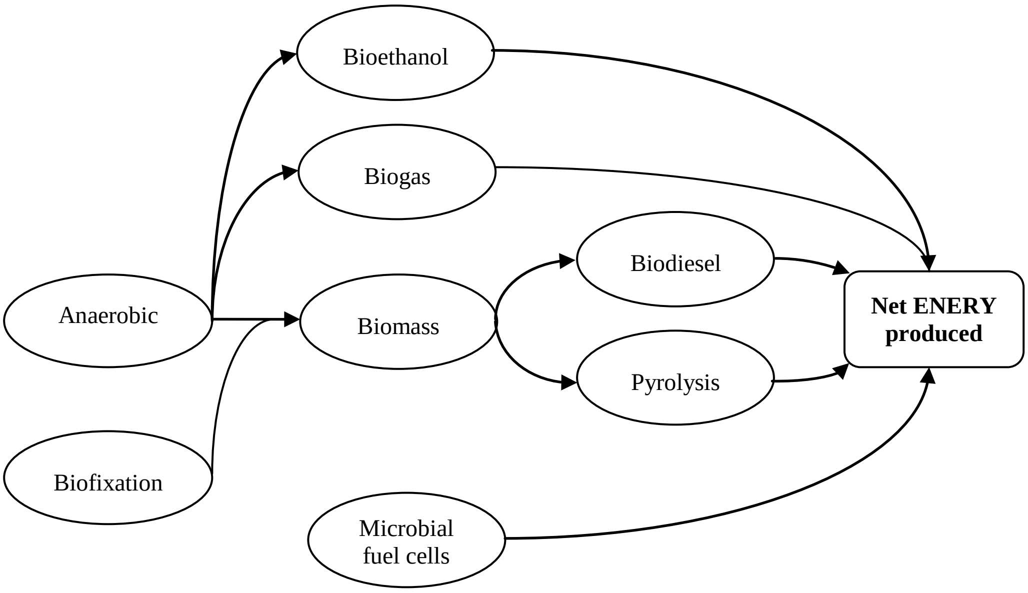


Figure 5.2 Appropriate technologies for energy extraction from wastewater and products (derived from Burton *et al*. 2009)

Anaerobic digestion is suitable for domestic sewage as well as in the industrial and agricultural sectors. Under anaerobic conditions, carbohydrate (sugar-rich) wastewaters such as that of the fruit industry are used for the well-established production of bioethanol through fermentation followed by an energy intensive distillation process. Through the completely anaerobic mineralisation process of hydrolysis, fermentation (or acidogenesis) and methanogenesis, organic matter in wastewater is converted to biogas (mainly methane and carbon dioxide, with very small fractions of hydrogen and nitrogen) and a stabilised sludge with high nutrient content (Tchobanoglous 1991b). After removal of non-methane components from biogas, energy recovery through internal combustion and generation of electricity can be achieved. According to Gijzen (2001), fully anaerobic treatment has the potential to recover as much as 90% of energy contained in wastewater compared to about a 60% equivalent in the case of aerobic wastewater treatment and anaerobic sludge treatment. In the case of fully aerobic treatment (including aerobic sludge stabilisation) net energy consumption is the result. For aerobic treatment further sludge processing is required (thickening and dewatering) before energy conversion could be achieved. This indicates that more direct and higher levels of energy recovery are potentially possible with employment of anaerobic treatment processes.

It is noted that all forms of biomass have energy generation potential. These would include unstabilised wastewater sludges as well as plants and algae biomass grown on wastewater.

Although biodiesel production from algae is technically feasible, no large scale production processes are currently operating (Burton *et al*. 2009). The use of biomass for energy generation will however compete with its potential use as natural fertiliser in agriculture which in turn reduces the large energy inputs required associated with phosphorus mining and nitrogen fixation for artificial fertiliser production.

Burton *et al*. (2009) pointed out that ease of separation of the energy from the wastewater is crucial to the feasibility of the process employed for energy recovery. Case in point is biogas which separates naturally from wastewater while bioethanol requires energy intensive distillation for its recovery.

Through microbial fuel cell (MFC) technology electricity could be generated simultaneously with aerobic wastewater treatment (Burton *et al*. 2009). The electrons released by bacterial oxidation of carbonaceous matter in wastewater treatment are transferred to an anode which is separated from the cathode by a proton exchange membrane. Via an external circuit electron flow takes place to the cathode to combine with protons and oxygen to form water. The difference in potential between anode and cathode due to the electron flow result in electricity production. As the rate of electron abstraction is very low, the corresponding MFC power generation is still very low. Energy output per unit volume of microbial fuel cell is in the order of 0.18 kW/m^3 of MFC and as an emerging technology has not reached large scale applications (Burton *et al*. 2009).

5.2.2 Wastewater reclamation, recycle and reuse

To allow a common understanding of terminology used in wastewater reclamation, recycle and reuse, these terms are defined next and also illustrated for clarity in Figure 5.3 (Asano 2002):

Wastewater reclamation defines the processing of treated effluent to make it suitable for a specific application. Reclaimed water is effluent from the treatment process suitable for beneficial use.

Water reuse is the use of treated wastewater for any beneficial application or purpose. Direct (water) reuse occurs when treated effluent is directly conveyed after treatment for the reuse application, while indirect (water) reuse is the discharge of treated effluent to receiving water body or river for assimilation and possible withdrawal further downstream.

Water recycling is when wastewater effluent that emanate from a particular use or application is captured and redirected back (with treatment) for the same use.

Central to water reclamation, reuse and recycling is the ***water utility*** concept in terms of which the primary objective is the matching of water quality with intended water use. This allows quality deterioration of resources to be minimised and allows for optimal water resource use. This also goes a long way towards implementing “principle 2” of the “cleaner production” concepts of not to use input materials of a higher quality (water quality) than strictly necessary.

It is noted that a main hurdle to overcome with regard to wastewater reclamation, reuse and recycling is due to the social and political perceptions of wastewater and the acceptance of reclamation, reuse and recycling by the society.

Reclamation, reuse and recycling and the hydrologic cycle

Wastewater reclamation, recycling and reuse are significant components of the hydrologic cycle in urban, industrial and agriculture areas as demonstrated in Figure 5.3. The quantity transferred via each pathway depends on the watershed characteristics, climatic and geo-hydrologic factors, degree of water use for various applications and degree of reclamation, reuse and recycling.

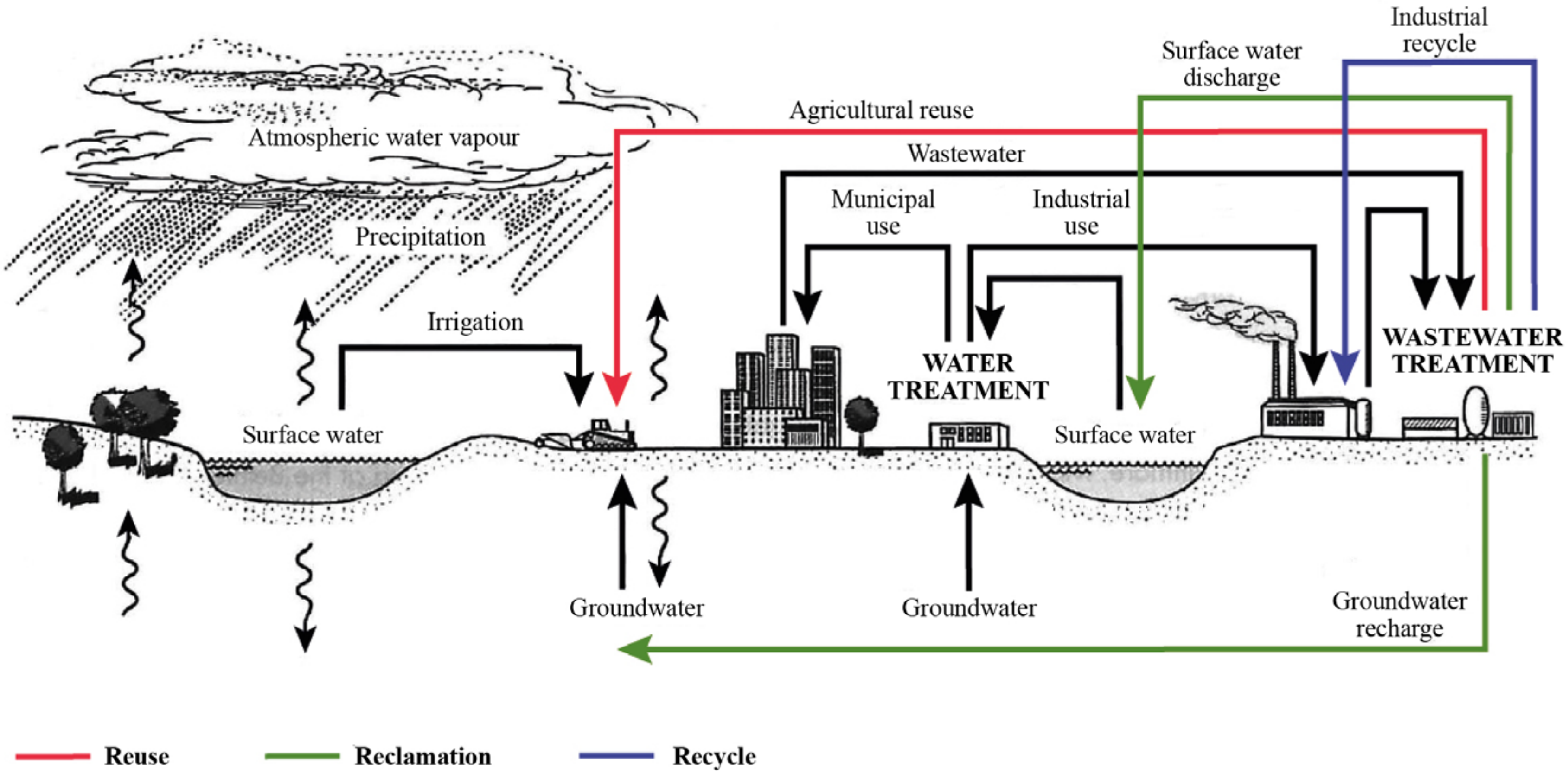


Figure 5.3 Hydrologic cycle and the major intrinsic value recovery pathways (derived from Asano 2002)

Water quality changes with urban use

According to Asano (2002) "*As water is used for various applications, the quality changes due to introduction of various constituents*". A conceptual comparison of the extent to which water quality changes through municipal applications is shown in Figure 5.4. Water treatment technologies are applied to produce high quality drinking water that meets applicable standards for domestic (drinking) water supply. Conversely, municipal and industrial water use tends to degrade water quality by introducing chemical and biological contaminants. The quality changes necessary to upgrade the wastewater then become the basis for wastewater treatment. In practice, treatment is carried out to the point required by regulatory agencies for protection of the aquatic environment and other beneficial uses. The dashed line in Figure 5.4 represents an increase in treated water quality as necessitated by water reuse. Ultimately, as the quality of treated water approaches that of unpolluted natural water, the practical benefits of water reclamation and reuse are evident. As more advanced technologies are applied for water reclamation, such as carbon adsorption, advanced oxidation, and reverse osmosis, the quality of reclaimed water can exceed conventional drinking water quality by most conventional parameters, and it is termed repurified water. To ensure minimum negative environmental impact and public health protection wastewater treatment is employed to allow an acceptable quality for effluent disposal to water bodies or further use. Depending on the quality requirements for particular applications of reuse, further advanced treatment processes may be required, for which currently the necessary technology are available to provide water of virtually any quality required (Asano 2002).

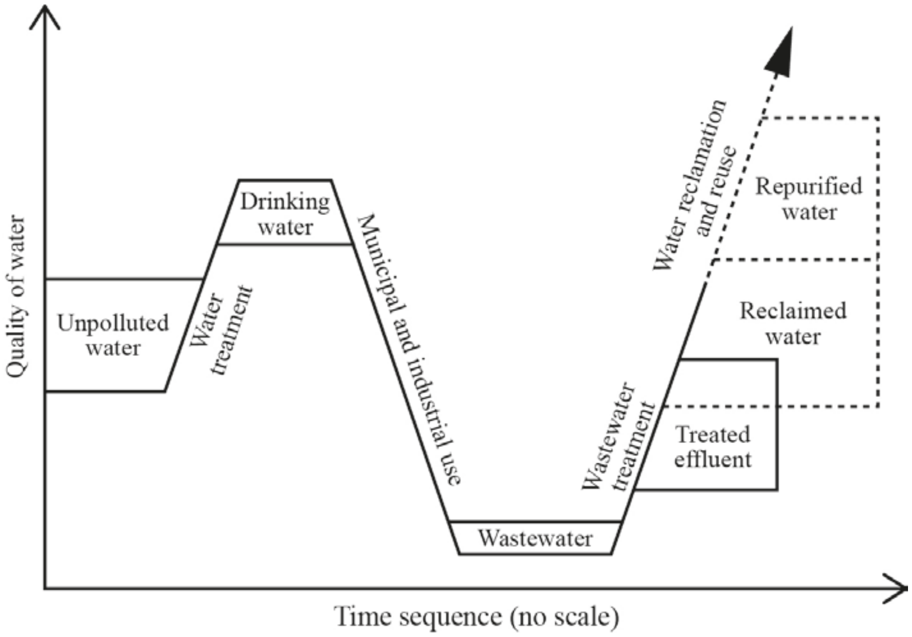


Figure 5.4 Change in water quality with use and treatment, reclamation and reuse (after Asano 2002)

Non-potable wastewater reuse

The potential benefits of wastewater reuse according to (UNEP/GEC 2004) are reflected in Table 5.3 below. Various applications of wastewater reuse are possible and the reuse categories and examples thereof are given in Table 5.4.

According to Asano (2002), 3 principles are foundational to water reuse, being: 1) provision of a reliable treatment to meet required water quality standards for the intended reuse; 2) the protection of public health by implementing appropriate measures for all reuse applications, and; 3) collaboration with society and public acceptance for reuse.

Several countries use raw wastewater (without any treatment) especially for agriculture and it is estimated that **about 20% of the world population's food is being produced using untreated wastewater** (UNEP/GEC 2004). Untreated wastewater can pose a serious health risks due to the presence of water-borne diseases, such as cholera, typhoid, dysentery, helminthiasis, etc. This risk can be mitigated and controlled by appropriate application techniques (for example subsurface injection and crop choice) although the practice, though beneficial for crop production, should be critically for any given situation. The analysis must take into account local conditions and requirements as wastewater quality differs for individual countries and regions.

To achieve optimum water use and cost advantage, the quantity and quality of wastewater available has to be weighed up against potential reuse applications, the corresponding quality requirements as well as associated health risk and the minimisation of such risk. Quality and health risk requirements are met through appropriate levels of treatment of wastewater and final effluent prior to any controlled reuse application.

Table 5.3 Potential benefits of wastewater reuse (after UNEP/GEC 2004)

• Wastewater reuse conserves freshwater supplies: Wastewater reuse increases the total available water supply. High-quality water supplies, such as for drinking water, can be conserved by substituting reclaimed water where appropriate.
• Wastewater reuse is environmentally responsible: Wastewater reuse can preserve the health of waterways, wetlands, flora and fauna. It can reduce the level of nutrients and other pollutants entering waterways and sensitive marine environments by reducing wastewater discharges.
• Wastewater reuse makes economic sense: Reclaimed water is available near urban development where water supply reliability is most crucial and water is priced the highest.
• Wastewater reuse can save resources: Reclaimed water originating from municipal wastewater contains nutrients; if this water is used to irrigate agricultural land, less fertiliser is required for crop growth. By reducing nutrient (and resulting pollution) flows into waterways, tourism and fishing industries are also helped.

The various reuse applications are as follows:

Urban non-potable reuse

Wastewater reuse could be either for potable or non-potable use. Non-potable use in general is socially and politically more acceptable and urban reuse is mostly restricted to this type of application. However, in arid regions where extreme water poverty exists, potable reuse has been implemented to supplement natural scarce water resources.

Table 5.4 Wastewater reuse categories and application examples (after UNEP/GEC 2004)

Category of reuse	Examples of applications
• Urban use - Unrestricted - Restricted - Other	 Landscape irrigation of parks, playgrounds, school yards, golf courses, cemeteries, residential green belts, snow melting Irrigation of areas with infrequent and controlled access Fire protection, disaster preparedness, construction
• Agricultural - Food crops - Non-food crops and crops consumed after processing	 Irrigation for crops grown for human consumption Irrigation for fodder, fibre, flowers, seed crops, pastures, commercial nurseries, sod farms
• Recreational use - Unrestricted - Restricted	 No limitation on body contact: lakes and ponds used for swimming, snowmaking Fishing, boating and other non-contact recreational activities
• Environmental enhancement	Artificial wetlands creation, natural wetland enhancement and stream flow
• Groundwater recharge	Groundwater replenishment for potable water, salt water intrusion control, subsidence control
• Industrial reuse	Cooling system water, process water, boiler feed water, toilets, laundry, construction wash-down water, air conditioning
• Residential use	Cleaning, laundry, toilet, air conditioning
• Potable reuse	Blending with municipal water supply, pipe to pipe supply

For these non-potable urban uses, a basic secondary treatment level is required with further quality enhancement by filtration and disinfection processes in most cases. With urban applications of wastewater and the high risk of human exposure to any disease causing pathogens possibly present therein, a major concern is to limit the risk of use to public health.

In the case of on-site decentralised wastewater management systems the recycle of grey water has been employed in the USA, Canada, UK, Australia, Japan, Israel, Jordan (Jeppesen 1996, Dixon *et al*. 1999, Al-Jayyousi 2003) and many other countries including South Africa (Prof P. Marjanovic personal communication on 30 March 2010).

Urban potable reuse

Apart from social acceptance issues, potable reuse will only be possible after extensive and costly specialised treatment processes to allow public health risk issues to be adequately dealt with. Potable reuse could take place in various ways. Either blending in reclaimed water with fresh water supplies stored in reservoirs and dams (indirect potable reuse) or by its direct input into water supply systems (direct potable reuse) (Asano 2002). Storage provided with indirect potable use between reclamation and consumption, provide a quality intervening environmental barrier that allows time for mixing, dilution, and natural physical, chemical, and biological processes to assist in the purification of the water (US National Research Council 1998a).

Despite the fact that technologies are available for adequate treatment to potable use quality and even higher than required standards, the concept of drinking wastewater still does not have wide public support. According to Dolnicar and Shafer (2009), there are several factors combined that hinder recycled water uptake for potable use. These include inadequate distribution infrastructure for supply (which applies to any reuse application as such), existing highly subsidised and comparatively low cost potable water resources, and a low level of community awareness of the limitations of freshwater resources, particularly in urban areas. It is further pointed out by the authors as well as the US National Research Council (US NRC) (1998b, 1998c) that the primary concerns are various pathogenic microorganisms (causing water-borne bacterial diseases, such as dysentery, typhoid, cholera, etc.) and although multi-barrier for its eradication is employed in treatment processes, risk of failure do exist. This is however relatively small as it would require a multiple simultaneous failure of the barrier systems. The US NRC also highlight the issue of trace compound of pharmaceuticals (or endocrine disrupting chemicals) as further concern being possible causes of loss of fertility and contributors to cancer. This present a chronic risk should long term exposure occur and generally do not pose an immediate health risk. It is also pointed out that chemicals added with the treatment process (such as coagulants and anti-scalants) and by-products formed during disinfection processes, although needing consideration, removal might be unsustainable or unnecessary. A combination of advanced physical treatment processes and strong chemical disinfectants should be the principal line of defence against most microbial contaminants.

A case of successful indirect potable reuse is that of the supply for the City of Windhoek in Namibia, where a consistent potable quality water have been supplied through employing a multi-barrier sequence of reclamation and routine quality monitoring (chemical, toxicity, virological, bacteriological, algal) and online quality monitoring system since inception in 1968 (Haarhoff and van der Merwe, 1996).

Reuse for environmental enhancement

Environmental enhancement, such as the augmentation of natural/artificial streams, fountains, and ponds in urban areas provide the opportunity for wastewater reuse. The resulting support of ecosystems ensures that aquatic life is sustained and creates pleasant scenery in urban open space for the enjoyment by city dwellers.

As human contact with reused water will take place public health concerns must be addressed adequately to avoid negative human health impacts. To avoid negative impact on the aquatic environment, nutrient levels of reuse water must be at such levels that unwanted algal blooms are avoided. (UNEP/GEC 2004).

Reuse for groundwater recharge

Groundwater recharge is used to mitigate decline in groundwater resource. It has the advantage of negligible evaporation, can prevent secondary contamination such as by animals as well as not having problems associated with water nutrients of algal bloom. It is also less costly compared to other options with very little if any pipe networks required.

Various methods are employed for recharge of groundwater such as recharge basins and direct injection. Recharge basins require large permeable soil areas with an unsaturated (or vadose) zone with unrestricting layers and an unconfined aquifer for transmissitivity. Through soil aquifer treatment, the vadose zone and aquifer work as natural filters that remove suspended solids, organic substances, bacteria, viruses and any other microorganisms as well as potential reduction of nitrogen, phosphorus and heavy metals. When aquifers are deep or inaccessible from the surface due to an impermeable layer, direct injection into it through injection wells can be employed. Although direct injection requires less land area oppose to recharge basins, the injection well is more costly to construct and maintain. In the case of direct injection the soil aquifer treatment normally relied on does not take place, and therefore advanced treatment of reuse water prior to recharge is required to effectively deal with any health or pollution problem concerns. Careful design of recharge systems has to be done to take account of hydraulic loading impact on achieving consistent soil aquifer performance (UNEP/GEC 2004).

Agricultural reuse

According to the projections made by Shiklomanov (2000), the fresh water consumption for agriculture by 2000 will amount to approximately 84% of total global fresh water use. This value correlate well with the global water footprint calculated for agriculture for the period 1997-2001 which amounted to around 86% (Chapagain and Hoekstra, 2004a). The Shiklomanov (ibid) assessment also projected that the already substantial agricultural fresh water demand will increase by a factor of 1.25 by 2025 which will escalate the pressure on the available finite fresh water resources of particularly arid and semi-arid areas. Reuse of suitably treated wastewater provide an ideal alternative resource for agricultural use as it not only provide an alternative water source to fresh water, but also plant nutrients and organics contained therein, which not only improve the soil structure by increasing in humic content but also save on artificial fertilising costs (WHO/UNEP 2006b).

The benefits of wastewater reuse (WHO/UNEP 2006b) for agriculture are summarised as follows: 1) conservation and more rational allocation of freshwater resources for high-quality uses such as drinking supplies, particularly in areas under water stress; 2) reduced artificial fertiliser requirement and associated reduction in industrial discharge and energy consumption; 3) increased food security; 4) better household nutrition and income generation; 5) reduce treatment cost by eliminating nutrient removal processes; 6) avoidance of surface water pollution expenditure; 7) soil conservation by humus build-up in soil and prevention of land erosion; 8) improved nutrition and food security for many households.

Large urban metropolitan areas potentially produce large wastewater volumes, while peripheral areas where agricultural land use normally is located may have water deficits. In the case of surplus or negative impacts having to be mitigated, treated effluents could be conveyed to other locations. Conveyance of treated water to remote locations will be at a cost premium, but negative environmental impacts avoided by reuse should be accounted for in economic analyses.

Combined domestic and industrial wastewater streams do contain toxic chemicals, salts or heavy metals that may restrict application for agricultural reuse. These pollutants may change soil properties, interfere with crop growth, and cause bioaccumulation of toxic materials in food crops. It would therefore be preferable to separate household and industrial effluent to avoid the undesirable components mentioned. Separation of such flows may not be feasible and therefore proper regulation, treatment and effluent monitoring must be practiced to prevent undesirable contaminants reaching treatment plants.

Negative health impacts could occur if good management practices are not in place. The WHO published a set of guidelines for wastewater reuse (WHO/UNEP 2006a, 2006b, 2006c, 2006d). These guidelines include recommendations for crops consumed cooked and uncooked or as feed stock, as well as for parks and localised irrigation. The objectives of these guidelines are to minimise exposure to workers, crop handlers, field workers and consumers, and to recommended treatment options to meet stipulated guidelines.

Wastewater reuse for agriculture needs to be planned with attention to target crops and existing water delivery methods to ensure that nutrients are not applied in excess to specific crop requirements. For instance, excess nitrogen may cause overgrowth, delayed maturity and poor quality of crops. Special attention should be given to prevent saline problems caused by wastewater reuse (UNEP/GEC 2004).

UNEP/GEC also states that examples from Latin America show that agricultural reuse with properly treated wastewater have a benefit-cost ratio of 1.2 to 2.2, depending on crop type and the treatment involved.

Industrial recycle and reuse

Approximately 20% of global freshwater withdrawal is expected to be used for industrial purposes by 2010 (Shiklomanov 2000). The larger proportion is for power generation (about 70%). The water demand for the industrial sector is expected to increase substantially in future (to about 1.5 times the current demand by 2025).

Reuse in industry can be in several ways (UNEP/GEC 2004). Options are municipal wastewater reuse in industrial processes, internal industry process water recycling and the cascading use of industrial process water and non-industrial reuse of industrial process effluents. Table 5.5 below give examples of the industrial uses mentioned.

Table 5.5 Industrial water reuse types and examples (after UNEP/GEC 2004)

Types of water reuse	Examples
Reuse of municipal wastewater	• Cooling tower make-up water • Once-through cooling • Process applications
Internal recycling and cascading use of process water	• Cooling tower make-up water • Once-through cooling and its reuse • Laundry reuse (water, heat, and detergent recovery) • Reuse of rinse water • Cleaning of premises
Non-industrial use of effluent	• Heating water for pools and spas • Agricultural applications

The water quality requirements here differ in accordance with types of application and individual needs. In most instances conventional wastewater has to be supplemented by high purification technology to provide suitable quality water that would inhibit reactive causes of corrosion, scaling, biological growth, fouling, etc. The treatment requirements prior to industrial use therefore depend on the effluent source (effluent from an external source to industry using it, or internal industry process water recycling).

The requirements of industry are established by themselves. The factors that would motivate industry to use wastewater are water pricing and possibly its subsidisation.

5.2.3 Conventional wastewater treatment and points of reuse

Generally conventional wastewater treatment processes are classified as preliminary, primary, and secondary followed by further advanced or tertiary treatment should higher levels of treatment be required. Figure 5.5 gives the various wastewater treatment processes normally used (for low cost and conventional processes) and indicate possible points along the process steps where reuse can be considered. In the wastewater treatment process, prior to any reuse application, disinfection is an essential step to minimise environmental and health risks.

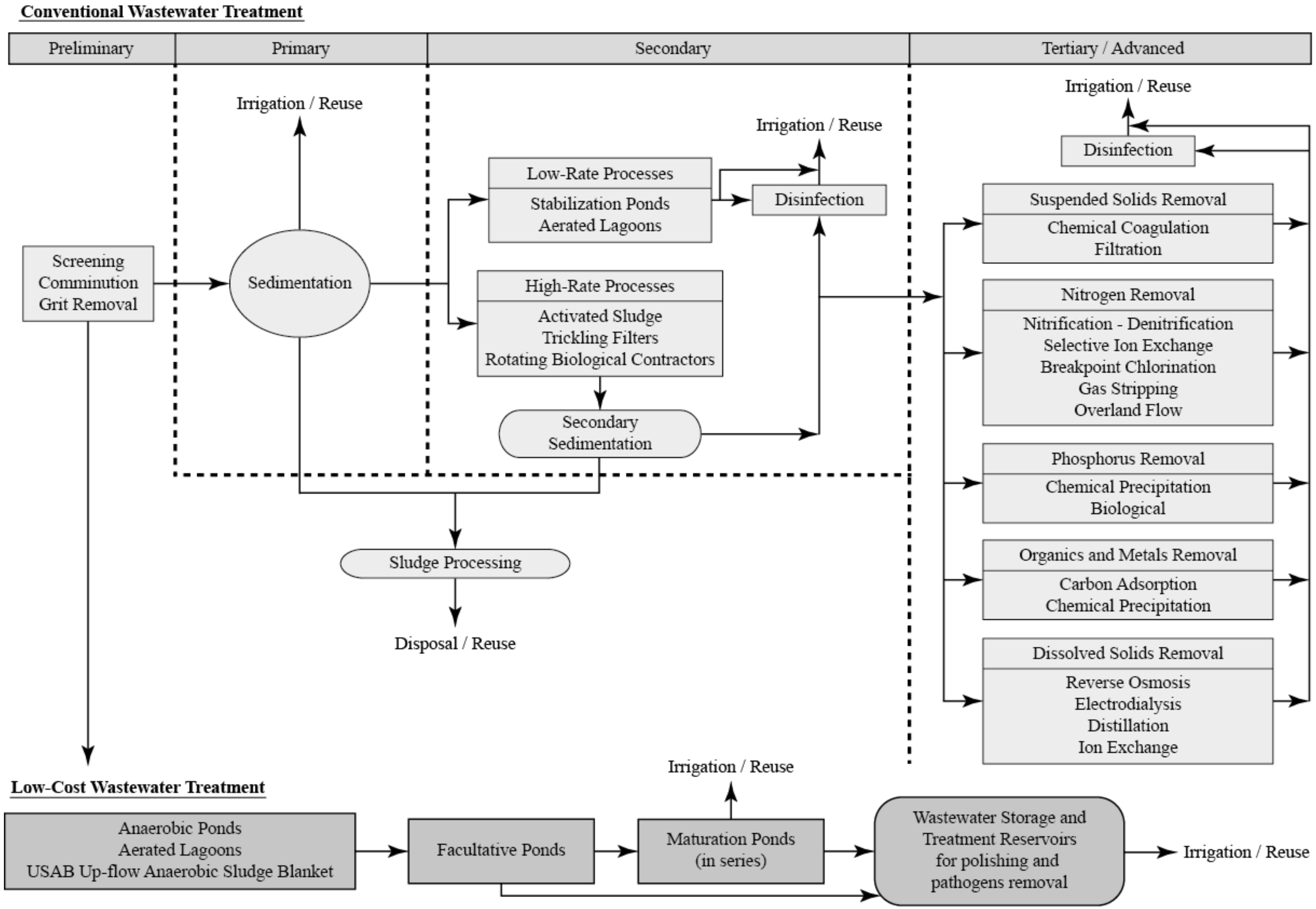


Figure 5.5 General wastewater treatment processes and potential points of reuse (after UNEP/GEC 2004)

The principal tertiary wastewater treatment processes employed for reuse are: 1) nitrification; 2) denitrification; 3) phosphorus removal; 4) coagulation and sedimentation; 5) filtration; 6) carbon adsorption; 7) advanced disinfection, and; 8) membrane processes (Tchobanoglous 1991a, 1991b, Tchobanoglous *et al*. 2004).

Nitrification is the process where ammonia nitrogen is converted biologically by nitrifying bacteria sequentially in both attached growth and suspended growth processes to alternative nitrogen chemical forms of nitrite and nitrate. Sufficient solids retention is required to avoid slow-growing bacteria to be washed out the system. Under well operated conditions the nitrification will have effluent with less than 1 mg/L concentrations of ammonia nitrogen.

Denitrification allows for complete removal of total nitrogen and is best achieved biologically and preceded by nitrification. The end product of nitrification (nitrate), in the absence of dissolved oxygen, used by bacteria as electron acceptor, is converted to nitrogen as which is released to the atmosphere. Effluent concentrations between 2 to 12 mg/L nitrate nitrogen can be achieved after denitrification processes.

Removal of phosphorus from wastewater can be achieved through enhanced biological removal or chemical precipitation or a combination of both processes.

Enhanced biological removal is based on aerobic bacteria assimilating excess amount of phosphorus under aerobic conditions when exposed to anaerobic conditions beforehand. Chemical removal through precipitation is facilitated by dosing metal salts of iron, aluminium and calcium. Removal of phosphorus in both processes is removed with excess sludge disposal. With chemical removal effluents with concentrations less than 0.1 mg/L can be achieved and biologically concentrations of between 1 to 2mg/L. In the case of chemical removal the dosage required for the various metal salt chemicals and associated cost would determine the chemical most appropriate for removal.

Chemical coagulation and sedimentation is employed for removal of suspended solids, heavy metals, phosphorus and trace elements by dosing with lime, aluminium sulphate (alum) and ferric chloride.

Through filtration particulate matter is removed from wastewater by use of a granular media such as sand, anthracite or garnet or alternatively through filter cloth prior to disinfection. The removal efficiency can be improved by additives such as coagulants or polymers.

Carbon adsorption by granular activated carbon (GAC) is effective for removal of organic constituents in secondary wastewater effluent by adsorption onto carbon. In addition carbon adsorption is able to remove several metal ions and in particular cadmium, chromium, silver and selenium. The removal of endocrine disrupters has also been removed effectively by means of carbon adsorption. Filtered secondary wastewater effluent followed by carbon adsorption can render effluent characteristics of COD and TOC of 3 to 25 mg/L and 1 to 6 mg/L respectively, while synthetic organics removal levels could be 75 to 85 percent.

Disinfection technology selection is a critical step in ensuring public health. The upstream treatment and effluent quality to be disinfected determines the dosage requirements for disinfection. Disinfection as a process on its own cannot ensure stringent health regulation compliance and has to be coupled with processes that would ensure its efficiency such as tertiary filtration or other suitable processes.

Ultraviolet (UV) technology for disinfection has increased in use largely due to reduced comparative cost and absence of toxic by-products, it has no residual which is mandatory for distribution systems and storage reservoirs.

The use of membranes to separate suspended solids, dissolved compounds and pathogens from treated wastewater have resulted in greater confidence in water reuse where direct and indirect human contact is likely (Fane 1996). Membranes were not generally used for wastewater treatment due to problems of rapid fouling. Success of membrane use depended on pre-treatment to avoid or limit fouling problems and good success were achieved with cellulose acetate membranes together with clarification and multi-media filtration pre-treatment. In the 1980s hollow fibre microfiltration with air backwash as pre-treatment to thin composite membrane reverse osmosis were developed which proved to be a tremendous improvement over the then conventional clarification and filtration pre-treatment.

Pressure driven membrane treatment are categorised by the particle size or molecular weight cut off (MWCO) rejected by membranes, broadly outlined in Table 5.6.

Table 5.6 Pressure membrane category classification

Membrane type	Particle size rejected
Microfiltration (MF)	0.1 µm (or 500000 MWCO)
Ultrafiltration (UF)	0.01µm (or 20000 MWCO)
Nanofiltration (NF)	0.001µm (or 200 MWCO)
Reverse osmosis (RO)	0.0001µm (or less than 100 MWCO)

The application of pressure membranes in wastewater treatment are briefly outlined as follows:

MF – can be used to replace secondary clarifiers and conventional sand filters after biological treatment and remove 3 to 6 log (99.9 to 99.9999 percent) removal of bacteria.

UF – similar use as MF, but is able to remove bacteria and protozoan cysts completely and 4 to 6 log (99.99 to 99.9999 percent) removal of viruses.

NF and RO – in addition to retaining smaller colloidal particles, can retain molecules and ions but require higher levels of both driven pressure and pre-treatment and typically have lower recovery rates.

Membrane bioreactors (MBRs) are systems where membrane technology has been integrated with biological wastewater treatment reactors (Melin *et al.* 2006). Membranes are either immersed directly into aeration basins or an external pressure-driven membrane units are used alongside aeration basins. MBRs typically consist of MF or UF membranes. Advantages include final effluent quality not being dependent on sludge settling characteristics; near complete removal of suspended solids, protozoan cysts and bacteria and partial removal of viruses, and; improved biodegradation of otherwise resistant compounds (grease and oils). Diffused aeration on feeder ends of membranes assist in reducing membrane fouling problems.

5.2.4 Low-tech wastewater treatment technology and reuse

Low technology can also be employed in water reuse. These processes include stabilisation ponds, infiltration-percolation, soil-aquifer treatment and wetlands. The disadvantage of these systems is the relatively large area footprint required for comparative treatment to take place. In a rural context with land more freely available and probably less competitive uses low tech systems would be feasible, but in an urban context with high competitive use and high cost premium for land smaller footprint conventional systems would be more appropriate. According to the WHO/UNEP (2006) multiple stabilisation ponds are capable to provide effluent suitable for unrestricted irrigation (less than 1000 FC/100 ml and less than one helminth egg/L). The disinfection rate of stabilisation ponds under optimal operating conditions are 3 to 5 log removal for faecal coliforms (FC) and increased removal of up to 5 to 6 log with maturation ponds included. A drawback of ponds is the restricted operational flexibility with flow and seasonal variations and high evaporation losses in arid zones. Activated sludge with ponds as tertiary treatment not only allows for efficient ultra violet radiation (UV) disinfection and elimination of FCs, viruses and helminth eggs, but also allows for storage for irrigational requirements.

5.2.5 Wastewater treatment process reliability and reuse

Due to the risk of public harm in the event of insufficient quality of reuse water, process design and operation has to be reliable ensuring strict regulation compliance.

The reuse system elements that are fallible consist of power supplies, treatment processes, mechanical equipment, maintenance programs and operating personnel. Back-up systems are essential for the reuse system elements that are vital for ensuring system efficiency and reuse water quality and particularly vulnerable in case of breakdown. According to the United States Environmental Protection Agency (US EPA) (2004), their Class I reliability criteria should apply to wastewater reuse and due consideration of the following:

1. Qualified personnel for operation of reuse systems and operator certification
2. Control systems for monitoring of treatment performance and malfunction alarms
3. Comprehensive quality assurance programs for sampling and laboratory analysis protocol
4. Emergency storage of unacceptable reuse water quality occurrences for retreatment or alternative disposal
5. Storage and/or supplementing water supplies to ensure user demand matching
6. Strong enforcement of sewer use, disposal and industrial pre-treatment ordinances to prevent discharge of hazardous materials or substances into wastewater collection systems that would cause interference with water reuse
7. Comprehensive operating protocol that stipulate duties and responsibilities of operational staff to ensure adequate procedures and practises for reliable reuse water production and delivery of adequate quality and quantity to consumers

5.3 QUANTITATIVE AND QUALITATIVE IMPACT OF WASTEWATER REUSE ON WATER SOURCES AND SUPPLY SYSTEMS

Urbanisation, population growth and the industrial supply demand as part of economic development has placed increased pressure on the available fresh water resources and will ultimately have to be balanced with water reclamation and reuse to relieve pressure on finite fresh water resource. Depending on the reuse level and number of cycles, as well as the extent of losses in fresh water supply systems, by employing reuse for a particular system, the net water availability could be much higher compared to a non-reuse scenario.

5.3.1 Reuse impact on river water sources

In order to pursue the question of potential net increased water availability as well as quantity and quality impacts on the water sources extracted from and effluent discharged, a water balance analysis was done by Grobicki and Cohen (1999) for a hypothetical supply area.

The analysis by Grobicki and Cohen (ibid) of reuse impacts on river flow volumes and quality regimes for two different scenarios are outlined in detail in Appendix A6. The two scenarios considered were: 1) fresh water withdrawal from and effluent return to the same surface water (river) source, and; 2) fresh water withdrawal from and effluent return to two different river sources, such as the case where inter-basin water transfers occur.

From the first scenario analysis, it was found that reuse increases river flow to downstream users due to a decrease in net water withdrawal. The mass balance done demonstrates that the total dissolved solids (TDS) quality of the effluent receiving river is not affected by reuse either. With the second scenario, similar to the first, flow of the river where supply is extracted from also increases compared to non-reuse. However, in this instance the TDS quality of the effluent receiving river would improve due to decreased levels of TDS being discharged compared to non-reuse.

The Grobicki and Cohen (ibid) findings confirms that reuse per say does not affect downstream river flow volumes and their TDS quality compared to non-reuse. Therefore no downstream user is detrimentally affected with reuse employed, nor the environment and river ecology. In fact, in situations where discharge takes place to a different river from which supply was extracted from, reuse would lower the level of TDS discharged and result in a relative improved quality opposed to that of non-reuse.

5.3.2 Reuse impact on a typical urban water supply system

Quantifying the impact of reuse on water availability for urban water supply systems allows linking of water reuse level and resource conservation benefits (being equivalent to the increased supply achieved) for inclusion into an integrated management system level analysis.

Simplified water balance model of urban water supply with reuse

The impact of different levels of reuse on the available water of a typical urban water supply was considered, using the simplified water balance model of Grobicki and Cohen (1999). The typical urban water supply with the various flow components allowed for in the simplified Grobicki-Cohen model are diagrammatically represented in Figure 5.6(a).

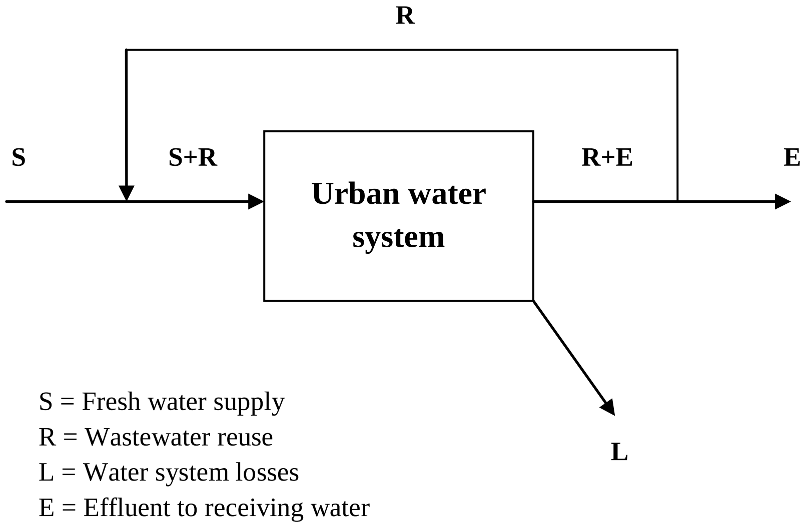


Figure 5.6(a) Simplified water balance model of an urban water supply system with reuse (after Grobicki and Cohen, 1999)

Considering a water balance over the whole water supply system in Figure 5.6(a) gives:

$$S = E + L \tag{5.1}$$

A water balance over the urban water supply system itself gives:

$$S + R = E + R + L \tag{5.2}$$

By considering various levels of urban network system losses (L) together with the water balance equations derived, the additional water supply made available through reuse was determined with the results shown in Table 5.7. The detailed water balance calculations are given in Appendix A7.

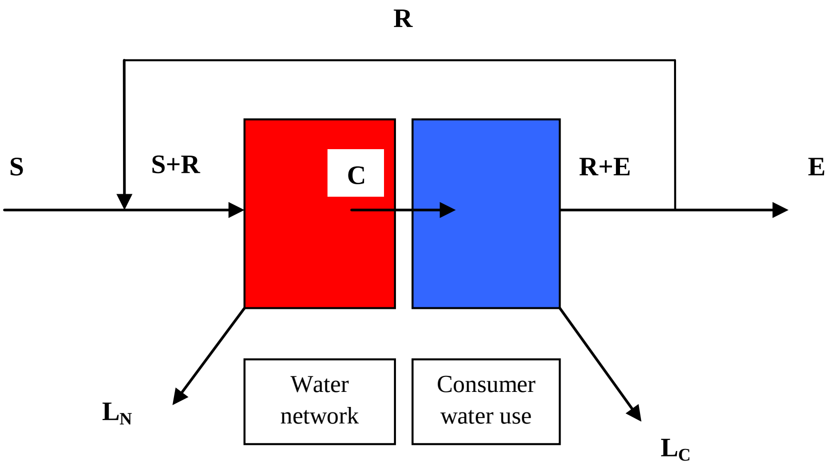
Table 5.7 Flow balance assessment of an urban water supply system with various levels of reuse

Assumed supply system losses (%)	Potential optimal reuse level (as % of supply)	Increase in available water supply @ optimal reuse level (%)
20	80	400
35	65	186
50	50	100
65	35	54

For a supply system loss of 20%, the increase in water supply with reuse based on the simplified model is 400%. The question arises as to what extent the simplified model could present actual conditions experienced in urban water supply systems. As different types of network losses are not distinguished and their particular impact not allowed for individually, the model as is falls far short of what is needed to be more representative of actual conditions in practise. There is therefore a need to refine the simplified model to become a closer representation of water supply systems and assess the impact of reuse on supplies more realistically.

Revised water balance model for urban water supply with reuse, differentiating between network and consumer-end related losses

As a first step towards refinement of the simplified model for evaluating the impact of reuse on urban water supplies, the Grobicki-Cohen model was revised to distinguish between network-related and consumer-end related losses. The network related losses is taken as that normally referred to by water services authorities or municipalities in an accounting context as “unaccounted for” water use. These losses include supply system deficiencies such as pipe leaks, inaccurate consumer supply meters and community services rendered without water consumption normally being metered (street cleaning, fire fighting and irrigation of public open spaces). Consumer end losses would be accounted for by that part of consumption not being part of the return flow to the urban wastewater system. The adjusted supply system with the network and consumer related losses are shown in Figure 5.6(a).



S = Fresh water supply
R = Wastewater reuse
L_N = Different water network losses
L_C = Different consumer type losses
C = Different consumer type water use
E = Final effluent to receiving waters body

Figure 5.6(b) Network-consumer differentiated urban water supply system with reuse

Considering water balance over the whole water system in Figure 5.6(b) gives:

$$S = E + (L_N + L_C) \tag{5.3}$$

A water balance over the urban water network gives:

$$S + R = L_N + C \tag{5.4}$$

A water balance over the consumer area gives:

$$C = L_C + R + E \tag{5.5}$$

A water balance over both the water network and consumer area gives;

$$S + R = (L_N + L_C) + R + E \tag{5.6}$$

A calculation was done to determine the increased water supply by reuse for the following typical scenario encountered in an urban supply system:

> Urban network losses or “unaccounted for” water use of 20% of total supply.
>
> Return flow to urban wastewater system of 70% as a fraction of consumption.

The increase in available supply comes to 126% with the revised model compared to an increase of 400% with the simplified model (where system losses are allowed for generally). By distinguishing between consumer end and network related losses in the revised model, a step is taken towards obtaining a more practical representative evaluation of the impact of reuse. Although this first model refinement falls far short of representing the actual situation in practise, it is a step in the right direction to assess impact of reuse closer to the actual situation in practise.

There is further room for improvement for achieving improved model-system representation. Improvements such as distinguishing between different types of urban consumption (i.e. domestic, industrial and commercial use) as well as to allow for the individual network component losses could be accounted for. However, the extent of refinement mentioned would be subject to availability of the corresponding data for urban systems.

The result obtained by the revised water balance model demonstrates the extent of increase in water supply that could be sustained through reuse and the advantage of possible deferred mobilisation of an equivalent additional fresh water resource. However, the question of matching water demand with appropriate reuse applications and treatment level requirements has to be taken into account to determine actual resource conservation possible.

The detailed water balance calculation using the revised model is set out in Appendix A8.

5.4 GREYWATER REUSE

Domestic/commercial wastewater consists of all wastewater of households, hotels, businesses, offices, shopping malls and other domestic type sources, while industrial sources are effluent from the manufacturing and production sector. Greywater refers to all domestic/commercial wastewater excluding human excreta (feaces and urine) from toilets. Greywater is therefore made up of some flows from bathrooms (from baths, basins and showers), kitchens and laundry purposes (WHO/UNEP 2006d). Water use for household cleaning purposes should also be part of greywater. The fraction from bathrooms (basin, bath and showers) are termed “light greywater”, while that from kitchens and laundry activities is known as “dark greywater” (Lazarova *et al*. 2003). Water used for household cleaning should also be part of the “dark greywater” fraction due to the associated use of cleaning solvents, soaps, etc.

5.4.1 Greywater reuse value

The total greywater fraction of combined domestic sewage is estimated to be around 75 % by volume and from a fresh water conservation point of view it is estimated that 30% to nearly 40% of the total household water consumption could be saved by reuse for flushing toilets and garden watering (Eriksson *et al*. 2002, Al-Jayyousi 2003). For public environments (such as offices and shopping malls) the proportion used for toilet flushing is as high as 48 to 63% (Lazarova *et al*. 2003). The problem in such cases is the limited availability of greywater of such uses and most likely will require supplementation from potable water supplies for toilet flushing application of greywater. When limited volumes of greywater are available, reuse of the larger available wastewater flow would be more appropriate for achieving fresh water resource conservation.

The characteristics of greywater are highly variable and depend on the quality of the water supply and activities in households, lifestyles, chemical household products used and extent of chemical and biological degradation of such products (Eriksson *et al*. 2002, Li *et al*. 2009).

Although certain greywater use initiatives resulted from short term responses to water resource problems rather than a focus on achieving long term sustainable urban water management, the benefits thereof has become more evident and emphasised the role of greywater reuse in fresh water resources conservation (Dixon *et al*. 1999). Examples of short term responses given by Dixon *et al*. (1999) are greywater reuse in Tokyo Japan to accommodate demand associated with high population density and small land space, and the US and Australia where drought conditions required greywater irrigation of gardens.

Outdoor applications for greywater could be window and vehicle washing, fire protection, concrete production, boiler feed water as well as irrigation of lawns and domestic gardens and to develop and preserve wetlands (Eriksson *et al*. 2002).

With regard to irrigational reuse, greywater provide only minor nutrient value, as the major fraction of nutrients is present in human excreta consisting of faeces plus urine (Table 5.2).

Indoor reuse application would be that of toilet flushing. This is justified based on the fact that the cumulative greywater flow generated are generally in excess of toilet flushing requirements which amount to around 25 to 30% of the total water use (Al-Jayyousi 2003, Li *et al*. 2009). With such applications only the “light greywater” fraction is used, excluding the “dark greywater” from kitchens (sinks and dishwashers) and laundry purposes. Kitchen (scullery) wastewater contains food wastes that would putrefy and cause bad odour and biological film build-up in reuse systems blocking pipes. Kitchen greywater accounts for about 5 to 12% of average household consumption and its omission from the greywater reuse source is therefore not significant (Christova-Boal *et al*. 1996, Li *et al*. 2009).

Lazarova *et al*. (2003) listed schemes or trails of greywater reuse for toilet flushing in various countries. These applications are mainly at household level (Australia, Canada, France, Germany and the UK) with instances of office buildings (Japan). They also mentioned instances where wastewater is the reuse source for toilet flushing such as the USA, UK, Canada and Japan.

There are a number of problems related to the reuse of untreated grey wastewater. There is a risk of spreading diseases when water is reused for e.g. toilet flushing or irrigation. Spreading of pathogenic micro-organisms in the water in the form of aerosols generated as the toilets are flushed allow spreading and both inhaling and hand to mouth contact are dangerous (Eriksson *et al*. 2002).

5.5 CENTRALISED SYSTEMS REUSE POTENTIAL

According to Gijzen (2001) maximising energy, water and nutrient recovery should be the objective for achieving improved sustainability for ‘end-of-pipe’ centralised wastewater treatment systems. Wastewater reclamation and direct reuse offer opportunities for achievement of water recovery goals though mainly non-potable use applications such as industry (production and cooling), recreational, environmental enhancement and various urban uses (landscape irrigation, fire fighting and construction) as well as residential uses such as toilet flushing and household cleaning. By agricultural use and landscape irrigation nutrient recovery would be achieved in addition to fresh water resource conservation.

The reuse applications in the case of centralised systems require a dual-pipe system for return of treated effluent to the point of use. Communities already served by centralised urban wastewater systems require an additional distribution system to make treated wastewater effluent available for industrial, agricultural or recreational reuse. Main considerations would be the cost competitiveness of such a resource compared to potable supply and a viable demand base for the reuse product.

The suitability of treatment sludge for agricultural use is a major issue with centralised treatment systems (Niemczynomicz 2001). The normally combined flows received from residential, commercial and industrial areas result in unsuitable hazardous and toxic substances ending up in treatment sludge (i.e. heavy metals, pharmaceuticals, pesticides, hormone-like substances, waste medicines, metabolites of medicines, etc.). Such toxins being taken up by crops and livestock and eventually causing humans to be at a health risk has resulted in such sludge not being used for agriculture without reservation. To deal with this issue large scale expense had to be incurred for alternative disposal expanding on the conventional technology for sludge dewatering, treatment and incineration facilities to achieve acceptable disposal.

Due to the major fraction of nutrients being contained in urine its separation from the domestic waste stream at source allow for the recovery of this valuable product and use as a natural fertiliser (Larsen and Gujer, 1996, Larsen and Boller, 2001). In the context of a centralised system, an interesting option would be urine separation at source and temporary onsite storage. Two options for its transport to a potential user could be considered being either by vehicle bulk collection, or alternatively controlled discharge from onsite storage into the centralised sewer network. However, to limit mixing of this concentrated nutrient with other wastes entering the sewer system, it would be best to release the stored urine during the low/minimum flow period in sewers (normally early before dawn). Once received at the treatment plant the nutrient could be channelled to a dedicated separate module at the plant for treatment and recovery. The latter option could be applied to the whole system or only for parts thereof depending on system characteristics to allow low solid-free flows and the travel time to the plant.

Apart from the nutrient recovery potential, the nutrient load to the plant would be reduced to such an extent that biological nitrification and denitrification would no longer be required. This in turn will increase the plant’s hydraulic and organic treatment capacity accordingly.

5.6 DECENTRALISED SYSTEMS REUSE POTENTIAL

Common concepts towards integrated resource conservation and environmentally friendly, ecologically and economically sound wastewater management can be summarised as follows (Larsen and Gujer, 1996):

- Integration at a local scale of water and wastewater management
- Separate collection and treatment of different waste streams
- Recovery of valuable substances and its use (water component, biogas and nutrients)

By integration of water and wastewater management at local scale, water demand could be drastically reduced (and also the wastewater that result), contributing to fresh water resource conservation as well as lessening potential wastewater impacts on the environment and ecology. With separate collection of different local waste streams the use of appropriate treatment process are possible that would focus on the end product quality to be achieved from a particular waste stream composition.

5.7 CHALLENGES ASSOCIATED WITH WASTEWATER AND GREYWATER REUSE

Although social support does exist for reuse, there are reservations of its applications, in particular where direct personal contact and ingestion is concerned.

According to a survey by Nancarrow *et al*. (2008), acceptance depended on the type of water being reused. A study by Simpson (1999) found that communities were prepared to consider potable reuse provided technology employed is safe and reliable and community health will not be compromised.

According to the WHO (2006), the question of public acceptance of greywater reuse is less problematic compared to wastewater reuse. This is attributed to users being in contact with greywater at source (bath, shower and basin) and generally being considered by them as not being harmful and that no religious edicts prohibit its reuse.

If the treated final effluent could be perceived as being ‘used water’ rather than sewage or wastewater, it would go a long way towards fostering a different public and political perception of this potentially useful resource. A pioneer of the Namibian wastewater reuse project for potable use said: “*water should not be judged by its history but by its quality*” (Haarhoff and van der Merwe, 1996). This is surely to be of fundamental importance when the issue of acceptance not for potable reuse alone but all applications of reuse is being dealt with by society.

PART II: ECONOMIC CONSIDERATIONS IN WASTEWATER MANAGEMENT SYSTEMS

Favouring an integrated approach for sustainable wastewater management resulted in the trend to close nutrient loops in urban cities, mitigate negative environmental impacts as well as make the most of available finite fresh water resources. Although the required technologies for achieving the new approach objectives are available and the approach has been accepted by the water sector as being essential to ensuring fresh water resource conservation and environmental protection, the actual switch to the new paradigm has not become ubiquitous.

A factor that would give momentum to the required switch is the support at the decision-making level. For this, not only must alternative system options be presented, but adequate financial facts also as they are an essential part of the decision-making process. To make meaningful comparisons of alternative solutions in an economic and financial sense, all aspects of environmental resource use need to be valued. Specifically, this requires that all the related costs and benefits as well as any related externalities are included in economic analyses.

5.8 WATER RESOURCES AND ECONOMICS

For objective economic comparison and decision-making, both in the public and private domain, the value of water resources has to be based on an objective market-related price. The major challenge in obtaining this is that water resources are generally considered a public good, are not traded in private markets nor subjected to the market price mechanism although a trend in this direction is well documented in the literature. The result is that water resources are considered to be of low market value and exploited (Birol *et al*. 2006). A further challenge is to account for the resource scarcity value (in terms of both quantity and quality) in addition to resource extraction costs. Birol *et al*. (2006) pointed out that if scarcity is not recognised, high resource use, wastage and pollution of water resources are likely to be the end result.

In addition, factors also contributing to this value distortion of water resources, amongst others, are government subsidisation and the practice of not accrediting polluting industries with environmental protection externality benefits achieved by them. To correct the value distortion of the water resources mentioned, all benefits obtained by use of water resources need to be captured in a total resource valuation.

Pearse and Turner (1989) points out that the values derived from environmental resources are not just that of direct use, but also non-use value. They refer to the *total economic value* (TEV) of an environmental resource which incorporates both use and non-use values. Use value covers benefits derived from direct utilisation, while non-use values are benefits obtained even if no direct use takes place.

Figure 5.7 illustrates graphically the effect of distortion of private good market value of water resources due to the factors mentioned. The MNPB-curve represent the corresponding *marginal net private water use benefits,* while the MNPB(sub)-curve represents the corresponding *marginal net private water use benefits exacerbated by government subsidy policies*. The MEC(L)-curve represents the *marginal externality cost of water resources borne locally*, while the MEC(L+G)-curve is the aggregated *marginal externality cost borne locally and globally*, as measured by the TEV of water resources. Water resource use values include direct and indirect use as well as an option value. Among direct water resource use are irrigation for agriculture, domestic and industrial use, energy resources, transport, recreation and amenity. Indirect use, amongst others, includes nutrient retention, pollution abatement, flood control, eco-system support and erosion protection. Option values relate to potential future uses in both a direct and indirect sense.

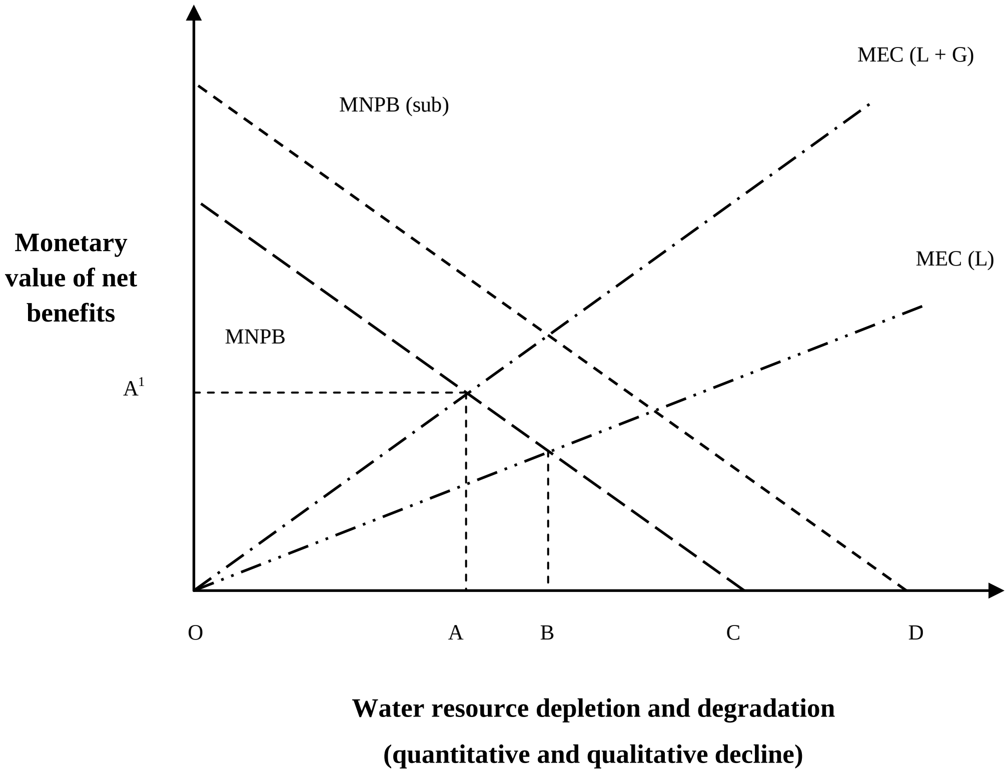


Figure 5.7 Illustration of water resource private good value distortion by governmental subsidy (after Birol *et al*. 2006)

In Figure 5.7 points C & D represent the relative impact that subsidies have on water resource use with all externality costs disregarded, while points A & B reflect the global and local optimums respectively should externalities be internalised.

For a global social optimum, the efficient water resources use is at level OA with corresponding net benefit value of OA^1 when all externalities are internalised.

If one prescribes to the paradigm shift that says that ***wastewater is a resource rather than a waste,*** then wastewaters enter into economic considerations as a replacement for natural resources either through reclamation and reuse or recycling. Whichever is the case, wastewater treatment through employed technology reduces the inherent pollution load of wastewater to such level that the resulting treated water product can be used safely as a replacement for a freshwater resource. This wastewater treatment process allows for biological assimilation and conversion of contaminants, release of process end products to the atmosphere (gaseous nitrogen and carbon dioxide) and separation through clarification of the solids sludge by-product from the treated effluent. The solids sludge by-product consists of the various pollution constituents together with cyclic disposed excess biological process mass. Both the liquid and sludge have valuable potential resource value. The resource potential is technically unlimited for both the liquid and sludge components provided the level of treatment is employed for the corresponding quality required for its planned use. The commodity value of these components is however related to its acceptance and suitability for a particular application.

The substitution of fresh water use by reclaimed, reused or recycled treated wastewater results in its value being mostly related to that of the ruling fresh-water market price.

In cases where benefits are without market-related value, such as prevention of pollution of water resources, the appropriation of monetary values to such benefits presents quite a challenge. However, various methods for valuing environmental resources can be employed and for this purpose these are briefly discussed next.

5.9 ECONOMIC VALUATION METHODS FOR ENVIRONMENTAL RESOURCES

Two groups can be distinguished for the methods developed for determining environmental resource values, namely indirect valuation (or revealed preference methods) and direct valuation (or stated preference methods) (Rocky Mountain Institute 2004, Birol *et al*. 2006).

5.9.1 Direct valuation methods

Direct valuation methods are twofold, being *contingent valuation* (CVM) and the *choice experiment* (CEM) methods. Direct methods are population survey-based and apart from the survey itself, survey composition and questionnaire development makes it a time consuming and quite costly exercise. Both interviewer and survey respondent biases play a major role in the outcome of such methods and in particular with CVM. Although the alternative CEM approach tends to eliminate several biases, the hypothetical scenario on which the survey is based makes it a formidable challenge to deal with.

5.9.2 Indirect valuation methods

According to Lancaster (1966) the indirect valuation method seeks out private marketed goods being traded that contains an environmental good or goods as a component thereof. Activities of such surrogate markets are then used as a measure of benefits derived from the use of the particular environmental resources.

The indirect valuation category include approaches such as *hedonic pricing, travel cost, replacement cost, avertive expenditure, net factor income, cost-of-illness* methods and the *production function* approach. The *hedonic* and *travel cost* methods are the most frequently applied methods of this category.

In this study the production function approach is used through analysis of a parameterised distance function for water resource valuation, which is discussed in more detail next.

5.10 PRODUCTION FUNCTION METHOD – USE OF DISTANCE FUNCTIONS

In a microeconomic sense, a particular technology used to produce outputs from various inputs is described by the so-called “production function”. The production function can be considered to be a literal depiction of the physical possible net outputs of the technology and can be expressed as a parametric functional form also known as an isoquant (Varian 1992).

The *distance-function approach*, as opposed to the conventional production function, is favoured (Färe *et al*. 1993, O'Donnell and Coelli, 2005) because:

1. it allows modelling the joint production of multiple outputs;
2. aggregation of outputs or inputs are not required for deriving shadow price;
3. no assumptions of production process behaviour such as cost-minimisation or profit-maximisation have to be made for deriving shadow prices, and;
4. it allows for shadow price derivation based on Shephard's duality theory (Shephard 1970).

The pioneering work of Farrell (1957) established the methodology of using frontier functions to analyse production efficiency, known as Data Envelopment Analysis (DEA). In terms of the frontier approach, a firm will be on the production frontier when it obtains maximum output for a certain vector of inputs or, if it produces a certain output for a minimum of inputs. The technical efficiency of a firm can therefore be measured in accordance with the maximum possible proportional increase in output produced compatible with its input level.

By exploring derivatives along the mentioned frontier of technology, shadow prices that support such technology can be derived (Färe *et al*., 1993).

5.10.1 Distance functions

The concept of distance functions were first introduced by Shephard (1970). Distance functions generalise, completely characterise and define conventional production functions and can therefore be employed as the equivalent and employed for production process analysis purposes (Chambers *et al*. 1998). Shephard's input and output distance functions respectively measure the largest radial contraction of the input vector and largest radial expansion of the output vector in relation to an optimal production frontier within the technically feasible domain. The use of this approach is termed as *analytical benchmarking* or *frontier methodology*.

In the case of polluting industries where both desirable and undesirable outputs are produced jointly, the objective would be to maximise desirable outputs while minimising undesirable ones. As mentioned before, the economic theory of duality between the output distance function and the revenue function is applied to derive shadow prices for both desirable and undesirable outputs. The duality here means that any concept defined in terms of one function's properties has a twin definition in terms of the properties of the other function and vice versa.

5.10.2 Review of studies employing distance function valuing

Various researchers have developed distance function based models to explore both polluting industries in general and wastewater treatment facilities as a special case of polluting industries.

Polluting industries: General

Coggnis and Swinton (1996) utilised an output distance function and the revenue duality to derive shadow prices for fourteen American coal-burning electricity generating plants using annual observations of a three year period. The desirable output considered was electricity with a single undesirable output being sulphur dioxide emission (SO_2). Four input components were distinguished being energy, sulphur (contained in coal throughput), labour and capital. The shadow price derived for sulphur dioxide abatement was compared to the corresponding prices observed with the national market for allowance trading in accordance with the US pollution control act for curtailing sulphur dioxide emission in the most cost efficient manner.

Reig-Martinez *et al*. (2001) used an output distance function together with its revenue function duality to derive shadow prices for eighteen Spanish ceramic pavement producer outputs. The desirable output was ceramic pavements and the joint undesirable outputs (or wastes) consisted of watery mud and used oil. Shadow prices of industrial wastes derived are indicative of the marginal loss of revenue of a firm should it need to reduce waste emission by a marginal unit.

Van Ha *et al*. (2008) also used an output distance function approach and revenue function duality to determine shadow prices for environmental outputs of sixty-three household-level paper recycling units in Vietnam. The outputs distinguished were the desirable paper product and process removed undesirable outputs of suspended solids (SS) and organics (BOD and COD) values respectively.

Polluting industries: Special case of wastewater treatment plants

Other studies considered wastewater treatment as a special case of polluting industries. Wastewater treatment employs appropriate technology to remove pollutants to produce treated water suitable for reuse, recycling or reclamation (discharge into the environment), opposed to a typical polluting industry which produces jointly a desired end-product together with pollution by-products. The following studies are briefly reviewed:

Molinos-Sante *et al*. (2010) undertook a cost-benefit analysis of twenty-two wastewater treatment plants in Spain using the output distance function approach to make a quantitative monetary assessment of both desirable output (treated water) and the undesirable output (wastewater contaminants removed by the treatment process) using shadow pricing. The undesirable outputs distinguished (as contaminants removed) were suspended solids (SS), organics (COD), nitrogen (N) and phosphorus (P).

The same researchers did a further study based on the same approach for forty-three wastewater treatment facilities located in Valencia Spain to determine the overall environmental benefit resulting from wastewater treatment. In this case five undesirable outputs (as contaminants removed) were considered being; suspended solids (SS); organics (BOD and COD respectively); nitrates (N), and; phosphates (P). (Hernández-Sancho *et al*. 2010).

Hernandez and Sala (2009) determined the efficiency of three hundred and thirty eight secondary process level wastewater treatment plants, both in technical and cost terms, using the *analytical benchmarking* or *frontier methodology*. Here, through scaling of the input distance function for each plant’s given output vector set, the extent of input vector minimisation was determined. Efficiency was based on the minimum use of resource inputs to reach a determined production output. Five individual cost inputs were considered, being; amortisation of capital costs; energy cost; labour cost; costs for chemicals; maintenance cost, and; waste management cost. A single undesirable output was considered being the aggregated pollutants removed, consisting of suspended solids (SS), chemical oxygen demand (COD) and biochemical oxygen demand (BOD).

5.10.3 Distance function formulation and development

In terms of Shephard's radial distance functions formulation given before (1970), an observed output vector is projected onto the boundary of the output set (or production frontier) by increasing all outputs proportionally (Färe *et al*. 2005). The projection of output vector OB onto the production frontier is illustrated in Figure 5.8.

According to Chambers *et al*. (1998), for a wastewater production process that uses *N* inputs (represented by a vector *x* and $x \in \Re_{+}^{N}$) to produce *M* outputs (represented by the vector *u* and $u \in \Re_{+}^{M}$), then the output distance function $D_o(x,u)$ on the set of all feasible output vectors that employ input vector *x*, *P(x)*, is defined as:

$$D_o(x,u) = \inf_{\theta} \{\theta > 0 : (u/\theta) \in P(x)\} \tag{5.7}$$

The ratio *u/θ* is the output ratio in relation to the production frontier, where *θ* is a factor with value between zero and one, and $D_o(x,u) \in [0,1]$.

This follows from the fact that the factor *θ* is indicative of the extent to which outputs can be expanded. For a firm with no expansion of output possible, *u/θ* has to be equal to *u*, or *θ* = 1, and such a firm is located on the production frontier in terms of output. However, under conditions where expansion of output is possible, then *u/θ* has to be greater than *u*, or *θ* < 1, and such a firm is located below the production frontier or has a lower efficiency in terms of output.

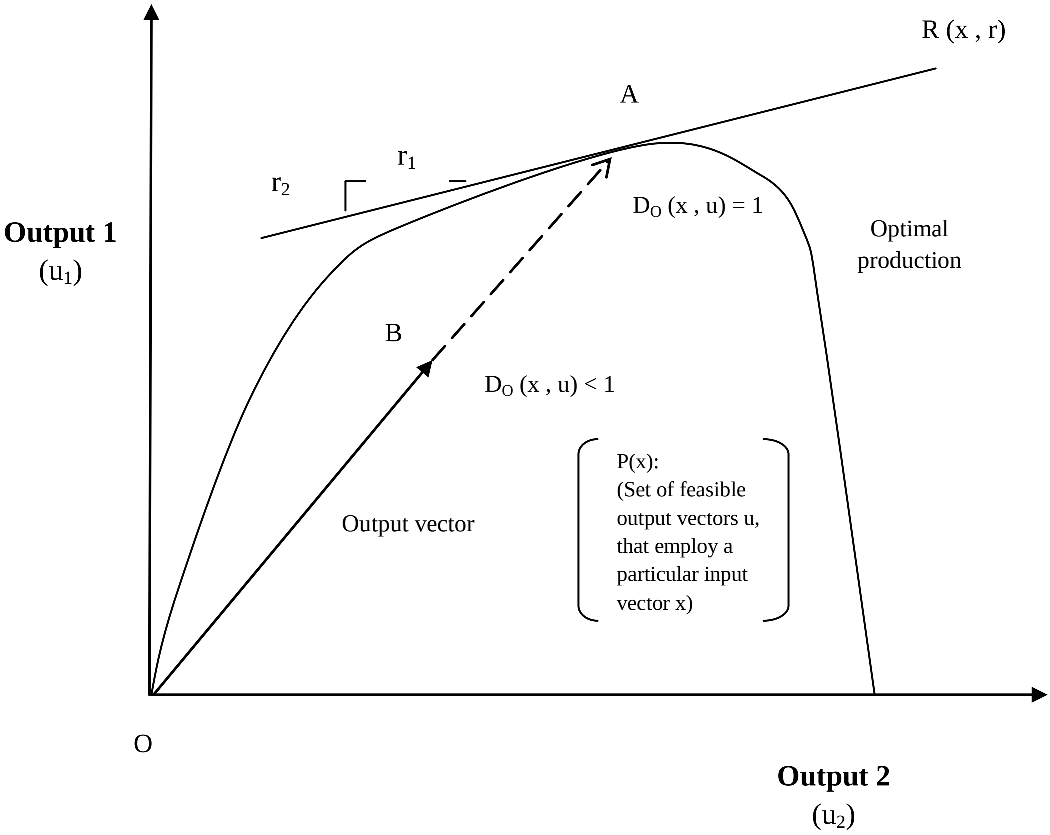


Figure 5.8 Output distance function on a feasible technology output set (derived from Coggins and Swinton, 1996)

Therefore, when the output distance function has a value of unity, the corresponding output vector belongs to the production frontier set. The said frontier is outlined by the set of output vectors for which there is an input at which $D_o(x,u) = 1$ (Coggins and Swinton, 1996). High process efficiency implies a value of $D_o(x,u)$ close to unity, while lower values towards zero indicate lesser efficiency in terms of output. Furthermore, in the case of zero output, the output distance function is zero, and $D_o(x,u) = 0$.

Figure 5.8 illustrates the concepts related to the output distance function mentioned and it follows therefore that for output vector OB the output distance function value is the ratio OB/OA.

In order to apply the shadow price expression, Färe *et al*. (1993) recommend the use of a parameterised form of the output distance function, also known as the *translog output distance function*. This function is considered best suited to parameter estimation as it allows greater flexibility and is best solved using a parametric linear programming method (Aigner and Chu, 1968). The production frontier is taken as an output distance function with frontier value of unity (Färe *et al*. 1993).

For an analysis of *k* units (number of treatment facilities), with *n* inputs and *m* outputs, the *translog output distance function* ($\ln D_0(x^k, u^k)$) has the form (Färe *et al.* 1993, Molinos-Senante *et al*. 2010):

$$\ln\ D_0(x^k, u^k) = \alpha_0 + \sum_{n=1}^{N} \beta_n \ln x_n^k\ + \sum_{m=1}^{M} \alpha_m \ln u_m^k + \frac{1}{2}\sum_{n=1}^{N}\sum_{n'=1}^{N} \beta_{n,n'}\ (\ln x_n^k)(\ln x_{n'}^k)$$
$$+\frac{1}{2}\sum_{m=1}^{M}\ \sum_{m'=1}^{M} \alpha_{m,m'}\ (\ln u_m^k)(\ln x_{m'}^k) + \sum_{n=1}^{N}\ \sum_{m=1}^{M} \gamma_{n,m}\ (\ln x_n^k)(\ln u_m^k) \qquad (5.8)$$

As the objective is to identify shadow prices that support the technology, the derivatives along the surface of the technology or the production frontier are evaluated, i.e. where $D_o(x, u) = 1$.

The function parameters are determined using Lagrangian optimisation of the following objective function (Färe *et al*. 1993):

$$\max \sum_{k=1}^{K} \left[\ln D_o(x^k, u^k) - \ln 1\right] \qquad (5.9)$$

subject to

(i) $\ln D_o(x^k, u^k) \le 0, \quad k = 1, \ldots, K,$

This constraint requires individual facility output distance function values to be less or equal to the unity frontier i.e. $D_o(x^k, u^k) \le 1$.

(ii) $\dfrac{\partial \ln D_o(x^k, u^k)}{\partial \ln u_m^k} \ge 0, \quad m = 1, \cdots, i,$

$k = 1, \cdots, K,$

This constraint covers multiple desirable outputs (1,…, *i*) and ensures they have non-negative shadow prices.

(iii) $$\frac{\partial \ln D_o(x^k, u^k)}{\partial \ln u_m^k} \le 0, \quad m = i+1, \cdots, M, \quad k = 1, \cdots, K,$$

This constraint covers multiple undesirable outputs (i+1,…, *M*) and ensures they have negative shadow prices. These values should be negative because undesirable outputs would present a negative externality if they were to be disposed of and pollute the environment.

(iv) $$\sum_{m=1}^{M} \alpha_m = 1$$

$$\sum_{m'=1}^{M} \alpha_{m,m'} = \sum_{m=1}^{M} \gamma_{n,m} = 0, \quad m = 1, \cdots, M, \quad n = 1, \cdots, N,$$

These constraints impose homogeneity of degree one, which also ensures the technology satisfies weak disposability of outputs. Weak disposability means any proportional contraction of good and bad outputs together is feasible, i.e. for given inputs *x*, reductions in bad outputs are always possible if good outputs are reduced in proportion.

(v) $$\alpha_{m,m'} = \alpha_{m',m} \qquad m = 1, \cdots, M; \; m' = 1, \cdots, M,$$

$$\beta_{n,n'} = \beta_{n',n} \qquad n = 1, \cdots, N; \; n' = 1, \cdots, N,$$

These constraints impose symmetry such that swapping around the alpha and beta coefficients of input/output indices in the product of natural logarithms in the translog output function are equal, for example $\alpha_{12} = \alpha_{21}$.

Individual facility observations are indexed as k = 1,……, *K*, while the desirable outputs are designated m = 1 *to i* and the undesirable outputs $m = i$ + 1,…., *M*.

The objective function minimises the sum of deviations of individual facility observations *k* from the unity frontier. But with $D_o(x^k, u^k) \le 1$, the natural log of the output distance function, $\ln D_o(x^k, u^k) \leq 0$ and the deviation of individual facilities *k*, $\ln D_o(x^k, u^k) - \ln 1 \leq 0$. Therefore, the objective function maximises the sum of the negative deviation of individual plants or facilities *k*.

5.10.4 Derivation of output shadow prices

Shephard (1970) proved the duality between the revenue function $R(x, r)$ and the output distance function $D_o(x, u)$. In terms of the duality, the revenue function $R(x, r)$ is derived by maximisation of the output distance function $D_o(x, u)$ with respect to outputs (see Figure 5.8), while the output distance function $D_o(x, u)$ is derived by maximisation of $R(x, r)$ with respect to the output prices, as follows:

$$\begin{aligned} R(x,r) &= \sup_u \{ru : D_o(x,u) \leq 1\} \\ D_o(x,u) &= \sup_r \{ru : R(x,r) \leq 1\} \end{aligned} \qquad (5.10; 5.11)$$

where the output prices $r = (r_1, \ldots, r_m)$ and $r \neq o$.

Färe *et al*. (1993) derived an equation for the absolute shadow prices of outputs making use of the above duality. This was done by:

1. proving that at the optimum, the negative of the Lagrange multiplier equals the revenue function;
2. the assumption that revenue and distance functions are differentiable, and;
3. introducing the assumption that ‘one observed output price equals its absolute shadow price.

It is assumed that the revenue and distance functions are differentiable.

Using the 1st part of the duality theorem & writing the Lagrange function, Λ, for revenue

$$\max \Lambda = ru + \lambda(D_O(x,u) - 1) \qquad (5.12)$$

The 1st order condition with respect to the outputs is:

$$r + \lambda \nabla_u D_O(x,u) = 0$$

or

$$r = -\lambda \nabla_u D_O(x,u) \tag{5.13}$$

where r & $\nabla_u D_O(x,u)$ have dimensions $(M \times 1)$ and the Lagrange multiplier λ is a scalar

For output distance function $D_O(x,u) \leq \alpha$ and following Jacobsen (1972), the Lagrange function becomes:

$$\begin{aligned} ru + \lambda(D_O(x,u) - \alpha) &= ru + \alpha\,\lambda\{D_O(x, {u}/{\alpha}) - 1\} \\ &= \alpha\,\{r({u}/{\alpha}) + \lambda\{D_O(x, {u}/{\alpha}) - 1\}\} \\ &= \alpha\,\{rv + \lambda\{D_O(x,v) - 1\}\} \\ &= \alpha\,\Lambda \end{aligned} \tag{5.14}$$

Differentiating both sides with respect to α

$$-\lambda = \Lambda \tag{5.15}$$

This shows that at the optimum, the revenue function equals the negative of the Lagrange multiplier, or $-\lambda = R(x,r)$

If we substitute $-\lambda = R(x,r)$ into the 1st order condition above, we get:

$$r = R(x,r) \cdot \nabla_u D_O(x,u) \tag{5.16}$$

To establish the relationship between the distance function gradient vector & shadow prices, use is made of the 2nd part of the duality theorem as follows:

$$D_O(x,u) = r^*(x,u)u$$

where $r^*(x,u)$ is the revenue-maximising output price vector

Applying the 2nd part of the duality theorem to the last equation gives:

$$\nabla_u D_O(x,u) = r^*(x,u)$$

Then

$$r = R(x,r) \cdot \nabla_u D_O(x,u) = R(x,r)\, r^*(x,u) \qquad (5.17)$$

Making the assumption that the observed price of the m^{th} output, r_m^o, equals its absolute shadow price r_m, then maximum revenue, R, becomes

$$R = {r_m^o}\Big/{r_m^*(x,u)}$$

Then undesirable output prices $r_{m'}$ (for all $m' \neq m$) are given by

$$r_{m'} = r_m^o \cdot \frac{\partial D_o(x,u)/\partial u_{m'}}{\partial D_o(x,u)/\partial u_m} \qquad (5.18)$$

for all $m' \neq m$, where r_m^o is the observed price of the m^{th} output that equals its absolute shadow price r_m.

With the output distance function solved, the first-order conditions thereof can be substituted for calculating shadow prices. **The shadow prices derived reflect the trade-off between desirable and undesirable outputs at the actual mix of outputs**. This mix does not have to represent that maximum allowed for under environmental protection regulation.

It is clear that the above methodology can be adopted to analyse the economic impacts associated with wastewater reclamation, reuse and recycling in principle, provided data and information is available on the relative utility values of different system components. The methodology can also be used in the context of comparative analysis of different wastewater management system options within the centralised-decentralised continuum and extended to the comparative analysis of appropriate technology option choices. **As the latter application of the methodology has not been implemented before, a methodology was developed for this in the research and hypothetically tested in Case Study 2 (Chapter 7).** The next section discusses such possible applications in more detail.

5.11 WASTEWATER TREATMENT AND POLLUTING INDUSTRY PRODUCTION FUNCTION ANALOGY

To employ the concept of production function valuing as it is used in the industrial sector for pollution control and wastewater treatment situations, analogies are drawn between the desirable and undesirable outputs in the two respective situations or ”production processes”. In the case of wastewater treatment plants, influent wastewaters are treated to appropriate levels to produce suitable quality effluent (a product) with value in reuse, recycle or reclamation.

First, the treated effluent is considered analogous to a desirable production output of an industry. The second aspect relates to undesirable outputs. In the case of industries the undesirable outputs are non-useful products and/or emissions to the environment which potentially cause environmental damage and if internalised can be valued. In the case of wastewater treatment facilities (plants) the sole objective is to remove pollutants present and produce an effluent of suitable quality for reuse, recycling or reclamation (final discharge). In the case of wastewater treatment facilities the undesirable output would be the contaminants removed for ensuring effluent quality. The analogy could be extended even further to include also a desirable output that can be of particular interest in a given situation such as the use for irrigation. In such instances the nutrient content would be seen as a beneficial replacement for artificial fertilisers. The undesirable outputs would be the remaining substances that could have a negative effect on irrigated crops (for example metals, other toxic substances, etc.).

It should be noted that each particular situation is unique and requires a careful application of the analogy principle so as to ensure adequate problem formulation.

With the appropriate application of the analogy principle a relevant problem formulation can be obtained for a thorough economic analysis of different wastewater management system scenarios.

The approaches for both wastewater treatment level and wastewater management system level analyses for the same sewage catchment area are illustrated in Figure 5.9.

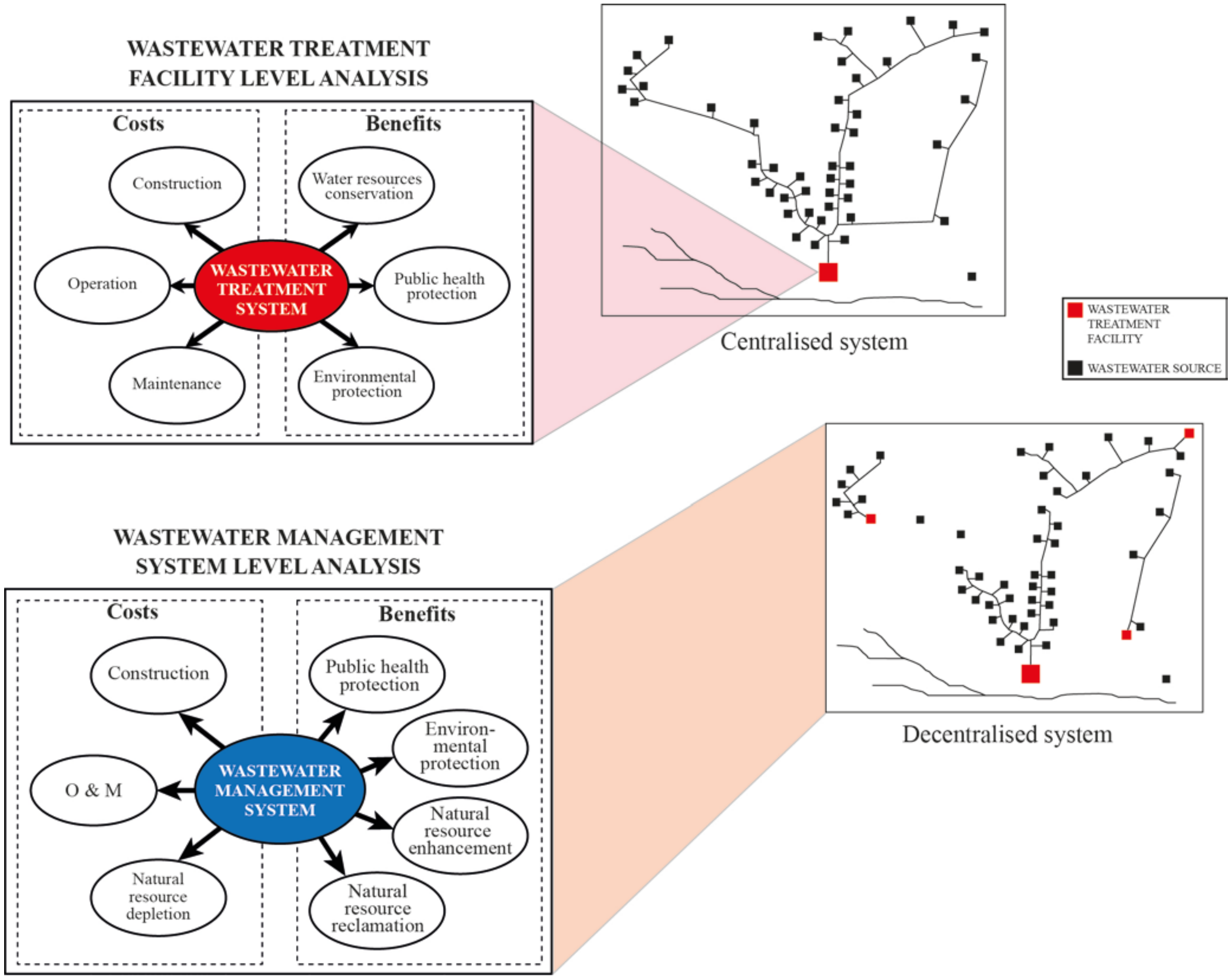


Figure 5.9 Illustration of wastewater treatment and wastewater management system level analysis

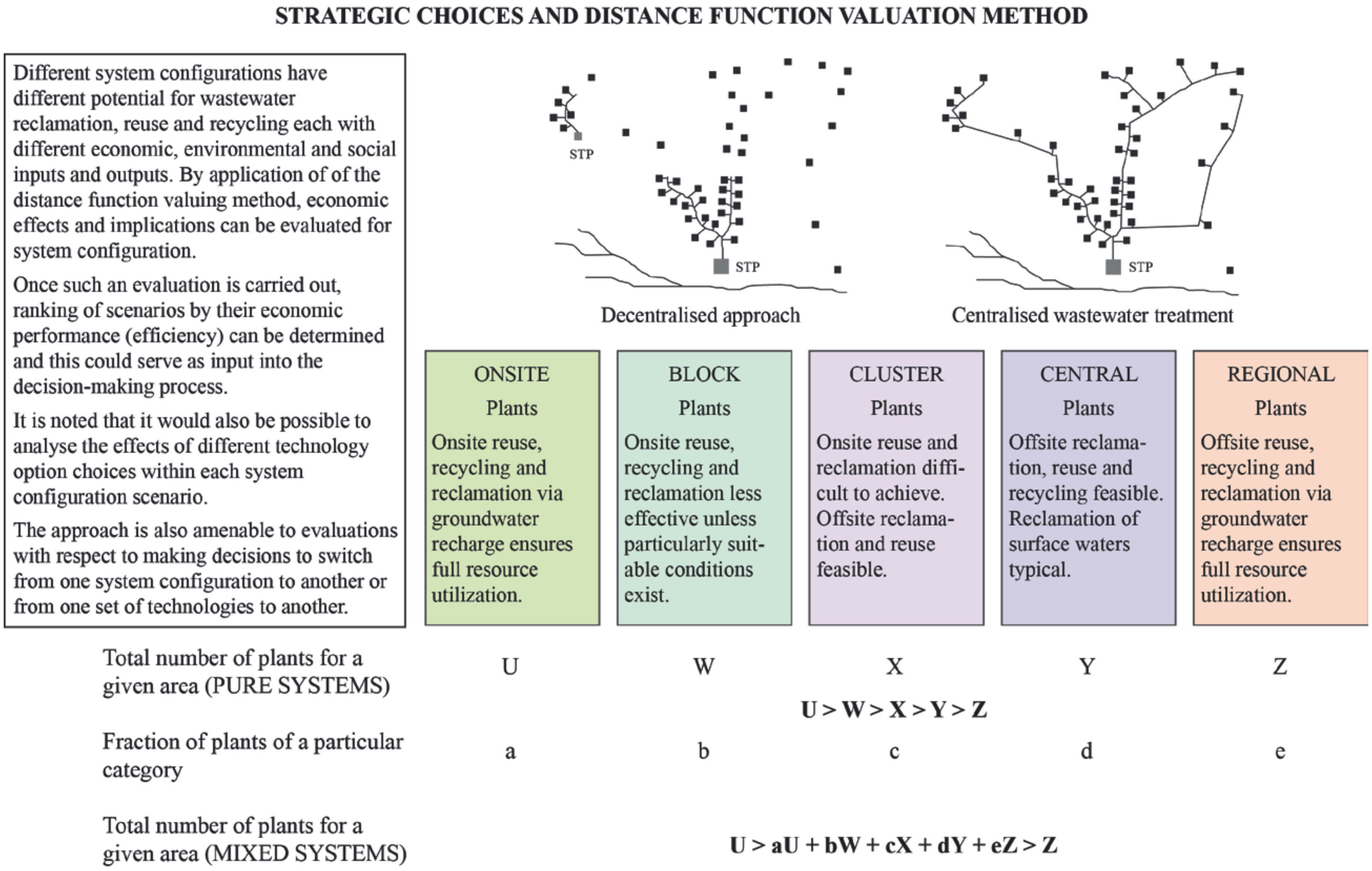
5.12 APPLICATION OF DISTANCE FUNCTION VALUING IN SYSTEM LEVEL PLANNING DECISION MAKING

As Hernandez and Sala (2009) have shown, the distance function valuing method can be used for the analysis of a large number of wastewater treatment facilities. By analogy, provided the necessary data is available, the distance function valuing can obviously be used for the analysis of a fully decentralised wastewater treatment system with each household operating their own “wastewater treatment facility”. The result of such an analysis can be used for comparison purposes of wastewater management of the same area, but using a single centralised wastewater treatment plant as a replacement for all the individual decentralised system plants (Figure 5.9).

By extension, if the above is possible, so would be the comparative analysis of any set of scenarios for the wastewater management system composition scale range (onsite, block and cluster, central and regional plants). The scenario analysis can then be used to evaluate the net economic effects of utilising different system configurations and technology options (Figure 5.10).

Theoretically one could also begin to ask questions regarding the economic effects of choices between reclamation, reuse and recycle or a combination thereof and analyse the economic performance differences between surface and ground water reclamation strategies.

With increased level of decentralised wastewater management onsite based resource recovery becomes more favourable and feasible, while at high centralised management scenarios offsite resource recovery through surface water reclamation are typical. For the latter groundwater recharge could potentially ensure optimal resource utilisation.



STRATEGIC CHOICES AND DISTANCE FUNCTION VALUATION METHOD

Different system configurations have different potential for wastewater reclamation, reuse and recycling each with different economic, environmental and social inputs and outputs. By application of of the distance function valuing method, economic effects and implications can be evaluated for system configuration.

Once such an evaluation is carried out, ranking of scenarios by their economic performance (efficiency) can be determined and this could serve as input into the decision-making process.

It is noted that it would also be possible to analyse the effects of different technology option choices within each system configuration scenario.

The approach is also amenable to evaluations with respect to making decisions to switch from one system configuration to another or from one set of technologies to another.

	ONSITE Plants	BLOCK Plants	CLUSTER Plants	CENTRAL Plants	REGIONAL Plants
	Onsite reuse, recycling and reclamation via groundwater recharge ensures full resource utilization.	Onsite reuse, recycling and reclamation less effective unless particularly suitable conditions exist.	Onsite reuse and reclamation difficult to achieve. Offsite reclamation and reuse feasible.	Offsite reclamation, reuse and recycling feasible. Reclamation of surface waters typical.	Offsite reuse, recycling and reclamation via groundwater recharge ensures full resource utilization.
Total number of plants for a given area (PURE SYSTEMS)	U	W	X	Y	Z
Fraction of plants of a particular category	a	b	c	d	e

$$\mathbf{U > W > X > Y > Z}$$

Total number of plants for a given area (MIXED SYSTEMS)

$$\mathbf{U > aU + bW + cX + dY + eZ > Z}$$

Figure 5.10 Strategic choices and distance function method application in wastewater management continuum

5.13 SYSTEM SCALE RANGE AND STRATEGIC CHOICES WITHIN THE CENTRALISED-DECENTRALISED WASTEWATER MANAGEMENT CONTINUUM

As illustrated in Figure 5.10 the centralised-decentralised wastewater management continuum include the full spectrum of system levels identified in the literature, starting from the most decentralised (individual onsite sanitation) to the extreme being offsite centralised management at regional level.

Onsite systems consist of either dry or waterborne sanitation technologies where effluent disposal occurs at the location where wastewater is generated, while with multiple plot (lesser decentralised) block or cluster levels link-up drainage conveys wastewater to dedicated block or cluster treatment facilities. Onsite systems allow reclamation at the point of wastewater generation via groundwater recharge ensuring efficient resource utilisation. However, in the instance of block/cluster systems with waste conveyed away from the point of generation, onsite reclamation and reuse are difficult to achieve and the offsite option is more feasible. For centralised and regional systems offsite reuse, recycle and reclamation are feasible. In addition with regional systems reclamation via groundwater recharge provide maximum resource utilisation possibility.

In addition to the pure system levels (block, cluster, centralised or regional), mixed system configurations consisting of various combinations of these system levels are also possible. Due to varied nature of wastewater catchment area characteristics such as size, shape, topography, geology and geotechnical issues, available water supply levels, spatial development land use issues and demographics, the set of feasible system level configuration options and optimal solution would be case specific.

5.14 SEWERED WASTEWATER MANAGEMENT SYSTEMS

The conveyance component for waterborne offsite systems forms an integral part of such wastewater management systems. It follows therefore that for feasibility assessment both treatment facility and conveyance system components have to be considered in the overall feasibility analysis.

Furthermore, from a reuse perspective the treated water distribution network to supply end-users is a crucial additional component that needs consideration apart from the sewered systems. The extent of the treated water distribution system would depend on user demand/s and location in relation to treated effluent source/s.

Case Study 2 (Chapter 7) focuses on sewered wastewater management systems feasibility analysis. Although the impact of effluent reuse is considered at treatment and system levels, effluent reuse distribution network analysis does not form part of the study.

5.14.1 Treatment plants

According to Chen and Beck (1997), a challenge faced in reuse planning analysis is to find suitable treatment trains from a large number of technically feasible combinations of unit processes. To find suitable treatment trains from candidate unit process combinations (candidate treatment trains), criteria has to be specified for their evaluation.

The choice and arrangement of unit processes, their operations and their design to form treatment trains (or their synthesis), allows for system design objectives to be met.

Different techniques to synthesis wastewater treatment trains have been incorporated into decision support systems (DSS) for optimal technologies selection for reuse. These include both quantitative and qualitative assessments of technical, economic and environmental factors of each unit treatment processes. Among DSS's available are:

1) Water and Wastewater Treatment Technologies Appropriate for Reuse (WAWTTAR); 2) Model for Optimum Selection of Technologies for Wastewater Treatment and Reuse (MOSTWATAR) developed by Dinesh and Dandy (2003); 3) Water Treatment for Reuse with Network Distribution (WTRNet) developed by Joksimovic (2006) as part of the AQUAREC project, and; 3) Waste Water Reuse Planning Model (WaswarPlamo) developed by Adewumi (2010).

Various reuse applications require different water qualities which can be achieved by using specific levels of treatment. To limit the numerous number of treatment trains possible due to a variety of unit process technologies available the following set of logical limitations are suggested by AQUAREC (2006):

- Primary treatment level
    - Not all primary processes need be evaluated further as many processes can lead to comparable process results;
    - Solubilisation processes of constituents have to be followed by biological secondary processes;
    - Advanced particle removal only gives limited advantages in the secondary step.
    - A combination of primary processes can realise total removal of particles.

- Secondary treatment level
    - Dissolved organic constituents (soluble COD) are handled effectively by biological processes;
    - Many biological processes lead to comparable results;
    - Nitrification/denitrification can almost completely remove nitrogen;
    - Removal of BOD, COD, N and P (if necessary) should be preferably done in the secondary treatment step.
    - Membrane bioreactors include some of the tertiary or advanced processes.

- Advanced treatment level
    - Porous media filtration is a common pre-treatment step for other tertiary processes;
    - Advanced treatment processes are very specific for certain components.

- All processes
    - Primary and secondary process sludges require further extensive treatment.

According to AQUAREC (2006) the European Union (EU) directives discharge limits should be the starting point for further treatment of municipal wastewater for reuse as many countries will indeed strive to meet these standards in the near future. It follows that in the short term for EU countries wastewater treatment train effluent will be the main primary source for wastewater reclamation and reuse. Based on this approach AQUAREC developed a set of typical or standard schemes related to specific reuse applications that are represented by many successful examples in practice.

These standard schemes listed in Table 5.8, appear to be representative of the majority of the possibilities in a reuse treatment chain and do not exclude any other possible ones.

The mentioned approach would also be applicable to the South African situation where clear discharge limits for wastewater facilities exist for all catchments country wide. Alternatives to the traditional treatment chain for achieving discharge limits would however be a long term feasibility option both for EU countries and South Africa.

Table 5.8 Standard/typical schemes for reuse applications (after AQUAREC 2006)

Standard/typical schemes	Reuse application
1. Conventional wastewater treatment (including P- and N-removal) followed by:	
Chlorination	Restricted irrigation
Lagoons or pond systems (occasional chlorination)	Highly restricted irrigation
Soil aquifer treatment (SAT)	Unrestricted irrigation (Israel)
Wetlands (natural/constructed)	Nature conservation, agriculture
Dual media filtration and disinfection (UV or Cl)	Urban applications, green landscaping, industrial reuse
Double membrane filtration (MF/UF + RO) and disinfection (UV)	High quality applications: industrial, household
2. Local membrane bioreactors (MBR)	Small scale treatment with localised reuse

In Case Study 2 of this research (Chapter 7) treatment train options are limited to two of the standard schemes listed in Table 5.8 as follows:

- Centralised systems – conventional biological nutrient removal (BNR) with chlorination
- Decentralised systems – membrane bioreactors (MBR) with chlorination

MBR was opted for in the case of decentralised systems because of the following attractions: 1) high compactness of the process compared to conventional processes (footprint could be approximately 1/10th the size); 2) higher biomass (MLSS) concentrations being possible with reduced quantities of sludge and disposal needs; and 3) good quality effluent partially disinfected (Fane 1996).

5.14.2 Collection networks

Wastewater collection networks form an integral part of sewered wastewater management systems. Although the primary function of collector networks is to convey wastewater flow generated from developments to the treatment facility for treatment, a collection system is also prone to possible illicit flows entering such networks. These illicit flows consist of groundwater infiltration through defective conduit joints and connections as well as wet weather storm inflows due to deficient sewer system appurtenances and storm discharge into the system through illegal connections. Apart from allowance for such flows, systems are designed hydraulically with flow velocity restraints for diurnal flows to avoid solids deposition and conduit scouring.

5.14.3 Treatment effluent quality and reuse

In South Africa two basic guidelines apply to treat effluent disposal or reuse. The first guideline by the Department of National Health and Population Development (DNHPD) specifies the permissible utilisation and disposal of treated effluent (1978). The second is the water quality guidelines of the Department of Water Affairs and Forestry (1996) that recommend required quality parameters for various reuse applications (domestic, agricultural, irrigation, livestock watering, aquaculture and aquatic eco-systems) irrespective of the water source. Ilemobade *et al*. (2009) pointed out that a “no potential risk” approach with reuse promoted by the DNHPD guideline, without specifying corresponding maximum allowable pollutant concentrations, result in high technology level employment with corresponding high cost. A more cost effective and feasible approach would be one that is aligned to specific quality requirement for effluent reuse, such as that of the US EPA (2004), the WHO guidelines for safe use of wastewater, excreta and greywater (2006a, 2006b, 2006c, 2006d) and other international guides.

In this research reuse applications recommended for use by employment of the standard AQUAREC (2006) schemes were considered (Case Study 2- Chapter 7).

5.14.4 Idle and overbuilt treatment capacity and costs

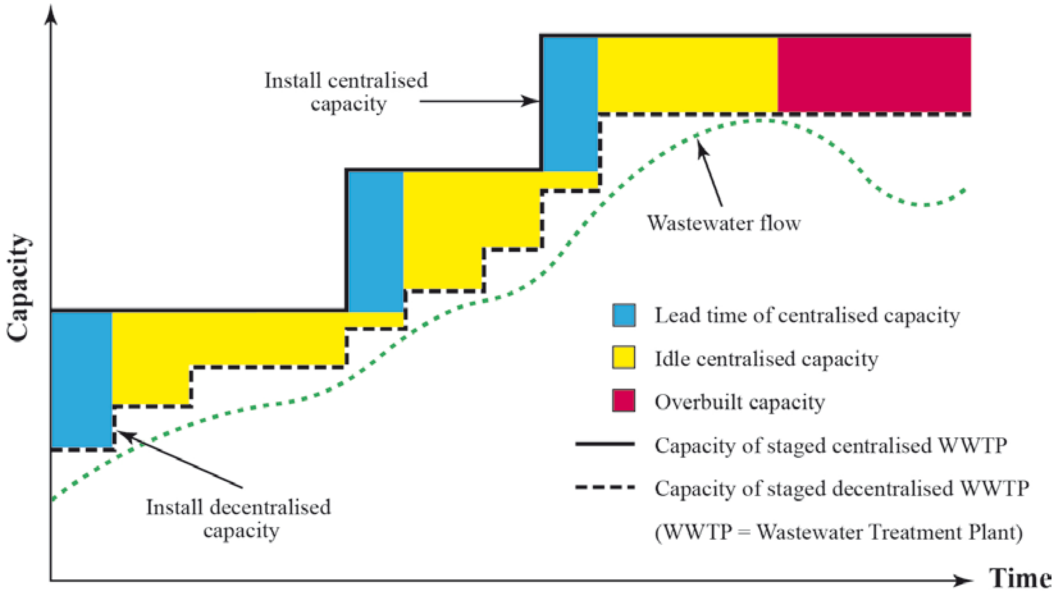


Figure 5.11 Treatment capacity vs. flow balance comparison for centralised-decentralised system level scale (after RMI 2004)

Figure 5.11 shows a relationship of changing wastewater growth compared to meeting demand with treatment capacity. Furthermore, it allows distinction of three different kinds of costs: 1) the costs of lead time to build capacity; 2) cost of idle capacity that exceeds current needs for sometimes significant periods of time; and 3) costs of overbuilt capacity that remains idle.

With the general trend of a diagonal growth path does not allow exact matching with large capacity increments. Differences in capacity vs. flow balances could be considered in opportunity cost terms as financial value foregone due to being tied up in overbuilt unnecessary capacity and that could have been alternatively used.

It is evident from Figure 5.11 that smaller modular capacity provision allows closer matching of flow both in time and quantity compared to large steps with the advantage of far lower cost and savings in the three kind of related cost mentioned. In situations when future demand fails to meet expectations, additional scheduled increments of smaller decentralised capacity can more readily than the case of large stepped increments be rescheduled or even abandoned avoiding the cost of overbuilt centralised capacity.

Centralised capacity additions inherently overshoot flow (gross under-forecasting of flow or step-function capacity increments) leaving substantial increments of capacity idle until flow materialise through growth. Smaller units in contrast can align better to gradual changes in flow meeting demand timeously and virtually when needed.

5.14.5 Existing infrastructure service life extension

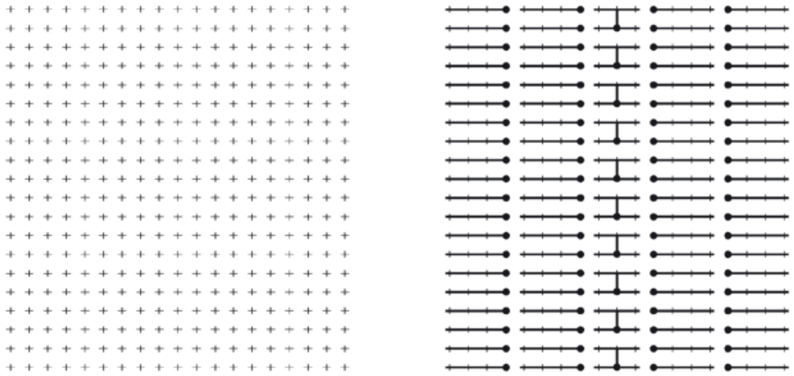
Smaller decentralised systems can help extend the useful service life of existing conventional infrastructure by reducing loads thereon. For example where systems are overloaded both in conveyance and treatment capacity, partial decentralisation could avoid high cost conveyance and centralised treatment upgrades by deviating flow to a separate localised plant where possible. The avoided high cost of major collector sewer upgrade and shorter lag-time of smaller modular capacity required might provide a more feasible solution economically.

This also pushes replacement project costs of conventional centralised systems into the future with reduced net present value of such management system options.

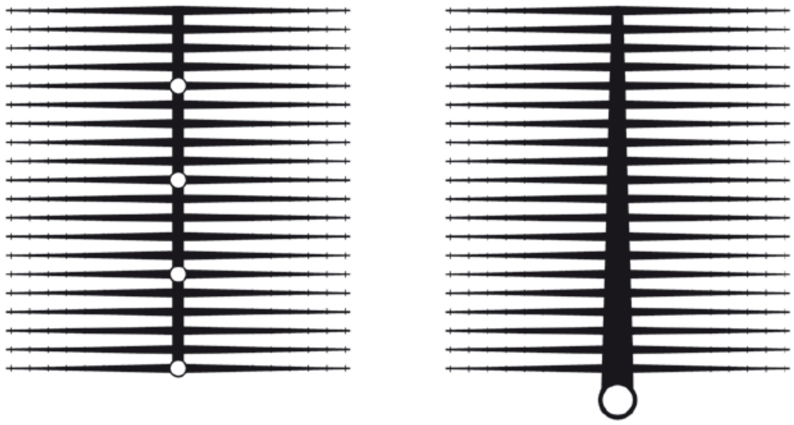
5.14.6 Returns to scale in sewered wastewater management

The planning focus of wastewater management systems to obtain economies of scale in treatment capital outlay and operations need careful consideration. Treatment plant capital costs typically reveal increasing returns to scale or **economies of scale**, i.e. costs per unit throughput decrease as size increases. However, decreasing returns to scale or ***diseconomies* of scale** (costs per unit increase as sewered system size increases) often occur in associated collection systems (Rocky Mountain Institute 2004).

Collection systems diseconomies of scale is conceptually illustrated in Figure 5.12, showing how increased centralisation (for a given population density) affects sewered system pipe lengths and sizes. It is evident from the illustration that as the system scale increases from individual on-site servicing to a larger common centralised system, both the total length and the maximum size of pipes required progressively increases. Since the number of service connections remains constant, it follows that the cost per service connection service must also increase with increased system scale.



(a) Onsite (b) Block



(c) Cluster/neighbourhood (d) Centralised

Figure 5.12 Conceptual illustration of collector network diseconomy of scale with increasing level of centralisation (pipe lengths and size) (after RMI 2004)

As collections systems often account for up to 70-90 percent of total sewered wastewater system capital costs, collection diseconomies of scale can easily offset the economies of scale of treatment capital and O&M costs. Analysing tradeoffs between treatment capital and O&M economies of scale and collection diseconomies is key in wastewater facility planning and system level evaluation of different wastewater system scale scenario's (ReVelle and McGarity, 1997). Total costs at wastewater management system level for all system components (treatment and collection) to allow account being taken of the returns to scale aspects mentioned.

According to RMI (2004) one of the few rigorous examinations of returns to scale in sewered systems is a study conducted for the Adelaide region in Australia by Clark in 1997. Although this study is based on particular regional characteristics of the location researched, further description is considered warranted due to general principles of returns to scale in wastewater management systems being illustrated.

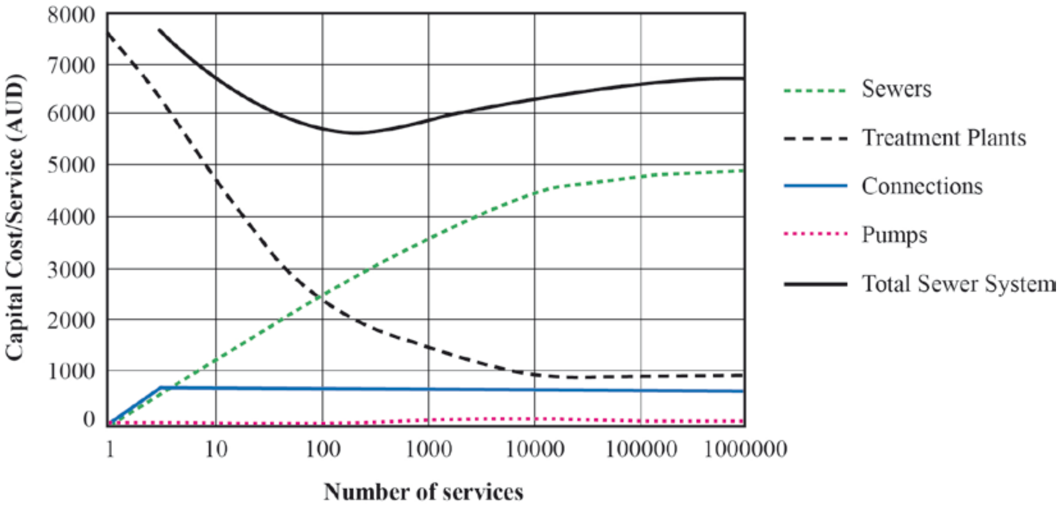


Figure 5.13a Wastewater systems capital unit cost vs. service scale in Adelaide Australia at 1997 year costs (Adapted from RMI 2004)

The Australian study considered typical services density ranges of 750, 1 250 and 1 855m^2 at typical urban house, residential subdivision and metropolitan levels respectively. Figure 5.13a shows the clear positive returns to scale (economies of scale) in treatment plant and negative returns to scale (diseconomies of scale) for collection network capital costs for that study. Furthermore, it also shows that capital costs of pumps and connections per unit are largely insensitive to system scale substantial economies of scale for treatment occur at higher service connection levels. For the particular study the lowest total system capital cost is approximately at approximately 200 to 300 service connections. Considering the treatment plant capital cost per connection curve, over 90 per cent of the potential saving compared to a larger 1 million services connection plant, is achieved at the 1 000 service level. This implies that good treatment economies of scale are possible at centralised levels of this nature and that further benefit of larger regional scale treatment is not necessarily justified economically, especially if the diseconomy of scale collection is considered.

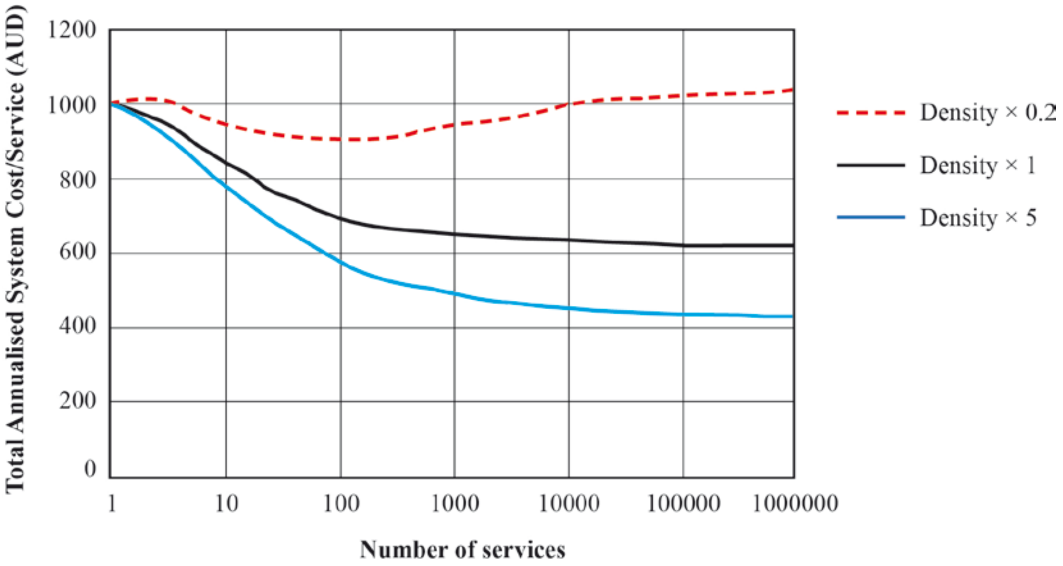


Figure 5.13b Total annualised system unit cost vs. population density in Adelaide Australia at 1997 year costs (after RMI 2004)

Figure 5.13b shows that economy of scale also occurs when total annualised system costs per service are considered. Much of the potential savings are again obtained within the 100 to 1000 number of services range. The impact of changed population densities on total annual system unit costs is also shown, which typically illustrate decreased unit costs associated with increased density and vice versa.

With the original data indexed as 1, an increased and decreased density by a factor 5 is also illustrated in Figure 5.13b. As higher population density results in shorter pipe lengths per service, the reduced diseconomy of scale in collection network translate into a net increased return to scale for total annualised cost per service. In the case of the lower population density the increased pipe and length per service connection result in increased diseconomy of scale for the collection network. With lower density here the minimum total annualised cost per service occurs at about 100 services and then start increasing for larger number of services.

This tendency of flattening of the cost curve for low population density should be considered with wastewater system planning in low-density rural and suburban areas.

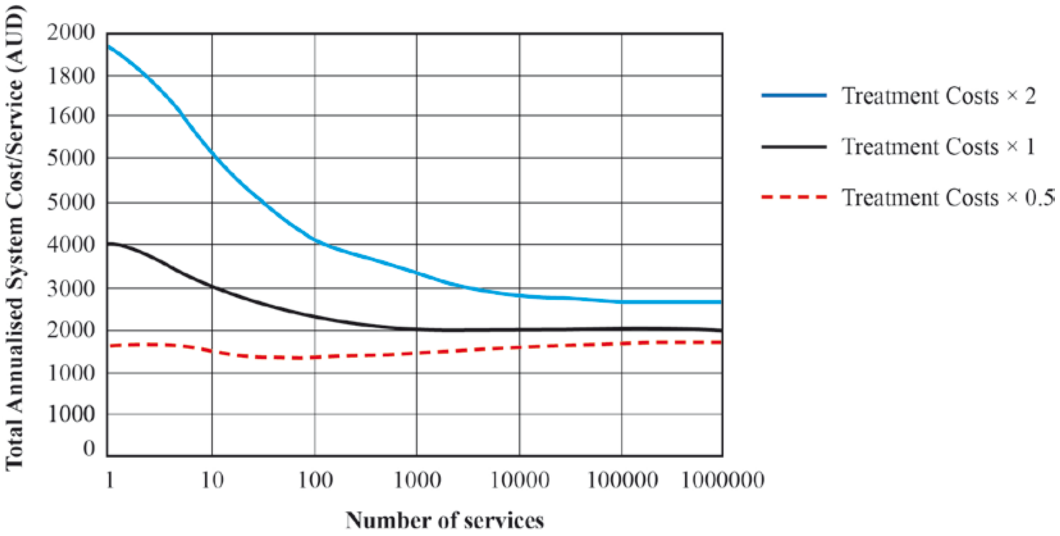


Figure 5.13c Total annualised system unit cost vs. treatment plant capital cost for Adelaide Australia at 1997 year costs (after RMI 2004)

The result of a sensitivity analysis done of the impact of increased capital treatment cost on total system annualised cost per service is shown in Figure 5.13c. Increasing treatment plant capital costs (by factor 2) shifts the entire cost curve upward resulting in a net increased return to scale effect due to the total savings across the scale range becoming greater. Initial portions of the total cost curve are quite steep, and most of the total possible savings are again captured at lower levels of 100 to 1 000 services. Should treatment plant capital costs be halved, the cost curve becomes quite flat across most of the scale range, which indicate total annualised cost per service being tending to be insensitive to scale. Again it need to be emphasised that where costs are insensitive to scale other non-monetary factors may and probably should predominate in decision making.

5.15 METHODOLOGY FOR WASTEWATER SYSTEM LEVEL DECISION MAKING

A structured systematic decision procedure is of key importance in catering for the multi-facetted nature in wastewater systems planning. For decision making for sewered systems both treatment/disposal and collection components must form part of such an evaluation.

The methodology developed for wastewater system level decision making is shown in Figure 5.14. The treatment level methodology by Marjanovic *et al.*(2009), modified by Musiyarira *et al*. (2011), was extended in this research further to achieve an overall wastewater management system level methodology.

The system level decision making methodology steps are described briefly as follows:

Step 1– Formulation of goal and scope of the decision support required

Within a wastewater management context, the broad scope of the related issues of point of generation, collection, conveyance, treatment, reuse and/or disposal has to be covered.

Step 2 – Define system boundaries

For the particular region under consideration catchment system boundaries as well as criteria for sustainability issues need to be defined. In this research the context is sewered wastewater management and considers wastewater from a point of generation, collection, separation, conveyance, storage, treatment, reuse and disposal. All these processes are critical for overall wastewater management. To ensure that all relevant issues are covered a checklist approach is essential to avoid some key aspects being ignored from the set of sustainability aspects and solutions sought.

Step 3 – Define system scale and technology alternatives

The issue of alternatives at both system scale and technology within a centralised-decentralised wastewater continuum needs to be identified for a specified wastewater service area. Alternatives must be selected on basis of the available knowledge, sound engineering judgement, and practical experience within the South African or particular local environment. Formulation of the problem oppose to emphasising on solutions results in better understanding of the nature of the problem and the better insight gained could result in a more holistic understanding of the challenge at hand and deriving more sustainable solutions more likely.

The screening of alternatives must be based on: 1) currently employed proven efficient systems and technologies, 2) new technologies with potential application in the South African context; and 3) available system configurations/technologies with potential for implementation although not fully implemented in South Africa yet.

As indicated before in Figure 5.10, the different system scale ranges (pure systems) and various combinations thereof (mixed systems) can form part of possible alternatives to be considered for a given catchment area. To assist with their identification the scope of alternative system scale scenarios and various technology combinations for a given catchment area are illustrated in Figure 5.15.

5.16 TECHNICAL AND DEMOGRAPHIC CONSTRAINTS IN SYSTEM LEVEL PLANNING

Various wastewater management system level constraints were identified during research done for the Gauteng Province by Marjanovic *et al.* (2009). The constraints relate system level range to level of water supply, population size and relative density aspects. An algorithm was developed to assist with selection of feasible system level alternatives based on available water supply level as shown in Figure 5.16. In addition the algorithm is supplemented to incorporate consideration of technology options associated with specific system scale ranges which are shown in Tables 5.9 and 5.10.

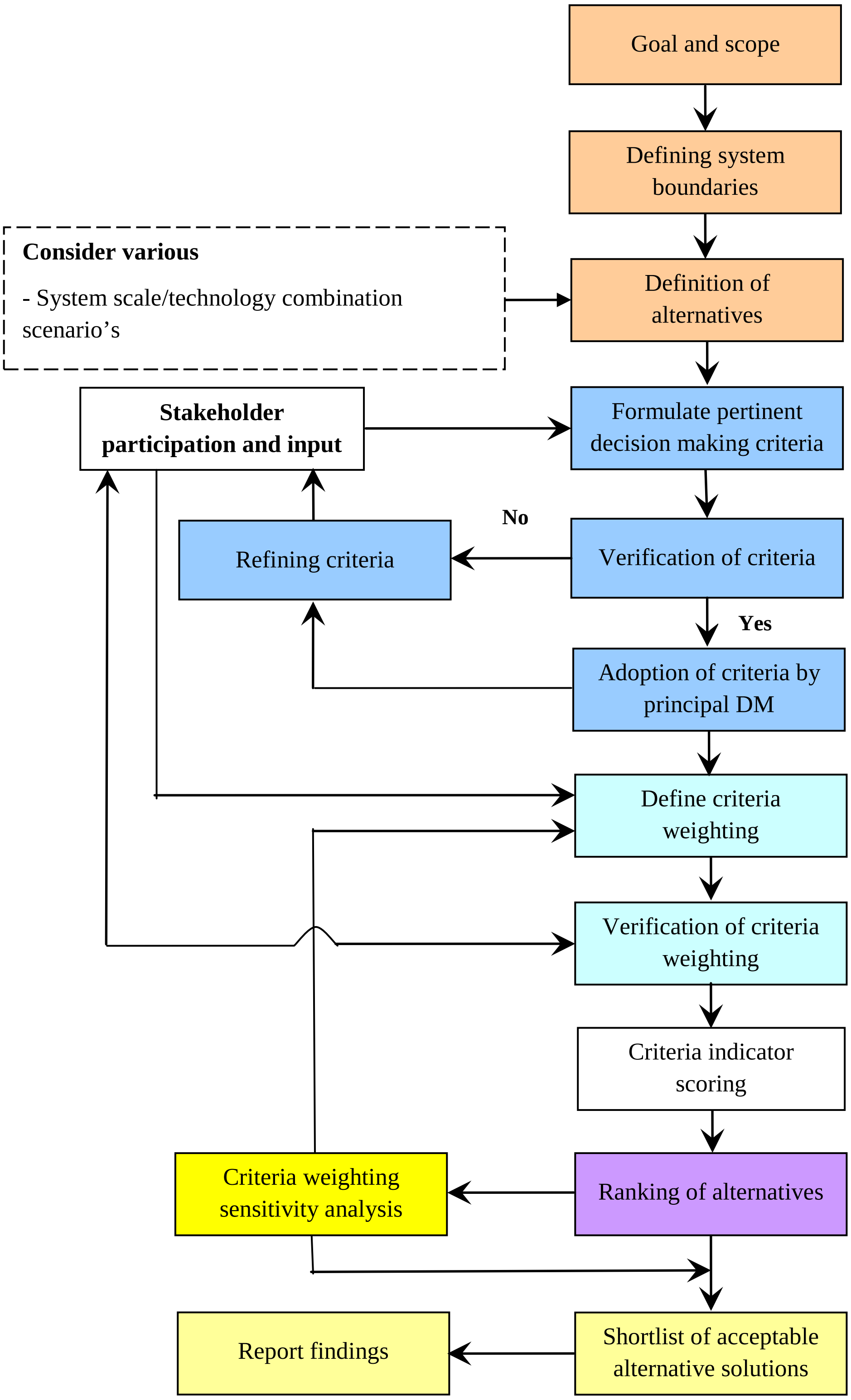


Figure 5.14 Wastewater system level decision methodology

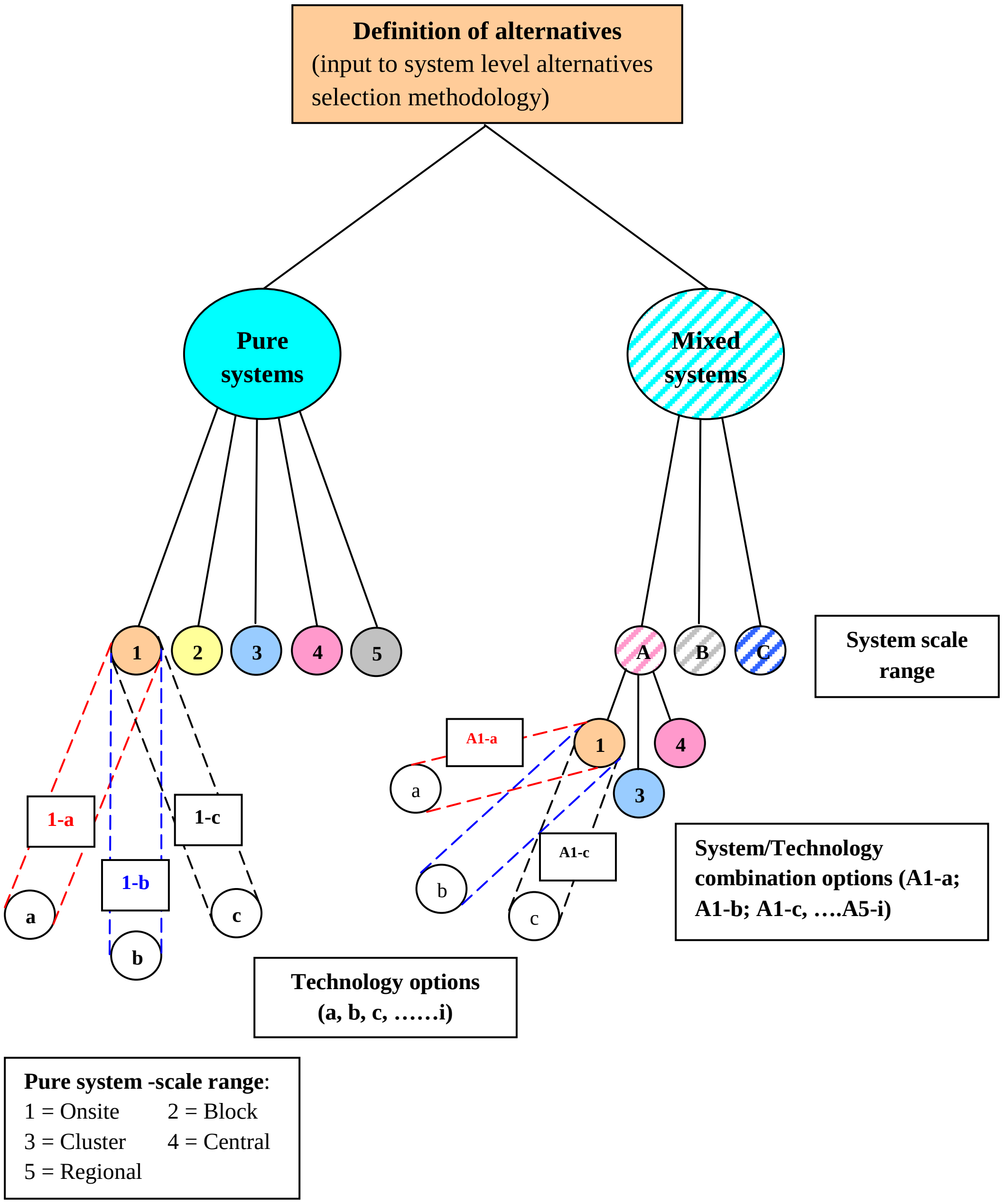


Figure 5.15 System level scenario's (system scale range/technology combinations)

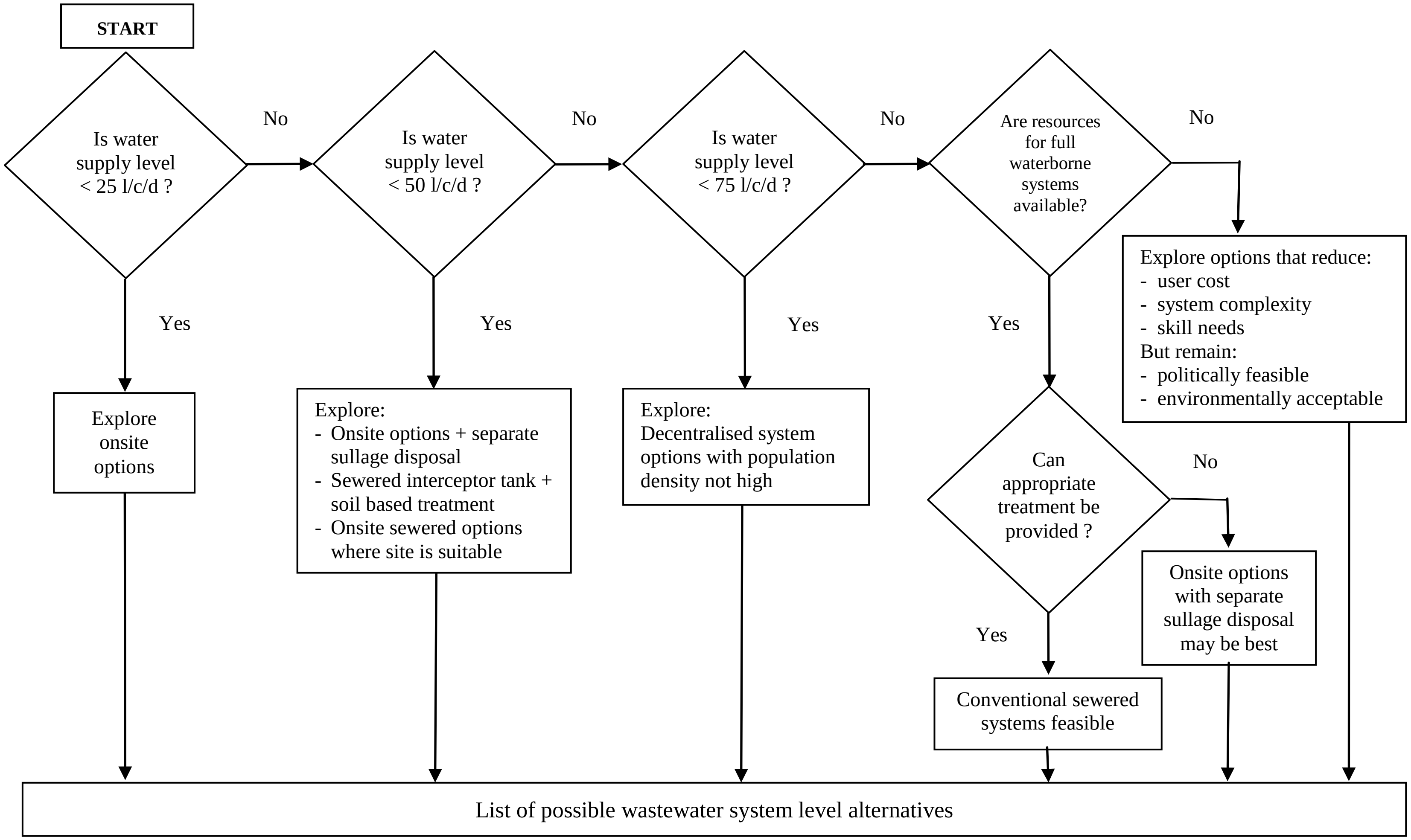
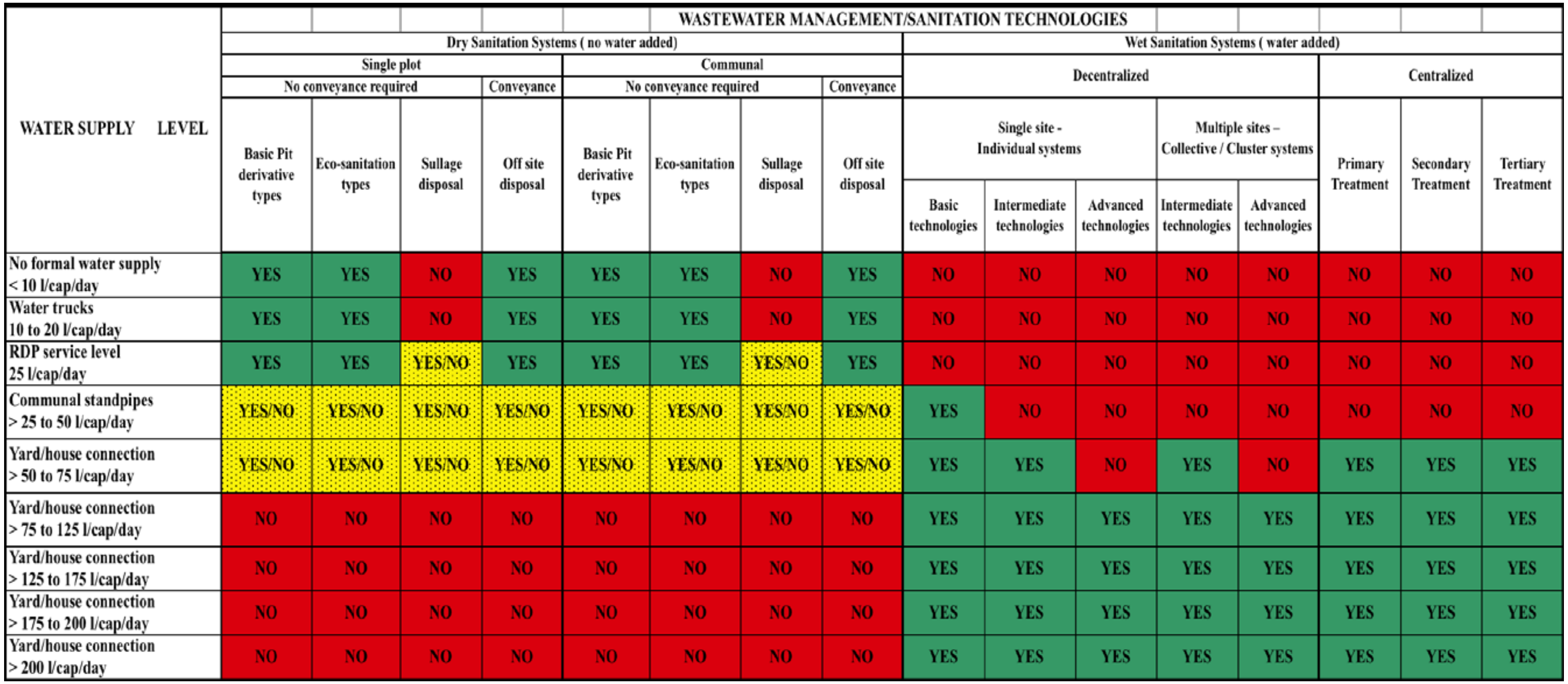


Figure 5.16 Algorithm for selection of feasible system level alternatives based on available water supply level (after Marjanovic *et al.* 2009)

Table 5.9 Appropriate water supply levels in the decentralised – centralised wastewater system continuum (after Marjanovic et al. 2009)



WATER SUPPLY LEVEL	WASTEWATER MANAGEMENT/SANITATION TECHNOLOGIES															
	Dry Sanitation Systems (no water added)								Wet Sanitation Systems (water added)							
	Single plot				Communal				Decentralized					Centralized		
	No conveyance required			Conveyance	No conveyance required			Conveyance								
	Basic Pit derivative types	Eco-sanitation types	Sullage disposal	Off site disposal	Basic Pit derivative types	Eco-sanitation types	Sullage disposal	Off site disposal	Single site - Individual systems			Multiple sites – Collective / Cluster systems		Primary Treatment	Secondary Treatment	Tertiary Treatment
									Basic technologies	Intermediate technologies	Advanced technologies	Intermediate technologies	Advanced technologies			
No formal water supply < 10 l/cap/day	YES	YES	NO	YES	YES	YES	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO
Water trucks 10 to 20 l/cap/day	YES	YES	NO	YES	YES	YES	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO
RDP service level 25 l/cap/day	YES	YES	YES/NO	YES	YES	YES	YES/NO	YES	NO	NO	NO	NO	NO	NO	NO	NO
Communal standpipes > 25 to 50 l/cap/day	YES/NO	YES/NO	YES/NO	YES/NO	YES/NO	YES/NO	YES/NO	YES/NO	YES	NO	NO	NO	NO	NO	NO	NO
Yard/house connection > 50 to 75 l/cap/day	YES/NO	YES/NO	YES/NO	YES/NO	YES/NO	YES/NO	YES/NO	YES/NO	YES	YES	NO	YES	NO	YES	YES	YES
Yard/house connection > 75 to 125 l/cap/day	NO	NO	NO	NO	NO	NO	NO	NO	YES	YES	YES	YES	YES	YES	YES	YES
Yard/house connection > 125 to 175 l/cap/day	NO	NO	NO	NO	NO	NO	NO	NO	YES	YES	YES	YES	YES	YES	YES	YES
Yard/house connection > 175 to 200 l/cap/day	NO	NO	NO	NO	NO	NO	NO	NO	YES	YES	YES	YES	YES	YES	YES	YES
Yard/house connection > 200 l/cap/day	NO	NO	NO	NO	NO	NO	NO	NO	YES	YES	YES	YES	YES	YES	YES	YES

Dry sanitation (no water added)		**Wet sanitation (water added)**	
Basic pit options	VIP's, VIDP's, ROEC's, VVT's , NOVAC and AMALOOLOO	**Decentralised technology**: Basic	Aqua privy, pour- and low flush, full flush – septic and conservancy tanks, effluent ground disposal
Eco-sanitation	UD's, continiuos composting toilets	Intermediate	Wetlands, lagoons, aquaculture, small bore sewers, etc.
Offsite disposal	Chemical and bucket toilets	Advanced	Shallow sewerage, package plants, proprietary technologies, mini or midi centralised technologies
Sullage disposal	Casual tipping, garden irrigation, percolation pits, infiltration ditches	**Centralised technology**	Conventional sewered collection networks with wastewater treatment (primary; secondary and tertiary/advanced treatment)

Table 5.10 System level range related constraints (sewered systems) (after Marjanovic *et al.* 2009)

Constraint	**Wastewater management system scale range**		
	Fully decentralised	**Block/cluster**	**Fully centralised**
Water supply level (l/c/d)	> 50	50 - 75	> 75
Population size (no. persons)	< 50 000	> 2 000; < 10 000	> 5 000
Population density	Low	Low - intermediate	High

5.17 MULTI-CRITERIA ANALYSIS (MCA) WITHIN SYSTEM LEVEL DECISION MAKING

Wastewater management has been considered historically mainly as an economic and a technical issue while other aspects of sustainable development have been neglected. In some cases of analysis the only criteria used for evaluation of candidate treatment trains are cost and treatment performance (Joksimovic, 2006).

Economic and technical criteria are just part of an array of factors that contribute to wastewater system sustainability. According to Foxon *et al.* (2002) the inclusion of environmental, social-cultural and political aspects into sustainability assessment and the adoption of transparent stake-holder sensitive processes are of key importance. In this way, a more balanced view is created rather than one that relies purely on quantifiable factors alone (Ilemobade *et al.,* 2009).

5.17.1 Methodology

The conventional most common multi-criteria evaluation methods simultaneously consider all alternatives against all the adopted criteria for determining a sustainability measure or index. In this research of sewered wastewater management systems the sub-system components (treatment and collection) are evaluated separately. This is necessary to allow different criteria impacts and intensity to be assessed in such a manner that allows comparison even at sub-system components levels.

For an overall aggregate system score individual component scores would in turn be aggregated by considering different proportionate contributions thereof deemed appropriate. With this research sewered sub-system component (treatment and collection) scores were aggregated based on their economic annualised cost ratio, while for sub-system aggregation the weighted averages with respect to the flow throughput of the sub-systems were employed. This exercise to achieve composite aggregate scores at sub-system and system levels is discussed in detail in Case Study 2 (Chapter 7.11.1).

5.17.2 Sustainability criteria classification

Sustainability is by definition a dynamic concept that with increased knowledge, changed ideas, situations and priorities, solutions currently identified as sustainable to be the case in the future. Any set of sustainability indicators defined should be seen as a first step and new indicators will be added and others, proven less effective will be removed. As 1st step in the above dynamic sustainability indicators for wastewater treatment system evaluation can be categorised into the following four main categories (van der Vleuten-Balkema 2003):

- Economic aspects (capital cost, O&M costs and replacement costs)
- Environmental aspects (emissions and use of resources, viz energy, land, nutrients and water)
- Socio-cultural aspects (acceptance, expertise, institutional, participation and sustainable behaviour)
- Functional or technical aspects (adaptability, maintenance, reliability, robustness)

Functional (technical), environmental and socio-cultural criteria are considered typically in a qualitative sense, while economic criteria are generally quantified whenever possible. The above mentioned four main criteria categories were used as framework for developing a wastewater management system level multi-criteria sustainability methodology in this research.

5.17.3 Criteria selection

According to Lennartsson *et al.* (2009) sustainability criteria has to be closely collaborated with stake holders and formulated within a local context of institutional matters, preferences among future users, and environmental and social conditions of the actual service area concerned. What may be judged as sustainable in one context might not be the same for another setting. Criteria choice that link to a local context is not only fundamental to the whole decision support methodology, but must account for the diverse community wastewater management needs.

When considering decision making in wastewater management the criteria to be used can be plentiful and diverse. In determining pertinent criteria for a specific situation or context is the challenge of finding a balance between an extensive number of criteria (allowing sufficient coverage of the problem) or a smaller set of criteria that does not cover the required areas of analysis fully but allow easier iterations. (Munda *et al*. 1994)**.** The disadvantage of the latter approach is that it could result in over simplification of the problem. In order for useful assessment the set of criteria need to be continuously revised due to socio-political dynamics of communities and criteria changes as knowledge advances takes place.

For the wastewater management system level focus of this research it was necessary to derive a sustainability criteria matrix that covers the overall spectrum of wastewater management as set out in Table 5.11. The approach taken to achieve this was as follows:

- Screening of the extensive quantitative and qualitative wastewater treatment related criteria from the literature (Joksimovic 2006, Adewumi 2010, Musiyarira *et al*. 2011) in terms of their applicability to collection networks
- Making allowance for the combined quantification, through use of the production function (distance function) approach employed in this research, of benefits related to both environmental protection, water resource conservation and public health protection
- Incorporating decentralised wastewater management system scale benefits and issues into the overall system level assessment. For this purpose a descriptive factsheet listing such possible benefits was compiled to assist with their consideration during analyses (Table 5.12)

The criteria matrix shows which of the criteria applies to treatment and collection.

This initial matrix serves as basis for screening and formulation through stakeholder participation and input as part of the system level decision making methodology (Figure 5.14). The stakeholder participation process allows for reduction, if necessary, of criteria to a manageable number after ranking and carrying out a sensitivity analysis test. Some criteria can then be eliminated and the remaining ones taken as appropriate for the particular context considered. As first iteration of the process a scale for acceptance or rejection of a criterion will be set in agreement with input from stakeholders. This process then leads to adoption of a defined core set of criteria to be taken up for evaluation within the decision making methodology.

In the absence of actual stakeholder survey and inputs to the MCA for Case Study 2 of the research, a hypothetical scoring and ranking analysis was done based on an assumed criteria weighting. Details of the assumptions made are given in Case Study 2 (Chapter 7.11).

The basic schedule of criteria for system level analyses as reflected in Table 5.11 are described next.

Table 5.11 Wastewater system level sustainability assessment criteria

Type of criteria	Sub-criteria	Wastewater system level components	
		Treatment	**Collection**
Technical			
Quantitative	Pollutant removal efficiency	Yes	**No**
	Sludge production	Yes	**No**
	Concentrates production	Yes	**No**
Qualitative	Reliability (adaptability to):		
	• upgrade	Yes	Yes
	• varied flow	Yes	**No**
	• water quality variation	Yes	**No**
	Ease of construction	Yes	Yes
	Ease of operation and maintenance	Yes	Yes
Economic			
Quantitative	Life cycle costs:		
	• Capital	Yes	Yes
	• O&M	Yes	Yes
	• System component replacement/retrofit	Yes	Yes
	Present Value (PV)	Yes	Yes
	Returns to scale	Yes	Yes
	Idle treatment capacity expense foregone	Yes	**No**
Qualitative	Affordability	Yes	Yes
	Risk of exposure	Yes	Yes
	Willingness to pay	Yes	Yes
Environmental			
Qualitative	Chemical requirement	Yes	**No**
	Energy requirement	Yes	Yes
	Land-use footprint	Yes	**No**
	Odour generation/control	Yes	**No**
	Impact on ground & surface water	Yes	Yes
	Water resource conservation	Yes	Yes
	Nutrient recovery (reuse and reclamation)	Yes	Yes
Environmental/ social Quantitative (distance function valuation)	Environmental protection Natural resource enhancement Natural resource reclamation Public health protection	Yes	Yes
Social			
Qualitative	Impact of system failure on health	Yes	Yes
	Public acceptability/aesthetics	Yes	Yes
	Awareness and participation	Yes	Yes
	Institutional requirements	Yes	Yes
	Job creation	Yes	Yes

Note: See detailed criteria descriptions **(15.7.4 – 15.7.7);** Yes/**No** = applicability to system components

Table 5.12 Factsheet - Decentralised scale beneficial aspects (derived from RMI 2004)

Category	Decentralised system benefits
Economic	1. Life cycle costs: • Postponement of capacity costs to the future result in reduced NPV costs • Deferring or downsizing replacement costs reduce NPV • Extend existing conventional infrastructure useful life. 2. Spreading cost opposed to upfront lessen user s financial burden and borrowing needs. 3. Allow upgrade focus on a small subset of overall capacity, saving substantial capital costs. 4. Returns of scale: • System scale impact (positive or negative): - Conventional collection networks - Positive in smaller system - Negative in larger system • Alternative treatment and conveyance options: - Maximum advantage smaller systems • Time buying of optimum technology by modular fashion deployment • Flexibility in: - Capacity versus actual demand balance - Reduced risk of financial expense when demand forecasts do not materialise - Less finance tied-up in overbuilt capacity - Less financial risk from variation and escalation in operating and energy costs - Ease of project reversal and downsize - Small systems less custom constructed components - Overall system cost susceptibility to inflation and cost escalation - Smaller systems with short-lead time technologies less exposed and also due to less excess capacity being carried • Financial borrowing needs: - Small systems by spreading costs likely to have borrowing needs to lesser extent 5. Reuse • Re-distribution systems: - Smaller systems avoid large expenses and allow cost-effective reuse at the site and neighbourhood scale • Reuse demand level: - Centralised potentially most cost-effective way to supply large users 7. Energy recovery Small systems lack necessary control and scale for cost-effective production and use of methane

Table 5.12 (continued)

Category	Decentralised system benefits
Environmental	1. Odour control: Typically less of a concern with smaller systems 2. Noise levels: Both centralised and decentralised systems can be noisy or quiet depending on the technology employed. 3. Consequences of system failure: Less for decentralised systems as small, widely distributed failures are limited while that of large, concentrated failures can be severe. 4. Hydrologic impacts: Small systems avoid the negative impacts that centralised collection systems can cause such as lowering water tables, drawdown of aquifers, riparian zone disturbance and stream base flow reduction.
Social	1. Local economy benefit: Small systems likely to support local income and job creation. 2. Expertise retention: Smaller systems have decreased expertise level and compensation and ability of retention advancing good will in small communities. 3. Local public empowerment: Smaller systems lend themselves to local decisions, enhancing public comprehension and legitimacy
Technical	1. System resilience Diversity of treatment units, ease of repair and other factors may make smaller systems more resilient depending on technology choices and local conditions.

5.17.4 Social criteria

Social aspects are the most difficult issues among the many criteria which may be used to assess the feasibility of wastewater systems. According to Panebianco and Pahl-Worst (2006) infrastructure can be viewed as the hardware and the social criteria the software. The ‘software’ of wastewater systems is often neglected which denies planners of a wealth of information about the sustainability of a system/ technology in a given setting as well as potential constraints to the implementation thereof.

System failure health impacts

Extensive system component failure (treatment process or collection network) is unlikely under general adequate preventative routine maintenance. However, risk of failure is always present. System overload could result in undesirable discharge of untreated/raw effluent to rivers and collector network malfunction could endanger public health due to possible exposure.

Public acceptability/aesthetics

Public acceptability may be influenced by people's opinions on matters of aesthetics, odour potential, familiarity, landscape, cultural identity, etc. According to Foxon *et al*. (2002) acceptability is influenced by public perceptions of the technology impacts on health and their environment. According to Ilemobade *et al*. (2009) people's repulsion sensitivity is likely to have an effect on decentralised wastewater systems acceptance levels.

Awareness and participation

As mentioned and laboured on before, community participation in the actual process of wastewater system selection and decision-making is of paramount importance to achieve sustainable systems. Marjanovic *et al.* (2009) emphasises that awareness is a major force to reckon with in the acceptability of a wastewater system since lack of awareness mainly leads to acceptance of non-sustainable solutions.

Institutional requirements

The main drivers for institutional changes are skill and regulatory requirements and managerial complexity. Since different wastewater treatments systems require different regulations and control mechanisms, the ideal would be if such requirements fit as much possible into the existing institutional infrastructure of the region under consideration.

Job creation potential

The number of jobs generated by the application of a proposed management system varies with technology type and automation level. Decentralised systems have the advantage of job creation at the local level and could generally be more labour intensive as well as less skilled compared to high technology centralised systems.

Higher skilled labour is required to operate and maintain advanced automated wastewater treatment facilities than the case of manually operated systems. Difficulties in estimating labour requirements for individual unit processes arises from the fact that the labour force is typically distributed to activities dealing with several processes along with some administration, which makes the development of expressions for individual unit processes more difficult.

5.17.5 Environmental criteria

Resource utilisation and environmental risk/impact criteria were distinguished as main criteria in this study.

- ***Resource utilisation***
  The resources under consideration in wastewater management are mainly chemicals, energy, water and land.

    - *Chemical requirements*
      The use of chemicals contributes to both the environmental risk and as well as the economic costs. Chemicals increase the environmental footprint of the technologies while at the same time they play a role in lowering pollutants to the environment. However, the disposal of sludges could be limited due to possible by-products present formed by chemical dosing.

    - *Energy*
      Energy requirements are usually a key aspect since energy costs have spiralled across the years. All the mechanical wastewater treatment technologies and pumps in collector networks need electrical energy for their operation. The energy consumption is a function of the type of equipment used. Some countries have reasonable rates for their energy

costs depending on whether they generate their own or import. Hence the energy requirement is a greater factor in technology selection. The energy balance for a particular technology will indicate how much energy is used, produced (for instance biogas), and lost. The question of energy production in the treatment process is not taken into account in this study.

  - *Land-use footprint*
    Different unit processes employ different mechanisms for pollutant removal and at the same time have different land-use footprints. For instance, short retention treatment unit processes like activated sludge, trickling filters, rotating biological contactors, etc. require less space compared to that required by natural processes like wetlands and stabilisation ponds. The amount and type of land required for wastewater treatment may be limited due to competitive land use requirements especially in an urban environment, and the occupation of large land areas by wastewater treatment systems may be undesirable.

- ***Environmental impact/risk***
  There has been world-wide concern on the impact of untreated wastewater on the environment. Impacts may both be on surface water and ground water quality. Pharmaceutical drugs taken by people also find their way into collection sewers and many of the treatment facilities are not designed to treat these. Hence, the risk of treated or untreated wastewater has become very high.

  - *Odour generation/control*
    Odour from treatment plants can be a nuisance and source of pollution and is a major factor in the acceptance of technologies by communities. Some technologies are high odour generators. The assessment of odour generation would depend on the potential of the technologies to generate or deal with odours. Collection networks could also cause odour nuisance due to gases escaping from pump installations and defective surface manhole structures but this is generally not as problematic as the case with treatment facilities. Odour control is typically less of a concern with smaller systems.

- *Groundwater impact*

  Discharging effluent to the ground has its own consequences. While the soil is a natural treatment medium, it is of limited capacity and if such discharges are not carefully considered groundwater pollution can result. The potential for groundwater pollution is very low for the majority of municipal wastewater treatment processes since the effluent is disposed into rivers. Infiltration of groundwater into collection networks through defective pipe components can result in aquifer drawdown and steam base reductions.

- *Surface water impact*

  Surface water pollution is a function of the treatment technology efficiency and the receiving medium's natural compensating capacity which depends on its state and the mass loadings disposed. Since 100% efficiency in treatment is rarely achieved, it means there is always some extent of surface water pollution on effluent discharge which can mostly be dealt with by the receiving water's natural compensating capacity. Decentralised systems can help reduce the proportion of landscape impervious surface and associated pollutant loading to surface water bodies (RMI 2004).

- *System failure impact on ecology*

  Wastewater systems may have an impact on water chemistry with resulting negative impacts on aquatic life and ecology.

- *Water resource recovery*

  By treatment of sewage and disposal of effluent of adequate standard into natural water bodies reclamation of natural water resources are ensured. This is however maximised in the event of groundwater recharge. The lesser extent of re-distribution networks associated with decentralised systems allows for possible cost-effective reuse of water at site and neighbourhood scale.

- *Environmental protection*

  By employment of wastewater management pollution of the natural environment is avoided. In the case of decentralised systems the risks and associated costs of system failure are generally less due to the consequences of small widely distributed failures being limited compared to severe large concentrated ones that are possible with centralised systems.

- *Nutrient recovery*
  By reuse of treatment sludges and effluent for agricultural use and other irrigation applications the inherent nutrients present therein allows not only for nutrient recovery but also the reduced need of artificial fertilisers. Ultra low or dry sanitation technology based on urine/faeces separation offer opportunities for improved capture and use of nutrients present in human wastes.

5.17.6 Technical criteria

Functional technical criteria indicate the effectiveness of a technology to achieve the service level required. Primary indicators proposed in this research were adaptability and flexibility (possibility to extend the system in capacity, or with additional treatment flexibility and ability to cope with fluctuations in the influent), durability (lifetime) and reliability (proven experience of being successful and sensitivity of the system to malfunctioning of equipment and instrumentation). The functional criteria distinguished are discussed next.

- ***Performance/removal efficiency***
  Performance refers to required or desired results of wastewater treatments systems, generally measured in terms of the pollutant removal efficiency. Performance levels are often defined by regulatory effluent standards. The following parameters normally used in wastewater quality were used as indicators to address performance of technologies (Tchobanoglous 1991)**.**
  - *Biodegradable organics* are principally made up of proteins, carbohydrates and fats and are commonly measured in terms of BOD and COD. If discharged into inland rivers, streams or lakes, their biological stabilisation can deplete natural oxygen resources and cause septic conditions that are detrimental to aquatic species.

  - *Suspended solids (SS)* can lead to development of sludge deposits and anaerobic conditions when untreated wastewater is discharged to the aquatic environment.
  - *Pathogenic organisms* measured as *Total coliforms (TC) and Escherichia coliforms (EC)* found in wastewater can cause infectious waterborne diseases.
  - *Nitrogen* and *phosphorus* are the principal nutrients of concern in wastewater discharges. Significant concentrations of nitrogen may have adverse effects such as: 1) accelerate the eutrophication of lakes and reservoirs and stimulate the growth of algae and rooted aquatic plants; 2) depletion of dissolved oxygen in receiving waters; 3) toxicity to aquatic life; 4) adverse impact on chlorine disinfection efficiency, and 5) creation of a public health hazard and wastewater that is less suitable for reuse.

  Consideration was not given to heavy metals concentration on disposal of complex industrial wastewater into urban sewage systems as these are not generally experienced where stringent legislated regulations are enforced through regular monitoring and sanction.

- ***Sludge and concentrates production***

  These are produced during biological treatment processes as well as with advanced membrane processes. Due to these substances still being volatile and/or hazardous it is normally subjected to further treatment (aerobic, anaerobic, incineration, etc.) before reused or disposed of.

- ***Adaptability***

  Given that many factors in the future are uncertain, the ability to respond to and accommodate changes, (for example changes in energy costs, legislation, labour costs, land costs, urbanisation rate) is very critical to the sustainability of any technology. The ability of the technology to adapt to changing circumstances, for instance the possibilities of implementation on different scales and increasing/decreasing capacity in time is critical for sustainability. Adaptability to upgrade as indicator reflects the ease with which both treatment trains and collector networks could be upgraded or combined with other processes. Although all technology processes are designed for certain influent conditions, some are more adaptable to changing conditions in terms of quantity and quality of flow. With collector networks a medium term phased approach would be more beneficial as the ultimate expected catchment capacity requirement based on projected growth not being achieved within the system life expectancy. By assigning different qualitative values to system/technology options these factors are accounted for.

- ***Ease of construction***

  According to Loetscher and Keller (2002) the ease of implementing technology is determined by its ease of construction, which in turn depends on: 1) required specialised knowledge and skills; 2) certain type of site conditions; 3) the coordination among agencies involved; 4) the availability of inputs; and 3) impediments encountered during construction. The time taken for construction from planning to full operation of the system can also be a factor in determining if the technology can be constructed easily. Typical modular short-lead-time decentralised type technologies do allow for shortened project lead times as well as for easier construction by reduced impediments being likely to be encountered.

- ***Reliability***

  Reliability is the rate of probability over time of attaining a performance level under a given set of operating conditions, which means being able to deliver the required services most of the time. The susceptibility of the system (treatment and collection) concerning malfunctioning of equipment and instrumentation, and fluctuations in utilities all affect the reliability of a system and treatment technology. Generally three variability sources are considered in wastewater treatment:

  - Variability in influent flow rate and characteristics
  - Inherent variability in wastewater treatment processes
  - Variability caused by mechanical breakdown, design deficiencies, and operational problems.

5.17.7 Economic criteria

In developing countries, economic indicators are often decisive when choosing a technology. Commonly used indicators are: 1) life cycle costs covering costs of investment, construction, operation and maintenance; 2) component replacement and decommissioning (if applicable) for both treatment plant and collection components. Other indicators are affordability, financial risk and willingness to pay (Massoud *et al*. 2009).

In most cases cost data are not readily available and many consulting firms or Water Services Providers (WSPs) are not keen to share or publish their data for reasons best known to them. In order to undertake a proper economic analysis of wastewater system level options where inadequate data is available, gaps can be filled by generating synthetic data that is appropriate for the particular locality considered.

In this study two further economically related aspects have been introduced which are relevant with system scale considerations. The first is differences in cost of idle capacity that exceed needs for significant periods of time which in opportunity cost terms can be considered as financial value foregone as discussed in section 5.14.4. These funds being tied up in overbuilt unnecessary capacity could have been used for other beneficial alternative investment. The second is returns to scale which could either be positive or negative, which is dealt with in detail in section 5.14.6.

The following economic criteria were considered in the MCA of Case Study 2 (Chapter 7) of this research.

Life cycle costs

Life cycle costs (including design, construction, operation, maintenance, repair and replacement) should be considered in the evaluation and selection of suitable wastewater system and technologies. Over the operational lifetime of the system the operation and maintenance costs are as important as construction costs. The methodologies for cost estimation of wastewater treatment processes are numerous, but not easily comparable or globally appropriate due to the assumptions used in their development. The same situation applies to cost data and methodologies concerning collection networks.

According to RMI (2004) the following aspects would be relevant to life cycle costs where decentralised and centralised systems are compared: 1) capacity costs are typically postponed to the future; 2) present values (PV) being reduced for replacement costs; 3) potential intervention for extended useful life of existing infrastructure; 4) financial benefits due to flexibility in matching capacity and flow, and; 5) spreading costs oppose to large financial layout upfront. Further economic benefits of decentralised systems include short-lead times that have less exposure to costs such as escalation and construction delays and substantial capital outlay savings due to the upgrade focus being on a small subset of overall capacity. Smaller decentralised systems scale avoids diseconomies of scale (less extent of collector networks required) which is typical of centralised systems. Careful consideration need be given to achieving centralised system positive returns of scale as these can be neutralised by the negative returns to scale of collection systems.

Idle capacity expense foregone

As discussed in section 5.14.4 funds tied up in idle capacity that exceed needs for significant periods of time can be considered as financial value foregone from an opportunity cost view. In Case Study 2 idle capacity was valued in terms of quantified actual idle capacity provided, being the difference between the latter and corresponding flow demand for each staged capacity period.

Returns to scale

This issue is dealt with in detail in section 5.14.6 and was considered qualitatively in the MCA. For treatment economy of scale was valued at a high level for centralised sub-systems compared to decentralised treatment, while for collection decentralised sub-systems were valued high compared to centralised system options.

Affordability

Affordability relates to the ability of householders to pay for services rendered. Affordability is usually based on the extent of services levy charged expressed as percentage of average household income.

Financial risk of exposure

Financial risk exposure relates to the risk of loss to the company or Water Service Provider associated with investment into the employed wastewater systems levels. This could be linked to system/technology failure events or also when radical changes in treatment are made due to technology changes. Financial risk exposure also covers issues of minimising regret if the plan/project is not completed.

Willingness to pay

The premium people are prepared to pay for a particular system or technology employed to secure health, safety and environmental benefits are being indicative of their willingness to pay. This would depend on such people’s perception of likely achievement of these benefits by the systems/technologies considered for employment.

5.17.8 Criteria weighting

Most multi-criteria decision models (CDMs) require assigned weights of importance to criteria. Usually these weights are normalised to add up to unity or 100 percent. The weights assigned with such summation become scaling constants which shrink or stretch scales to make them comparable (Joubert and Stewart, 2004).

Weights combine the comparison of the relative size of the swing from best to worst on the different criteria with the notion of intrinsic importance. It is important that the weights are found after the range of worst to best have been defined for each criterion/index.

The swing weight approach is a relatively simple approach to eliciting weights. The procedure for the ranking would be to ascertain from stakeholders which criterion they would choose if it were possible to improve on one criterion to its best level. Such designated criterion would then be ranked number 1. The same procedure is repeated for the remaining criteria until all criteria are ranked. The highest ranked criterion would then be given a weight of 100.

Stakeholders would then be required to indicate how important the swing of "worst to best" on ranked 2 criterions is relative to the ranked 1 criterion. The response would generate a percentage score and the same procedure will continue until all the ranked criteria have scores (percentages values with reference to the criterion ranked highest).

Criterion weights (W_i) are then found through normalisation by dividing each percentage by the sum total of all the percentages as shown by Eq 5.19.

$$W_i = {p_i} \Big/ {\sum_{i=1}^{m} p_i} \qquad (5.19)$$

where

p_i = criteria or sub-criteria under consideration **(**$i = 1$ *to* m)

Scoring development and data assessment

Scoring systems reflect levels of achievement of individual criteria and is associated with interval scale scores. The first step in scoring development is to define "worst and best" levels for each criterion. The best level is given a score at one end of the scale and the worst at the other, e.g. values of zero (0) and 10. Intermediate levels are subsequently defined and its associated score. The emphasis is on evaluating the relative gaps between defined levels of the criterion considered.

Weighted sum method

The weighted sum method (WSM) is relatively simple and easily explained to and understood by decision makers generally and do not place any substantially greater restrictions on the preference structures as with more complicated aggregation formulae. The weighted scores of each candidate solution are summed and the candidate solution with the highest score is considered best. The aggregate score is a qualitative measure of the degree of sustainability for an alternative solution (measured by the set of criteria).

The range of the scoring system for individual criteria and whether the scale from high priority to low priority is ascending or descending is immaterial provided a consistent system is used for all criteria.

The value measurement of alternative solutions are computed through maximising the expected utility function (aggregate score), H_j, as shown in Eq 5.20.

$$H_j = \sum_{i=1}^{m} w_i v_{ij} \tag{5.20}$$

Where

m is the number of criteria of alternative solution j,
v_{ij} is the value of the j th alternative solution with respect to the i th criterion, and
w_i is the weight of importance assigned to criterion i,

with the following constraints:

$w_i \geq 0$, and

$$\sum_{i=1}^{m} w_i = 1$$

The additive utility assumption governs this approach, i.e. the total value of each alternative is equal to the sum of the products as given in Eq 5.20. The results from the evaluation are tested with a sensitivity analysis to assess the confidence of the solution.

5.17.9 Criteria indicator scoring

A scale of 1 to 5 is used to generate a score from the set of criteria indicator questions. The summed result of all questions is then aggregated to obtain a standardised outcome score on the scale of zero (0) to 10 for main criteria (technical, economical, social and environmental). Arithmetic mean is used as basis to aggregate the standardised value using equations 5.21 to 5.22.

$$d_{ave} = \frac{1}{m} \sum_{i=1}^{n} X_{ij} \tag{5.21}$$

where

d_{ave} = aggregation result for assessment criterion j ; (j = 1, 2, 3, 4…m)

X_{ij} = merit of criteria j with regard to statement i ; (i = 1, 2, 3, 4…n)

The final score on a scale of 0 to 10 is derived from the following defined constraints:

When the indicator target is to maximum score, then

$$Score = (d_{ave} - d_{min})/(d_{max} - d_{min}) \times 10 \tag{5.22a}$$

When the indicator target is to minimise score, then

$$Score = \left| (d_{ave} - d_{min})/(d_{max} - d_{min}) - 1 \right| \times 10 \tag{5.22b}$$

where

d_{min} = the minimum value of the range of scale considered.

d_{max} = the maximum value of the range of scale considered.

5.17.10 Criteria sensitivity analysis

Subjectivity is inherent in all decision making and in particular with criteria choice on which the decision is based and the relative weight given to such criteria. Multi criteria decision aids do not dispel subjectivity, but simply seeks to make subjective judgements explicit and ensure transparency of the process whereby criteria are taken into account (Belton and Stewart, 2002).

The results of the ranking can never be completely objective because of the weighting procedure, but confidence in the results can be increased by carrying out a sensitivity analysis. This is done by considering the effects on ranking when changes in the criteria weighting is made. Those criteria most open to subjective interpretation can be selected and their weights slightly altered and final scores determined and candidate solutions re-ranked. Comparisons of the ranking order for different scoring and weighting scenarios indicate the level of confidence that can be given to the results.

Weighting changes that result in minimal altered ranking indicate a low level of sensitivity to weighting changes and a high degree of confidence in such results can be placed. Conversely, wide variations in ranking would indicate that the results are highly sensitive to weighting change and results should then be treated with care.

5.18 SYSTEM LEVEL COMPONENT COSTS

Total direct monetary costs for a wastewater management system include the following for both treatment facility and collection networks:

- capital costs;
- operation and maintenance costs.

Additional direct monetary costs may be incurred if components or facilities are added to take advantage of synergies with other infrastructure. Case in point would be where treated water reuse is employed, the additional treatment unit processes as well as reuse distribution systems would be incorporated into the economic analyses. These additional treatment units and infrastructure would typically also have direct monetary benefits that in turn allow for compensation for some or all of their costs.

In this thesis costs are quantified through use of cost algorithms and actual cost data and combined benefits (environmental protection, water resource reclamation and public health protection) valued in monetary equivalents by deriving shadow prices for avoided pollution with an output distance function approach.

5.18.1 Wastewater treatment facilities

Costs of system components vary depending on local conditions, cost structures as well as different development assumptions and methodologies employed, making such costs not easily comparable and also inappropriate in a global sense (Joksimovic 2006). Various costing tools available were considered for use to derive costs in Case Study 2. The objective of achieving realistic and appropriate costs within the local South African context with using the available tools presented quite a challenge and required specific measures which are described later in the study. Two of the available decision making tools were considered for use for this study. The first is the South African developed *WaswarPlamo* software (Adewumi 2010) and the second the cost algorithms of Joksimovic (2006). In Chapter 7.3.1 the screening done for selecting an appropriate costing tool for estimating wastewater treatment costs are discussed in detail as well as the reasons for the final choice made.

For treatment train total cost determination the sequence followed is outlined in Figure 5.17. Varied extent of ancillary costs (piping, controls and instrumentation, site development, site electrical, etc.) are generally expressed as a percentage of the treatment train cost and added to obtain a total treatment facility cost. The extent of these ancillary costs is specified in the actual case study where applicable.

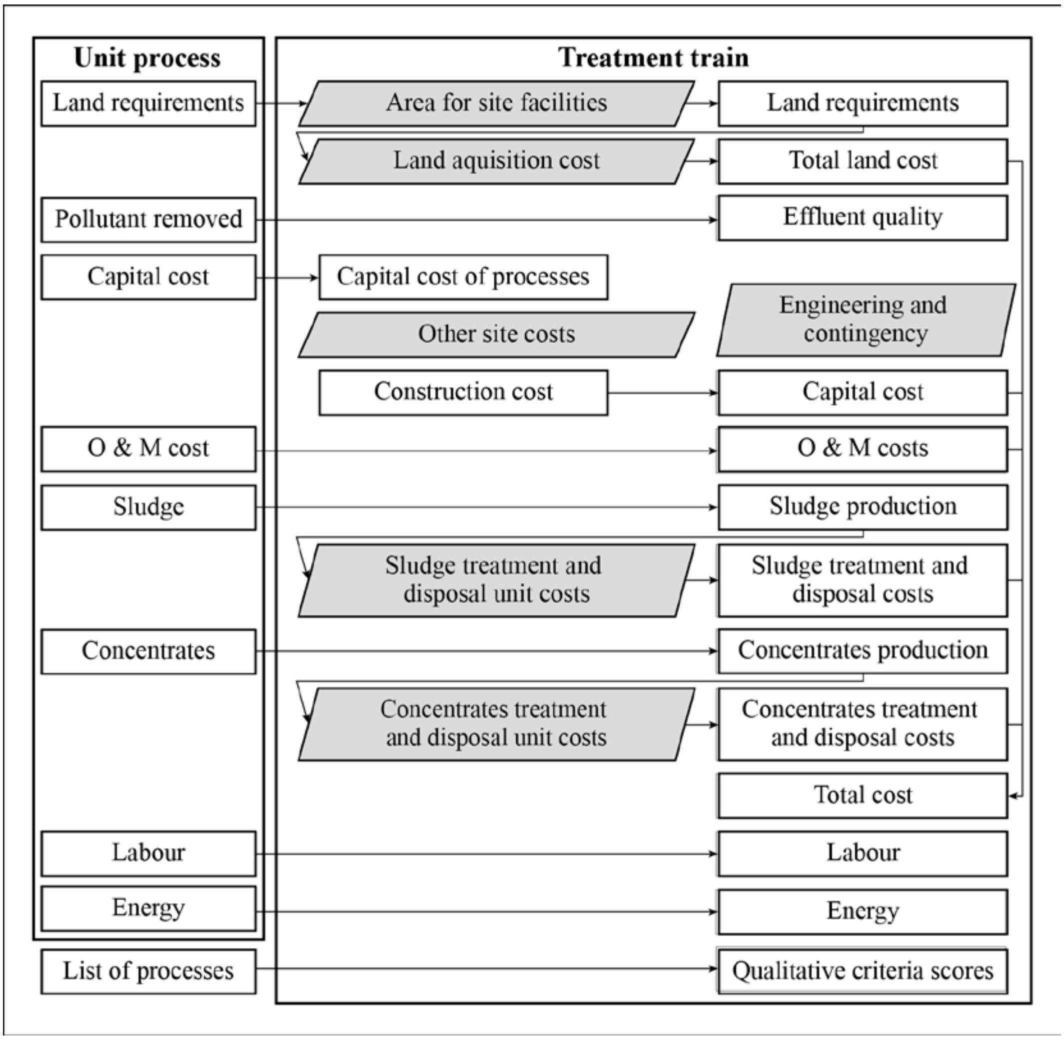


Figure 5.17 Treatment train total cost estimating sequence (after Joksimovic 2006)

5.18.2 Collection networks

As in the case of treatment plants costs collection network costs vary depending on local conditions and cost structures and are therefore not appropriate in a global sense.

Various sources of cost exist among which are those of the US EPA (1999) being a summary of U.S.A. pipeline installed costs for sewers ranging from 150 mm to 1,80 m in diameter. The Construction costs for municipal conveyance systems by the US EPA (1981) gives extensive costs for collector network components such as gravity sewers and rising mains (different pipe materials) as well as pump stations and sewer manholes both in tables and cost curves.

The use of these international cost data mentioned is problematic in the sense that even after adjustment for difference of currency and cost base year, appropriate adjustment is further needed to account for differences in cost structures between the country of origin of such cost data and the locality for which costs are being estimated for. These cost structure adjustment factors are not necessarily available or known and application of foreign costs data need to be used with the caution and verification as far as possible to ensure the appropriateness of estimates to the particular locality intended for. It would therefore always be preferable to used cost data as localised possible if available.

Due to a composite costing exercise being necessary for sub-systems (treatment plus collection) in Case Study 2 it was essential to employ both a common cost year base and cost structure. In order to allow cost projections to be aligned with this approach average local collector network cost data were resorted to. These were made available by a South African based consulting engineers firm’s cost data base of projects undertaken in Gauteng Province of South Africa (IMQS 2009/2010). These costs curves are given in Appendix C3, Figures C3.1 to C3.3.

5.19 SYSTEM LEVEL LIFE CYCLE AND RELATED COSTS

The most suitable approach for economic comparison of wastewater system level options is the Life Cycle Cost (LCC) approach. Life Cycle Cost analysis is an economic assessment technique that determines the total cost of any facility over a useful period of time, being the summation of cost estimates during it life time from inception to disposal (cradle to grave) taking cognisance of the time value of money. The objective of LCC analysis is to choose the most cost effective approach from a series of alternatives to achieve the lowest long-term cost thereof. LCC results are presented as present value (PV) by considering the capital costs, operation and maintenance, energy and replacement cost and any final salvage value. Life cycle cost analysis (LCCA) provides a significantly improved assessment of a projects long-term cost efficiency compared to alternatives where the focus is limited to initial costs or short term operation-related cost only (Fuller and Petersen, 1996).

For obtaining wastewater management system level life cycle cost (ito PV) the individual sub-system component life cycle costs (treatment and collection) are summed as follows:

$$LC_{SL} = LC_{TF} + LC_{CN} \tag{5.23}$$

where

LC_{SL} = wastewater management system level lifecycle cost
LC_{TF} = treatment facility lifecycle cost
LC_{CN} = collection network lifecycle cost

The lifecycle cost of the sub-system components are calculated by adding initial and discounted recurrent costs. These would include future replacement cost of civil and electromechanical works (EM), sludge and concentrate disposal costs and O&M costs over the life of the project.

The following equations were used for life cycle costs estimation:

1. Treatment facilities

$$LC_{TF} = CC_{TF} + OM_{TF}\left(\frac{(1+r)^{n}-1}{r(1+r)^{n}}\right) + \sum_{i-1}^{N} RC_{i}\left(\frac{1}{(1+r)^{z}}\right) \tag{5.24a}$$

Or

$$LC_{TF} = CC_{TF} + OM_{TF} \times \left(P/A, r\,\%,\ n\right) + \sum_{i-1}^{N} RC_{i} \times \left(P/F,\ r\%,\ z\right) \tag{5.24b}$$

$$AC_{TF} = LC_{CN}\left(\frac{r(1+r)^{n}}{(1+r)^{n}-1}\right) \tag{5.25a}$$

Or

$$AC_{TF} = LC_{TF} \times \left(A/P, r\,\%, n\right) \tag{5.25b}$$

2. Collection networks

$$LC_{CN} = CC_{CN} + OM_{CN}\left(\frac{(1+r)^{n}-1}{r(1+r)^{n}}\right) + \sum_{i-1}^{N} RC_{i}\left(\frac{1}{(1+r)^{z}}\right) \qquad (5.26a)$$

Or

$$LC_{CN} = CC_{CN} + OM_{CN} \times \left(P/A, r\,\%,\ n\right) + \sum_{i-1}^{N} RC_{i} \times \left(P/F, r\,\%,\ z\right) \qquad (5.26b)$$

$$AC_{CN} = LC_{CN}\left(\frac{r(1+r)^{n}}{(1+r)^{n}-1}\right) \qquad (5.27a)$$

Or

$$AC_{CN} = LC_{CN} \times \left(A/P, r\%, n\right) \qquad (5.27b)$$

where

CC_{TF} = wastewater treatment capital cost.
CC_{CN} = collection network capital cost.
OM_{TF} = annual wastewater treatment operation and maintenance costs.
OM_{CN} = annual collection network operation and maintenance costs.
RC_i = component i replacement cost in year z.
AC_{TF} = wastewater treatment annualised cost.
AC_{CN} = collection network annualised cost.
r = annual interest rate or rate of return in percent.
n = number of interest periods (years).
N = number of components being replaced over system life.

Functional expressions:

(P/A, r %, n) = uniform series present worth factor.
(P/F, r %, z) = single payment present worth factor.
(A/P, r %, n) = capital recovery factor.

where

P = present monetary value.

F = monetary value at the end of n periods from the present that is equivalent to P at rate of return r.

A = uniform series for n interest periods equivalent to P at rate of return r.

With the break-even economic analysis to determine an appropriate baseline reuse tariff taking in consideration increased value of the 2010 fresh water tariff (FWT_{2010}) at various rates of escalation, the following equation was used:

$$FWT_{@\, i\,\%\, pa} = FWT_{2010} \times \left(1 + \frac{i}{100}\right)\left(A/G, r\,\%, n \right) \qquad (5.28)$$

where

$FWT_{@\, i\,\%\, pa}$ = Discounted annualised fresh water tariff at an escalation rate of i % pa.

FWT_{2010} = Bulk fresh water tariff for the year 2010 (Randwater South Africa).

i = annual FWT tariff escalation rate in percent.

$(A/G, i\,\%, n)$ = gradient series to equivalent uniform annual series conversion factor.

G = uniform arithmetic gradient of disbursements.

The functional expressions given above for the “uniform series present worth factor”, “single payment present worth factor”, “capital recovery factor and gradient series to equivalent uniform annual series conversion factor” are alternatives to the corresponding mathematical expressions used in engineering economics. Appropriate values for functional expressions are given in the various economy textbooks.

CHAPTER 6

CASE STUDY 1: INDIRECT PRODUCTION FUNCTION VALUING OF ENVIRONMENTAL BENEFITS (OF CONTAMINANT REMOVED) FOR NINE WASTEWATER TREATMENT PLANTS IN GAUTENG PROVINCE

SOUTH AFRICA

Case Study 1 considers inherent resource recovery valuing at a treatment level. The assessment is based on actual treatment level data of nine centralised wastewater treatment plants made available for the research by the management agencies responsible for their operation.

6.1 COSTS AND BENEFITS FOR WASTEWATER TREATMENT PLANTS

The links of wastewater treatment costs and benefits at facility level are shown in Figure 6.1. The links identified were derived from a comparative cost-benefit study by Chen and Wang (2009) of decentralised sanitation and reuse systems (DESAR) and a centralised system. For this research the benefit links are environmental, public health and water resource conservation related, while the cost links are amortised construction costs, and annual operational and maintenance costs.

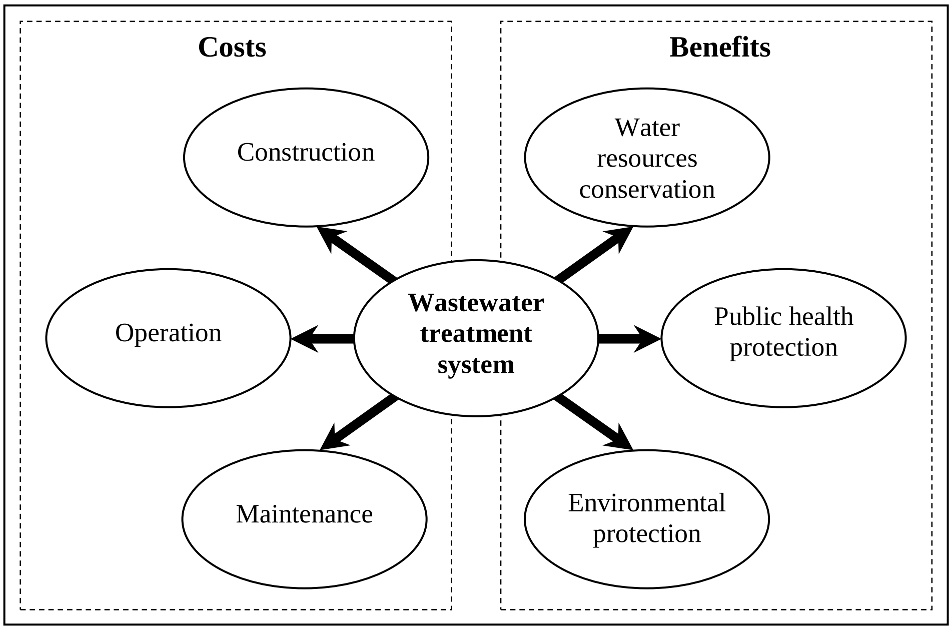


Figure 6.1 Wastewater treatment system cost and benefit factor links (derived from Chen and Wang, 2009)

6.2 METHODOLOGY AND STEP SEQUENCE FLOW DIAGRAM FOR TREATMENT LEVEL ANALYSES

The objective is to carry out an economic cost-benefit analysis for centralised wastewater treatment facilities, using facility costs and treatment process contaminant removal (avoided pollution) data to jointly quantify environmental, public health and water resource conservation benefits. For the purposes of this research economic evaluation of water resource and public health effects is considered to be inclusive for the simple reason of 100% of resource conservation benefits (full effluent reclamation) and 100% of public health protection benefits (whole catchment area fully sewered and final effluent disinfection treatment employed) are achieved and no further improvement will be possible. From now on in any reference to total environmental benefits, it will mean inclusive benefits of both public health and water resource conservation.

The impact of treated wastewater reclamation and reuse (excluding any conveyance to point of use) on the treatment facility economic viability is also explored in the research.

Data for the analysis were obtained from the operating agencies of nine centralised wastewater treatment plants (WWTPs) in the Gauteng province of South Africa. The plants have similar treatment trains with some variation in actual technologies employed for particular unit processes. Treatment plant costs and contaminant load and effluent throughput data for the facilities were quantified by the operating agencies for a single one-year period. Five different facility outputs were distinguished, consisting of a single desirable output (treated effluent throughput) together with four undesirable outputs as recorded by the operating agencies (or contaminants removed), being; suspended solids (SS), chemical oxygen demand (COD), nitrogen (N) and phosphorus (P). The facility input cost components made available were variable, manpower, maintenance, depreciation and running costs.

The methodology sequence of steps for the mathematical optimisation and economic analysis at treatment plant level is given in Figure 6.2 and briefly summarised as follows:

Phase 1 – Parametric output distance function analysis for shadow price derivation:

- Step 1: Model input data capture for individual WWTPs. This covers facility cost components, desirable (treated effluent) and undesirable outputs (contaminants removed) for a particular time cycle. In this analysis the data set is for a single one-year period.

- Step 2: Solving the translog output distance function algorithm parameters by maximisation of the objective function, being the summation of differences between output distance function and an optimum efficiency frontier. Details of the translog function (Eq 5.8) appear in Chapter 5.10.3. The *Matlab* software optimisation toolbox was used for the optimisation analysis and is described in more detail later.

- Step 3: Calculation of output distance function values for every WWTP utilising the optimal parameter values obtained in step 2.

- Step 4: Application of the revenue-output distance function duality to derive shadow prices for undesirable outputs (contaminants removed). The approach followed is similar to that of Färe *et al.* (1993) as outlined in Chapter 5.10.4 with application of Eq 5.18 to derive shadow prices. The approach requires a monetary objective value assumption for the desirable output (treated water) for calculating comparative prices for undesirable outputs (SS, COD, N and P). In this case study a unit objective value assumed for the desirable output (treated effluent) was a monetary value of 1 ZAR /m^3.

Phase 2 – WWTP cost-benefit economic viability analysis:

- Step 5: The first step of phase 2 is to determine environmental benefits of avoided pollution due to contaminant removal. This is done by applying shadow prices derived in step 4 to the different contaminants loads removed of each plant.
- Step 6: Economic viability analysis. This is based on a conventional cost-benefit analysis that assesses two scenarios. For the first, only environmental benefits are considered. The second allows for combining potential reuse benefits with the environmental benefits. For viability, the net benefit (total benefits less total costs) has to be greater than zero for each scenario.

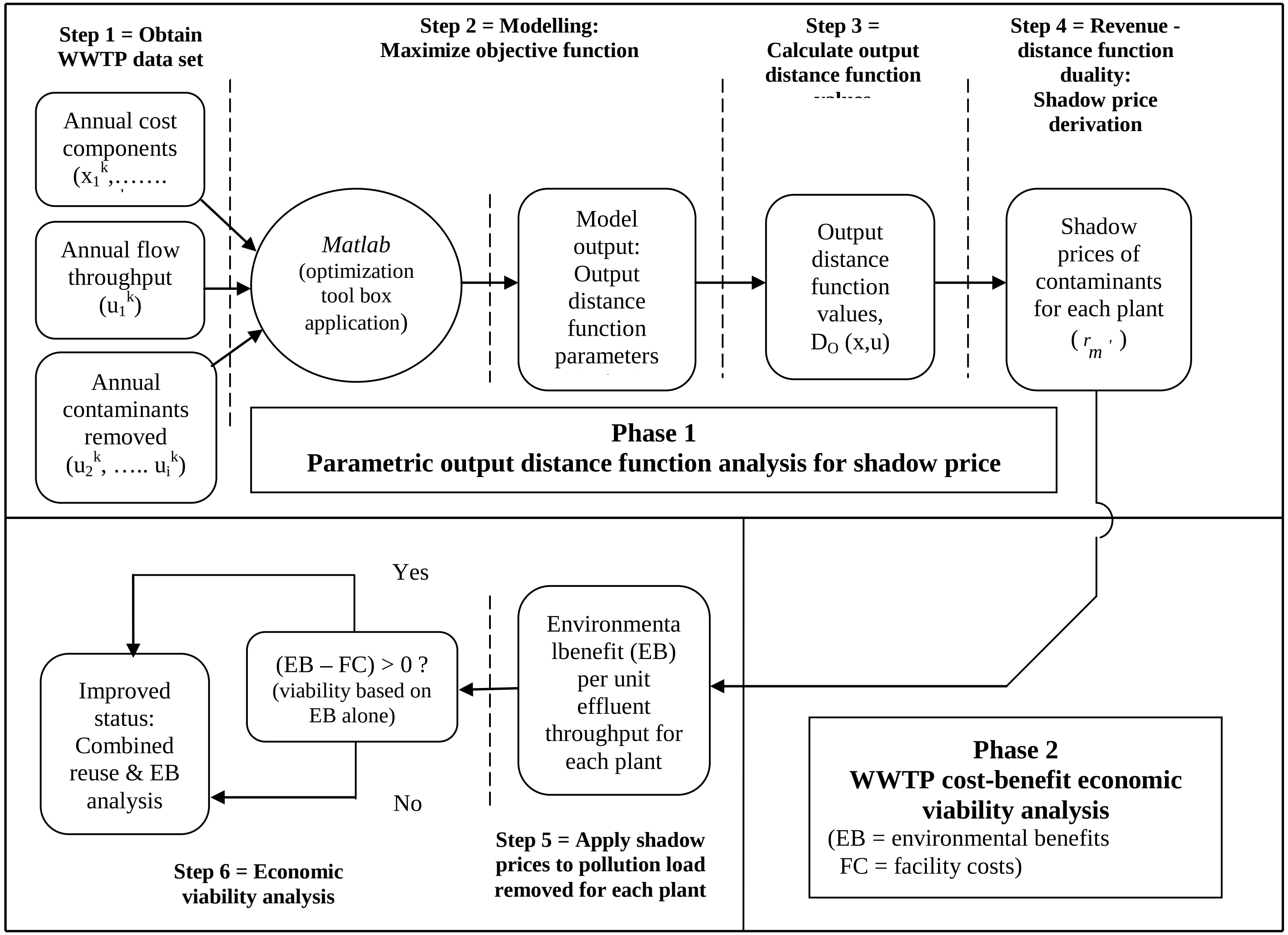


Figure 6.2 Methodology flow diagram – environmental benefits valuing and cost-benefit analysis.

6.3 WASTEWATER TREATMENT FACILITY DATA

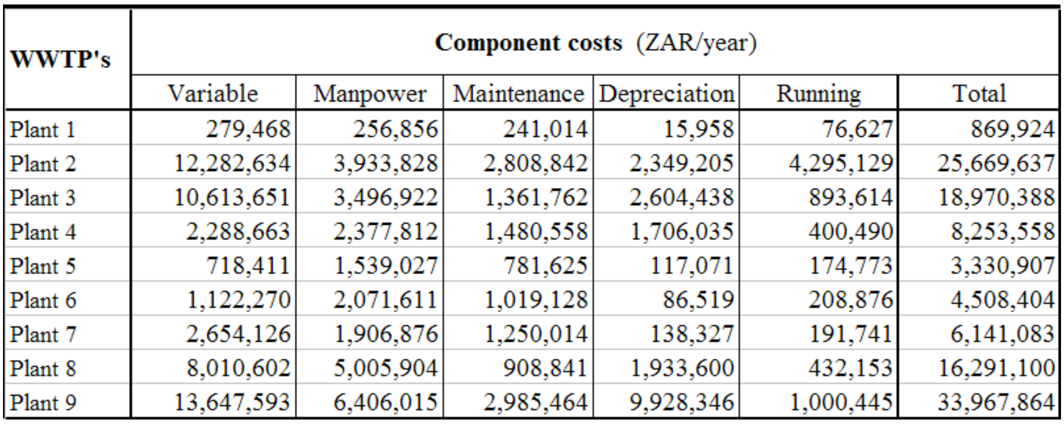
6.3.1 Treatment plant technologies employed

The sample treatment plants analysed employ similar levels of treatment which can be categorised as follows: 1) preliminary treatment inclusive of screening, grit removal and balancing; 2) primary treatment consisting of sedimentation; 3) secondary treatment of a biological nature with either biological filters, activated sludge or a combination thereof and final clarification of treated effluent, and; 4) tertiary treatment for nutrient and pathogen removal.

6.3.2 Plant costs

The cost data made available for the nine plants analysed are shown in Table 6.1. The cost data applies to a single one-year time cycle for the period July 2009 to June 2010.

Table 6.1 Cost data for treatment plants



WWTP's	**Component costs** (ZAR/year)					
	Variable	Manpower	Maintenance	Depreciation	Running	Total
Plant 1	279,468	256,856	241,014	15,958	76,627	869,924
Plant 2	12,282,634	3,933,828	2,808,842	2,349,205	4,295,129	25,669,637
Plant 3	10,613,651	3,496,922	1,361,762	2,604,438	893,614	18,970,388
Plant 4	2,288,663	2,377,812	1,480,558	1,706,035	400,490	8,253,558
Plant 5	718,411	1,539,027	781,625	117,071	174,773	3,330,907
Plant 6	1,122,270	2,071,611	1,019,128	86,519	208,876	4,508,404
Plant 7	2,654,126	1,906,876	1,250,014	138,327	191,741	6,141,083
Plant 8	8,010,602	5,005,904	908,841	1,933,600	432,153	16,291,100
Plant 9	13,647,593	6,406,015	2,985,464	9,928,346	1,000,445	33,967,864

6.3.3 Desirable and undesirable plant outputs

The analysis distinguishes a single desirable output (treated water) and four undesirable outputs (in terms of contaminants removed). Both the desirable output and undesirable outputs were calculated based on monthly influent and effluent related data quantified by the operating agencies. The detailed monthly contaminant related data and calculated contaminates removed, are given in Appendix B1.

A summary of annual contaminant removal per unit throughput of plants are given in Tables 6.2(a) and (b) respectively and illustrated in Figure 6.3.

Table 6.2(a) Annual contaminant removal and effluent throughput of WWTPs

WWTP's	**Total Flow per year** (m^3)	**Contaminants removed** (kg/year)			
		COD	**SS**	**N**	**P**
Plant 1	256,780	272,720	130,306	4,934	1,686
Plant 2	31,636,780	37,225,045	15,765,233	934,165	192,848
Plant 3	21,407,700	19,801,760	17,791,391	248,974	91,188
Plant 4	14,800,440	5,851,851	1,446,895	118,282	20,605
Plant 5	4,090,020	2,399,650	648,597	64,756	14,176
Plant 6	5,822,860	1,675,293	625,881	90,089	17,490
Plant 7	10,289,230	8,653,728	2,834,108	295,690	62,131
Plant 8	46,491,640	24,903,406	8,469,957	581,448	122,338
Plant 9	67,914,570	43,956,012	15,749,896	917,912	234,827

Table 6.2(b) WWTP contaminant load removed per unit throughput

WWTP's	**Contaminants load removed** (kg/m^3)			
	COD	**SS**	**N**	**P**
Plant 1	1.062	0.507	0.019	0.007
Plant 2	1.177	0.498	0.030	0.006
Plant 3	0.925	0.831	0.012	0.004
Plant 4	0.395	0.098	0.008	0.001
Plant 5	0.587	0.159	0.016	0.003
Plant 6	0.288	0.107	0.015	0.003
Plant 7	0.841	0.275	0.029	0.006
Plant 8	0.536	0.182	0.013	0.003
Plant 9	0.647	0.232	0.014	0.003

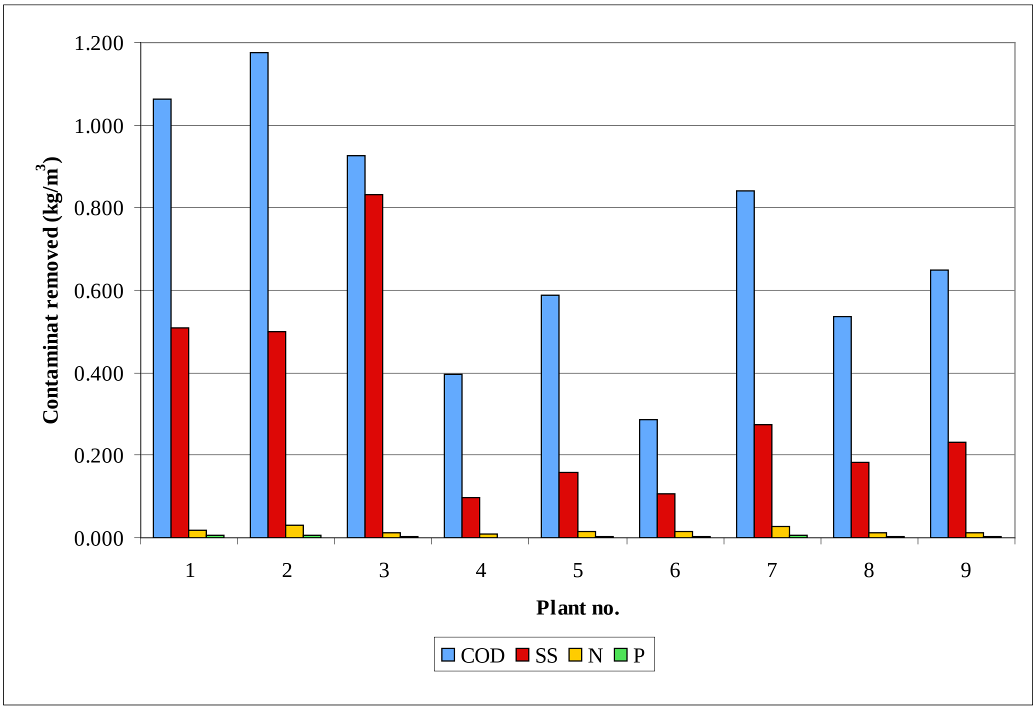


Figure 6.3 Plant contaminant loads removed per unit throughput

From Figure 6.3 it is evident that consistently over all plants the contaminant load removed is highest for COD, followed by SS, N and the lowest P.

The corresponding contaminant removal efficiencies for each plant is shown in Figure 6.4. These efficiencies are within the general operational envelopes associated with the technology types employed at the plants (Vernick and Walker, 1981, Tchbanoglous and Burton, 1991, McGhee 1991).

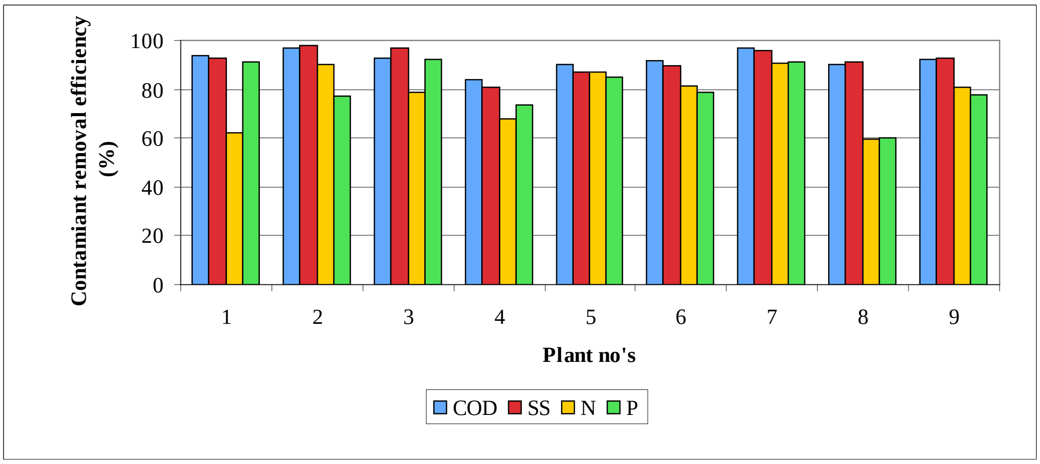


Figure 6.4 Contaminant removal efficiency of plants

6.4 ECONOMIC MODELLING AT WASTEWATER TREATMENT LEVEL

The output distance function, as outlined before in Chapter 5.10.3, was used to model the economics of the wastewater treatment facilities. The model parameters for each treatment plant are solved by using an optimisation approach. Once the optimal distance function parameters are determined, shadow prices are quantified for process undesirable outputs (consisting of the various contaminants removed) based on an assumed market monetary value for the desirable output (treated effluent). The derived monetary shadow prices, in turn, allow for quantification of the equivalent environmental benefits (of avoided pollution) for each treatment facility.

The economic analysis approach used is a break-even point sensitivity exercise which relates varying levels of reclamation or reuse with the current bulk fresh water supply tariff applicable in Gauteng (the region where the treatment facilities are located). Through the analysis, a basic economic viability benchmark price for treated effluent was established (in relation to a bulk fresh water tariff), which requires adjustment to allow for the general market related supply-demand forces. Although not taken into account at this particular level of analysis, conveyance system costs from point of supply to potential users also need to be considered when determining the final price for treated effluent.

6.5 MODEL DEVELOPMENT

Through the use of numerical computing and a fourth-generation programming tool *Matlab*, a suitable user interface was developed for doing the analysis. Obtaining the optimal set of parameters of the output distance function is essentially a constrained, multi-dimensional linear optimisation problem. This is done by extremising the Färe objective function (Eq 5.9) for a given set of restraining data, using the ‘linprog’ procedure in the *Matlab* Optimisation Toolbox. Shadow prices were then derived by utilising the Färe equation (Eq 5.18) in Chapter 5 (Färe *et al*. 1993). The inputs to the model algorithm are as follows:

1. the objective function to be minimised (in vector form)

2. a matrix and vector encoding of the linear inequality constraints of the problem

3. a matrix and vector encoding of the linear equality constraints of the optimisation problem.

The Färe linear inequality and equality constraints were encoded in matrix and vector format. The symmetry constraints were achieved by only solving for independent elements of the set of parameters to be optimised. The objective function used was the negative of the Färe objective function to allow converting it to a minimisation problem as used by the *Matlab* Optimisation Toolbox. The derivation of the desired shadow prices for each plant was achieved by substituting the set of optimal parameters into the Färe shadow price equation (Eq 5.18) along with an assumed observed market monetary price of 1 ZAR/m^3 for the desirable output (treated effluent).

Based on the five model inputs (cost components) and five model outputs (treated effluent plus four different contaminants removed), the corresponding translog output distance function for analysis is as follows:

$$\begin{aligned} ln\ D_0(x^k, u^k) &= \alpha_0 + \sum_{n=1}^{5} \beta_n \ln x_n^k + \sum_{m=1}^{5} \alpha_m \ln u_m^k + \frac{1}{2}\sum_{n=1}^{5}\sum_{n'=1}^{5} \beta_{n,n'} (\ln x_n^k)(\ln x_{n'}^k) \\ &+ \frac{1}{2}\sum_{m=1}^{5}\sum_{m'=1}^{5} \alpha_{m,m'} (\ln u_m^k)(\ln x_{m'}^k) + \sum_{n=1}^{5}\sum_{m=1}^{5} \gamma_{n,m} (\ln x_n^k)(\ln u_m^k) \end{aligned} \qquad (5.19)$$

The nine individual facility observations were indexed as $k = 1, \ldots\ldots, 9$.

6.6 SCENARIO CONSIDERED IN ANALYSIS

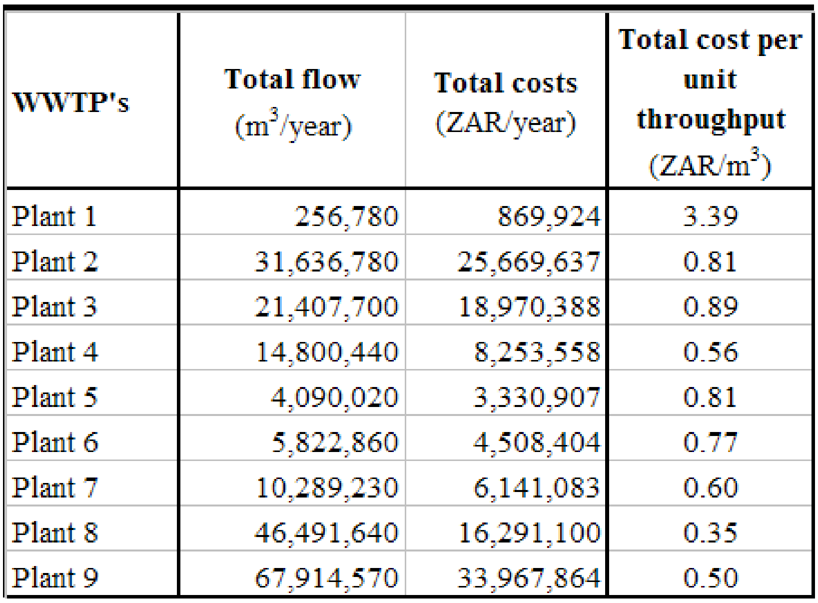
All the treatment plants analysed employ preliminary, primary, secondary and tertiary treatment and the levels of treatment are compatible. However, the different plants do operate at various degrees of their individual design capacities which could affect the individual plant treatment process efficiency. The analysis considers the current status only and no adjustments are made for any future capacity extensions and the associated increased costs thereof. These aspects could be considered with further research.

With Case study 2 (Chapter 7) these aspects are taken into consideration with staged capacity versus flow balances for the period of system analyses.

6.7 ANALYSIS RESULTS

The current annual facility throughput and total cost together with the costs per unit effluent throughput of the treatment facilities are given in Table 6.3.

Table 6.3 Unit costs of different WWTPs



WWTP's	**Total flow** (m^3/year)	**Total costs** (ZAR/year)	**Total cost per unit throughput** (ZAR/m^3)
Plant 1	256,780	869,924	3.39
Plant 2	31,636,780	25,669,637	0.81
Plant 3	21,407,700	18,970,388	0.89
Plant 4	14,800,440	8,253,558	0.56
Plant 5	4,090,020	3,330,907	0.81
Plant 6	5,822,860	4,508,404	0.77
Plant 7	10,289,230	6,141,083	0.60
Plant 8	46,491,640	16,291,100	0.35
Plant 9	67,914,570	33,967,864	0.50

6.7.1 Distance function parameters and shadow prices

The output distance function optimal parameters using the Färe objective function (Eq 5.9) are listed in Table 6.4 and the corresponding output distance function values and derived shadow prices (with assumed desirable output value of 1 ZAR/m^3) are listed in Table 6.5.

Table 6.4 Output distance function optimal parameters

Output distance function - optimal parameter values							
Parameter	**Value**	**Parameter**	**Value**	**Parameter**	**Value**	**Parameter**	**Value**
α_0	-7.20E-03	γ_{22}	4.14E-03	γ_{54}	-1.05E-02	β_{11}	1.76E-03
α_1	2.24E-01	γ_{23}	-2.04E-02	γ_{55}	-9.51E-03	β_{12}	-2.07E-01
α_2	1.76E-01	γ_{24}	-4.30E-03	α_{11}	4.85E-03	β_{13}	-8.39E-02
α_3	1.82E-01	γ_{25}	-1.27E-02	α_{12}	1.33E-02	β_{14}	3.16E-01
α_4	2.13E-01	γ_{31}	1.59E-02	α_{13}	3.63E-02	β_{15}	-4.79E-03
α_5	2.06E-01	γ_{32}	-1.36E-02	α_{14}	-3.88E-02	β_{22}	3.44E-02
β_1	-8.59E-02	γ_{33}	3.14E-03	α_{15}	-1.56E-02	β_{23}	1.79E-01
β_2	-4.63E-02	γ_{34}	-6.16E-03	α_{22}	-1.36E-02	β_{24}	-2.14E-01
β_3	-4.94E-02	γ_{35}	6.52E-04	α_{23}	-1.65E-02	β_{25}	8.16E-02
β_4	-8.53E-02	γ_{41}	-4.55E-02	α_{24}	9.21E-03	β_{33}	2.12E-02
β_5	-5.27E-02	γ_{42}	-2.59E-03	α_{25}	7.59E-03	β_{34}	-1.13E-01
γ_{11}	3.69E-02	γ_{43}	7.32E-04	α_{33}	-3.08E-02	β_{35}	-1.95E-02
γ_{12}	-4.01E-03	γ_{44}	2.44E-02	α_{34}	1.22E-02	β_{44}	4.57E-03
γ_{13}	-4.12E-03	γ_{45}	2.30E-02	α_{35}	-1.19E-03	β_{45}	1.55E-02
γ_{14}	-1.41E-02	γ_{51}	1.22E-02	α_{44}	1.26E-02	β_{55}	-7.39E-02
γ_{15}	-1.46E-02	γ_{52}	3.59E-03	α_{45}	4.86E-03		
γ_{21}	3.32E-02	γ_{53}	4.18E-03	α_{55}	4.34E-03		

Table 6.5 Output distance function values and undesirable output shadow prices of WWTPs

WWTP's	**Output distance function values**	**Shadow prices - undesirable outputs** (ZAR/kg) (assumed desirable output objective price = ZAR 1/m^3)			
		COD	**SS**	**N**	**P**
Plant 1	0.999999218	-0.03	-0.09	-2.49	-6.57
Plant 2	0.999999252	-0.05	-0.14	-1.38	-7.87
Plant 3	0.999999269	-0.07	-0.11	-2.38	-8.98
Plant 4	0.999998613	-0.11	-0.29	-6.27	-21.19
Plant 5	0.999999898	-0.05	-0.22	-3.72	-13.57
Plant 6	0.999998548	-0.06	-0.18	-5.35	-21.94
Plant 7	0.999999347	-0.05	-0.19	-1.94	-8.96
Plant 8	0.999999152	-0.08	-0.33	-3.59	-16.67
Plant 9	0.999999565	-0.09	-0.29	-2.01	-7.58

The distance function values being close to unity is evidence that the optimisation algorithm objective was achieved.

The shadow prices of undesirable outputs are negative. This corresponds to the general rule that such values be constrained as negative or zero (non-positive) values, as imposed by the relevant constraint on the optimisation objective function (Färe *et al*. 1993).

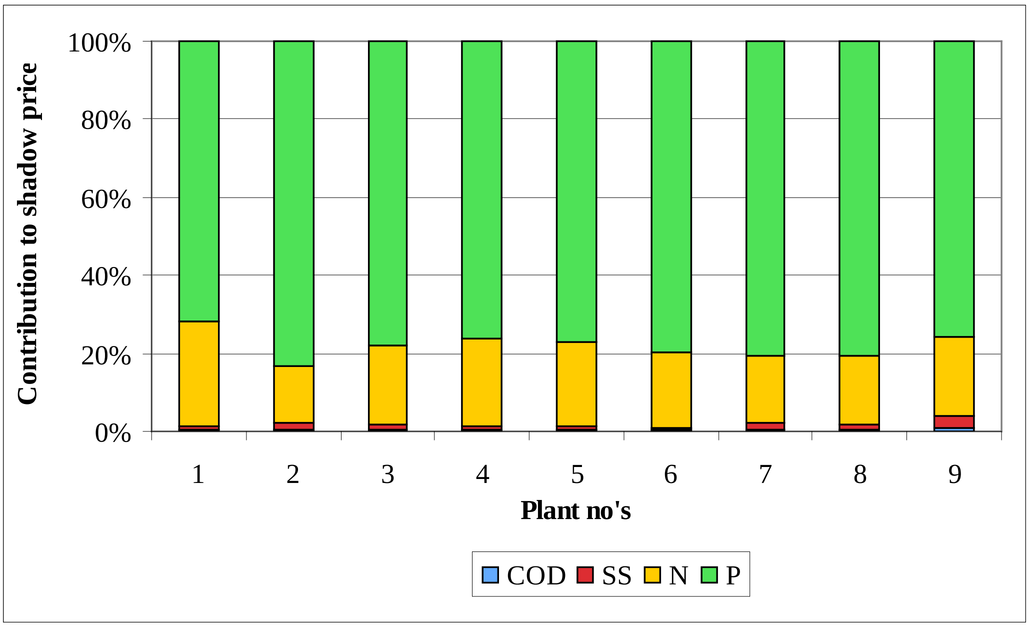


Figure 6.5 Contribution of contaminant shadow prices per plant

It is clear from the contaminant shadow price data of plants in Table 6.5 (and illustrated in Figure 6.5) that the shadow price (in ZAR/kg) for phosphorus (P) is consistently highest for all plants, followed by nitrogen (N), suspended solids (SS) and organics (COD) the lowest. However, the opposite trend exists for contaminant load removed (in kg/m^3) for all plants, i.e. P being the lowest, followed by N, SS and COD the highest (Figure 6.3).

An inverse trend therefore is evident between contaminant shadow price (ZAR/kg) and its load removed (kg/m^3) for all the plants analysed, i.e. high contaminant shadow price corresponding to a low contaminant load removed and vice versa as was expected thus confirming the soundness of the algorithm used. This amounts to a relative high marginal cost (shadow price) having to be incurred for every additional unit of removal of contaminants with current low load removed and vice versa.

As the output distance function algorithm is a function of the plant costs and contaminants removed in a particular time cycle, with shadow prices in turn derived from the algorithm optimal value, variations in any of these factors will affect the unique relationship between contaminant shadow prices and load removed of a particular plant. It would be interesting to assess the effects of any changes in these factors on plant contaminant shadow prices which could be pursued further with future research.

6.7.2 Environmental benefits of wastewater treatment

The environmental benefits (*EB*) of contaminants removed (avoided pollution) for each plant (in ZAR/m^3), was calculated using the following equation:

$$EB = SP \times CLR \tag{6.1}$$

where

SP is the plant specific contaminant shadow price in ZAR/kg (Table 6.5).

CLR is the plant specific contaminant load removed in kg/m^3 (Table 6.2(b)).

By avoiding discharge of contaminants to the environment, mitigation of their negative impact is achieved and shadow prices revert to positive values when the environmental benefits (EBs) are determined. The EB values due to contaminant removed and the contribution to total EB achieved are given in Table 6.6. The EB values are also based on a unity treated effluent value of 1 ZAR/m^3 as is the case with shadow prices.

As established previously, at individual treatment plant level, the contaminant with lowest load removed (kg/m^3) has the highest shadow price (ZAR/kg), and vice versa.

Table 6.6 Environmental benefits and contaminant contributions for each plant

WWTP's	Annual effluent throughput (m^3)	Environmental benefits (EB) in ZAR /m^3 and % contribution (Based on absolute price of treated effluent = ZAR 1/m^3)				
		COD	SS	N	P	Total
Plant 1	256 780	0.033213 (19.70%)	0.044440 (26.36%)	0.047800 (28.35%)	0.043152 (25.59%)	0.168605
Plant 2	31 636 780	0.057322 (26.25%)	0.072197 (33.07%)	0.040873 (18.18%)	0.047951 (21.96%)	0.218344
Plant 3	21 407 700	0.066401 (29.40%)	0.093532 (41.41%)	0.027689 (12.26%)	0.038258 (16.94%)	0.225879
Plant 4	14 800 440	0.041862 (27.95%)	0.028328 (18.91%)	0.050086 (33.44%)	0.029494 (19.69%)	0.149770
Plant 5	4 090 020	0.028168 (16.72%)	0.034316 (20.37%)	0.058967 (35.00%)	0.047021 (27.91%)	0.168472
Plant 6	5 822 860	0.017740 (9.53%)	0.019697 (10.58%)	0.082755 (44.47%)	0.065910 (35.42%)	0.186101
Plant 7	10 289 230	0.039136 (19.44%)	0.052232 (25.95%)	0.055795 (27.72%)	0.054111 (26.88%)	0.201275
Plant 8	46 491 640	0.040559 (21,40%)	0.060207 (31.76%)	0.044934 (23.71%)	0.043854 (23.14%)	0.189554
Plant 9	67 914 570	0.059233 (32.79%)	0.068017 (37.65%)	0.027204 (15.06%)	0.026198 (14.50%)	0.180652

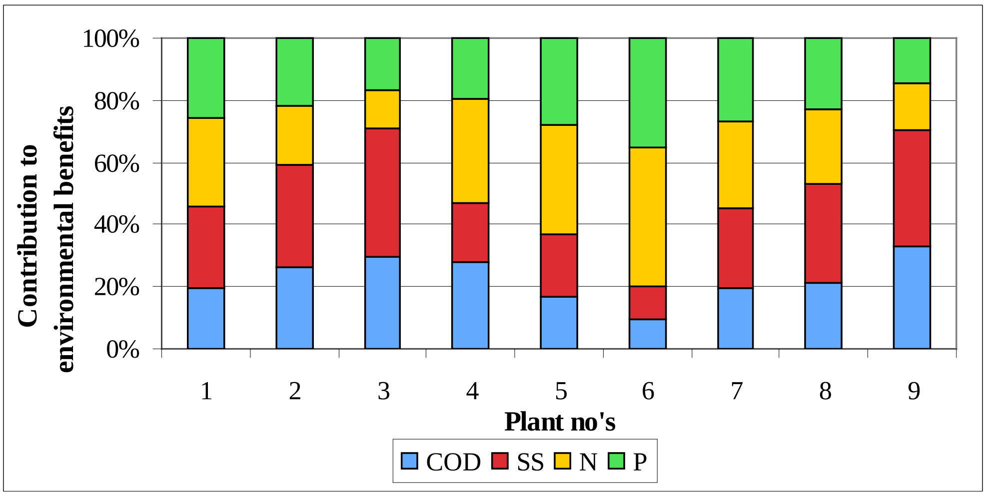


Figure 6.6 Contaminant contribution to environmental benefits of each plant

6.7.3 Value ranking of suitability of plants for agricultural reuse

The inverse contaminant shadow price and removed load relationship established at treatment level in the research, was explored further to identifying the link between wastewater intrinsic value recovery through agricultural reuse and the contaminant shadow price relationship mentioned. The approach and reasoning consisted of the following:

Since the environmental benefit of the removal of a particular contaminant is equal to the mathematical product of plant throughput and shadow price, it follows that environmental benefit and load removed is also inversely related. Therefore, where a **large environmental benefit** occurs, a low removed load applies or **high remaining fractions of such contaminant in the treated effluent result** and vice versa.

Table 6.7 Value ranking of plant suitability for nutrient recovery with agricultural reuse

Agriculture reuse value ranking of plants for potential nutrient recovery		**Nutrient (N and P) contribution to plant total environmental benefits (%)**
Ranking	**Plant ID no.**	
1	6	79,89
2	5	62,91
3	7	54,60
4	1	53,94
5	4	53,13
6	8	46,85
7	2	40,14
8	9	29,56
9	3	29,20

Therefore, the most beneficial wastewater intrinsic value recovery (or beneficiation) related to nutrients for agriculture, would then be achieved by a plant with corresponding high fraction of environmental benefit contribution of such nutrients (N and P).

Based on this reasoning and considering the nutrient related environmental benefit contribution data in Table 6.6, together with the representation given in Figure 6.6, a value ranking of suitability of the plant effluent for agricultural reuse was derived related to nutrient recovery, the result of which is given in Table 6.7.

Apart from wastewater beneficiation related to nutrient recovery by reuse, the recovery of other wastewater constituents beneficial to enhancement of soil fertilisation and stabilisation on shadow prices could be explored with further future research.

6.8 ECONOMIC VIABILITY ANALYSIS OF TREATMENT PLANTS

For economic viability the net benefits (total benefits less total costs) must be non-negative. The equation used for calculating the minimum required fresh water rate ($FWR_{REQ}^{Environ+Reuse}$) for economic viability which takes into account both environmental benefits and varying reclamation or reuse levels for each facility is as follows:

$$FWR_{REQ}^{Environ+Reuse} = \frac{C}{EB + (R_L / 100)} \qquad (6.2)$$

where

C is the total input cost per unit throughput of effluent for each plant, in ZAR/m^3 (Table 6.3).

EB is the total environmental benefits per unit throughput of effluent for each plant, in ZAR/m^3 (Table 6.6).

R_L is the percentage direct reuse level.

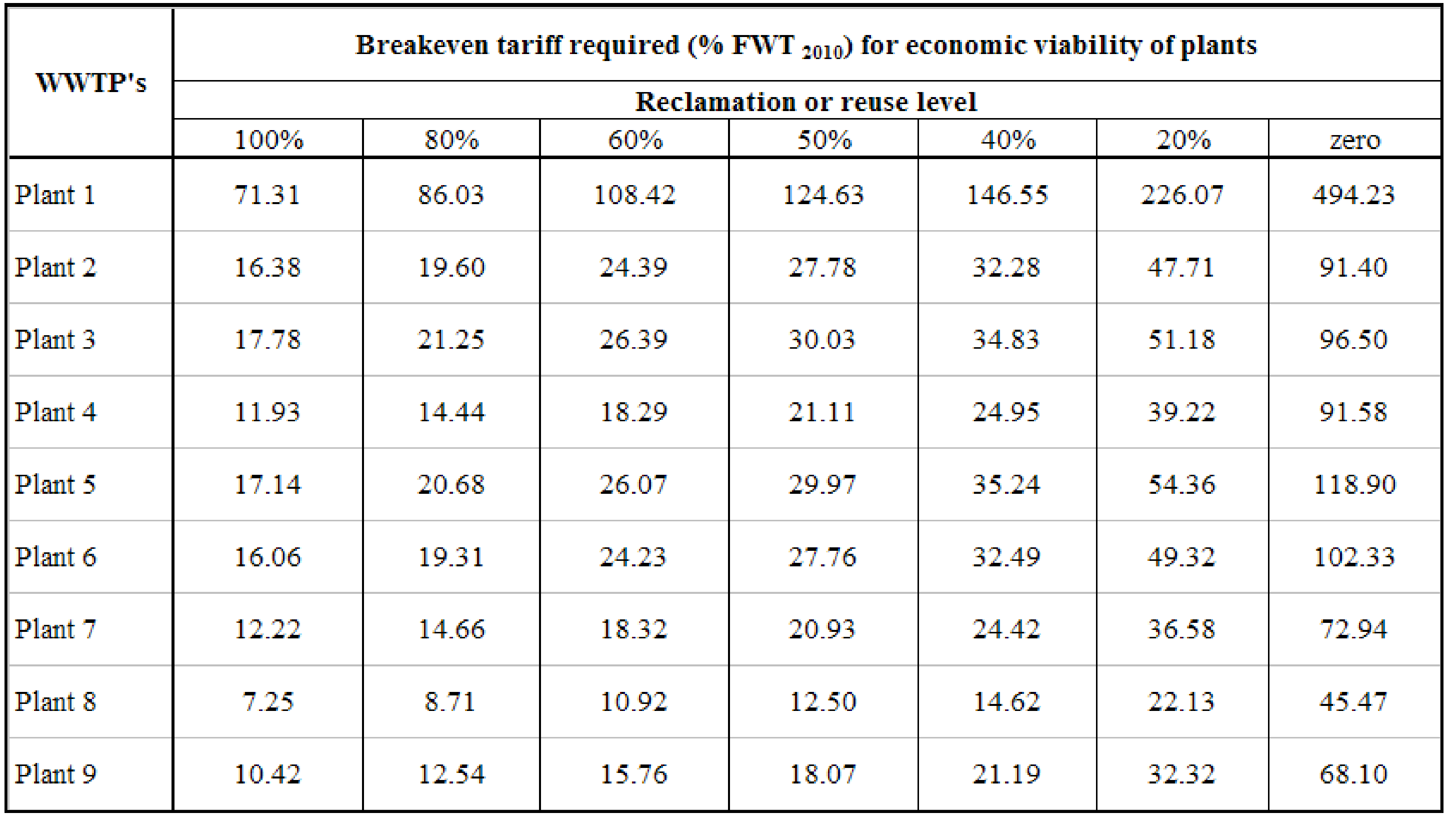
At zero reclamation or reuse level, environmental benefits alone contribute to the economic viability of the plants.

The required $FWR_{REQ}^{Environ+Reuse}$ was then expressed in terms of the current bulk fresh water tariff (FWR_{2010}), allowing direct comparison between the two. The 2009/10 Rand Water tariff for bulk municipal water supply (4.065 ZAR/m^3) was used for FWR_{2010} in the analysis (Rand Water South Africa 2010). The Rand Water South Africa tariffs for bulk supply to different categories of consumers for the period 2009/2010 are also given in Appendix B6.

The results of economic viability considering various levels of reclamation or reuse are given in Table 6.8 (see Appendix B7 for detail calculations).

The graphical representation in Figure 6.7 reflects the minimum reclamation or reuse water tariff required for economic viability (expressed as a percentage of the FWR_{2010}) for the various plants.

Table 6.8 Breakeven tariff required (as % of bulk fresh water tariff = 4.07 ZAR/m^3) for economic viability of plants at different reclamation or reuse levels



WWTP's	Breakeven tariff required (% FWT $_{2010}$) for economic viability of plants						
	Reclamation or reuse level						
	100%	80%	60%	50%	40%	20%	zero
Plant 1	71.31	86.03	108.42	124.63	146.55	226.07	494.23
Plant 2	16.38	19.60	24.39	27.78	32.28	47.71	91.40
Plant 3	17.78	21.25	26.39	30.03	34.83	51.18	96.50
Plant 4	11.93	14.44	18.29	21.11	24.95	39.22	91.58
Plant 5	17.14	20.68	26.07	29.97	35.24	54.36	118.90
Plant 6	16.06	19.31	24.23	27.76	32.49	49.32	102.33
Plant 7	12.22	14.66	18.32	20.93	24.42	36.58	72.94
Plant 8	7.25	8.71	10.92	12.50	14.62	22.13	45.47
Plant 9	10.42	12.54	15.76	18.07	21.19	32.32	68.10

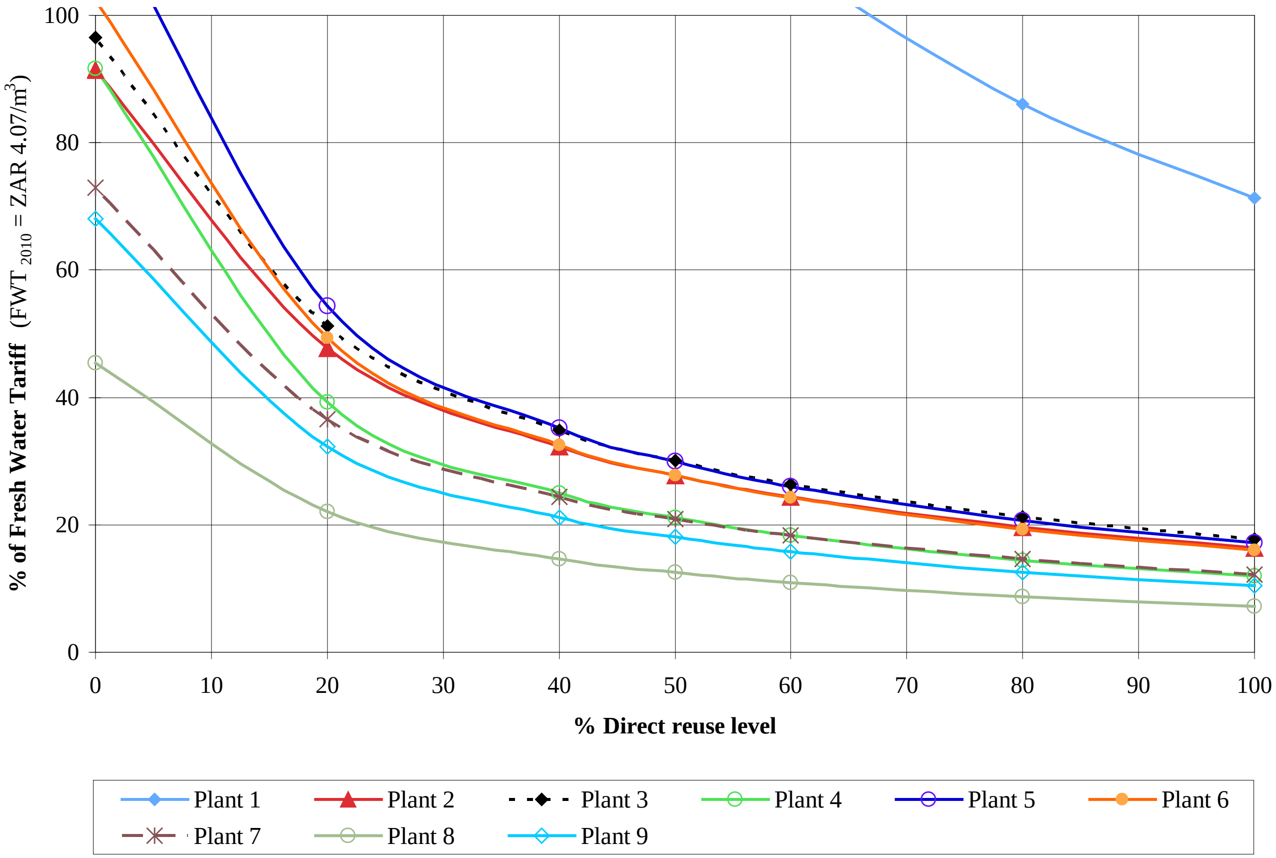


Figure 6.7 Breakeven tariff required (as % of bulk fresh water tariff = ZAR 4.07/m^3) for economic viability of plants at different reclamation or reuse levels

6.9 ECONOMIC VIABILITY ANALYSIS CONCLUSIONS

The conclusions drawn from the economic viability analysis results illustrated in Figure 6.7 are as follows:

1. With zero reclamation or reuse level (only environmental benefits considered):

    1.1 For water value of 100% of the FWT_{2010}:
    All plants except plants 1, 5 and 6 (plant 6 being borderline) are economically viable.

    1.2 For water value of 50% of the FWT_{2010}:
    Only Plant 8 is economically viable.

    1.3 For water value of 25% of the FWT_{2010}:
    None of the plants are economically viable.

2. Considering benefits of employing different levels of reclamation or reuse and the environmental benefit achieved by avoided pollution:

    2.1 For water value of 100% of the FWT_{2010}:
    Plant 1 & 5 will require reclamation or reuse in the order of 70% and 10% respectively to be economically viable.

    2.2 For water value of 75% of the FWT_{2010}:
    Plants 2, 3, 4, 5 & 6 will require reclamation or reuse of between 10 to 15%, except Plant 1 which will require virtually a 100% reuse level to be economically viable.

    2.3 For water value of 50% of the FWT_{2010}:
    All plants will require between 10 to 25% reclamation or reuse, except Plant 1 which is not viable at this particular FWT_{2010} level.

    2.4 For water value of 25% of the FWT_{2010}:
    All plants will require between 20 to 70% reclamation or reuse, except Plant 1 which is not viable at this particular FWT_{2010} level.

3. From Figure 6.7 it is evident that for a reclamation or reuse level below roughly 20%, the tariff required for economic viability increases quite rapidly as reuse level decreases, except for plant 1which is only viable at levels of reuse higher than approximately 70%.

   For reuse around 20 to about 50%, the required tariff flattens out and steadily declines for higher levels of reuse.

As mentioned before, the minimum value derived for treated effluent (compared to the current fresh water tariff) should serve as a benchmark indicator value for achieving economic viability for a particular treatment facility. However, the benchmark value needs to be adjusted for any conveyance system costs of treated effluent supply to potential consumers. Should an integrated approach for costing be followed with conveyance as part of the reuse system, the additional conveyance costs will contribute towards an increased total cost of water reclamation or reuse. With this inclusive higher system input cost (conveyance plus treatment) as a basis and similar contaminants removal load, shadow prices are expected to decrease due to a relative decline in facility economic efficiency. For economic viability, this probable reduction in shadow prices is likely to require higher treated effluent tariffs and reuse levels compared to those excluding conveyance costs.

With regard to provision of reserve treatment capacity to accommodate future development, the following needs to be noted. Provision of such spare capacity has corresponding increased facility input costs, as well as a negative impact on treatment efficiency and expected lower levels of contaminants removal load. At best, if a similar contaminants load removed is possible, with the higher facility cost shadow prices are expected to decrease and a decline in facility economic efficiency is likely to result similar to the impact of conveyance costs.

It would be more prudent to ensure that such spare facility capacity be of the smallest practically possible increments in order to, not only avoid large additional expense and corresponding financial burden (high tariffs for capital expenditure together with financing cost of such expenditure) but also the negative impact on process efficiency and lower plant economic viability.

All of this is suggesting that a move towards decentralised systems would be economically justifiable.

Decentralised wastewater systems, as opposed to centralised ones, would present positive advantages in regard to some of the aspects mentioned. The generally closer location of decentralised wastewater systems to waste source as well as potential users of treated effluent would contribute to reducing conveyance and associated costs. In addition, such systems being of smaller scale result in better amenability for smaller increments of treatment capacity. This not only reduces the level of under-capacity operational problems as such, but through flexible smaller scale phased capacity increases, financial benefits of avoided expense towards large underutilised over-built capacity also result. Furthermore, it also contributes to improved plant economy as discussed previously and a more competitive tariff of treated effluent for reuse or reclamation. However, decentralised system may have a disadvantage in the case of large volume users such as industries and large landscape irrigational use, since extensive conveyance systems from a large number of source points are needed to make the required volume available. As large volume use may be the most cost efficient applications of reuse, careful consideration need be given to the conveyance cost component in finding an optimal management system.

Apart from the system related economic aspects mentioned, another aspect that will greatly affect and ultimately determine the value of treated effluent is the market supply-demand forces.

6.10 FINAL CONCLUSION

At the level of wastewater treatment internalisation of externalities such as environmental benefits of pollution avoided allows for more realistic and holistic assessments of treatment facility economic viability. This directly impacts on the future sustainability of such facilities but does not lead to an overall system level optimal solution which, if it is to be achieved, must be analysed at the wastewater management system level rather than the treatment plant level. Although monetary values for environmental benefit can be derived that allow for economic analyses, these benefits have to be converted into real cash flow for such facilities to contribute positively to their sustainability.

As the environmental protection achieved by these facilities extends beyond their service areas and are considered to be of regional and even national interest from a water resource protection point of view, introduction of a suitable mechanism with a regional or national base is essential for future sustainability of these facilities or in other words to achieve national or regional goals wastewater management system level analysis is a must. This is not to say that treatment level analysis are of no value, but that caution should be exercised not to interpret the findings of such treatment level analysis beyond that being justified.

The concept of an environmental pollution mitigation allowance in the form of a direct government subsidy or tax rebate could be a possible option. This allowance could be related to the environmental and ecological sensitivity of the particular catchment where effluent disposal takes place. For example, where special regulatory effluent standards have to be introduced for this purpose, the marginal cost of increased contaminant removal to avoid undesired negative impacts that could not be tolerated, could be part of such an allowance. In addition, where reuse or reclamation of treated effluent is practised an equivalent marginal cost for fresh water mobilisation could be incorporated into the allowance. For proper regulation and management of such allowances it would have to be incorporated into the permitting process of every plant with the explicit incorporation of the allowance conditions being strictly administered by the regulating authority.

The USA approach used for achieving environmental standards of tradable permitted allowances also needs mention. This system was originally developed for polluting power generation industries. Researchers have proved that under competitive markets permit-trading provides a suitable alternative to regulatory schemes and could achieve the given environmental standards at relatively lower cost (Coggins and Smith, 1993, Coggins and Swinton, 1996).

CHAPTER 7

CASE STUDY 2: A SYSTEM LEVEL WASTEWATER MANAGEMENT FEASIBILITY COMPARISON OF CENTRALISED AND DECENTRALISED OPTIONS FOR THE URBAN DEVELOPMENT ZONE OF THE MIDVAAL LOCAL MUNICIPALITY IN GAUTENG PROVINCE SOUTH AFRICA

7.1 INTRODUCTION

The system level case study investigated the feasibility of introducing decentralisation wastewater management within the existing centralised Midvaal Local Municipality urban zone. The existing system consists of a sewered collection network and single centralised wastewater treatment plant. Figure 7.1 shows a map of the Midvaal municipal area and the location and extent of the urban development zone. An enlarged map of the urban centralised development zone is given in Figure 7.2.

All physical sewer infrastructure data used in the study (gravity pipe sizes and lengths, pump station rising mains, pump station mechanical and electrical installations) were based on information obtained from the Midvaal municipality infrastructure engineering consultants responsible for maintaining the municipality infrastructure assets register (IMQS 2009/2010).

7.2 SYSTEM OPTIONS CONSIDERED IN ECONOMIC ANALYSIS

For a centralised/decentralised feasibility comparison smaller decentralised zones were identified within the existing urban centralised zone. The approach followed was to demarcate these smaller zones such that optimal use of the current collection infrastructure would still be maintained.

This resulted in the demarcation of two possible decentralised zones on the outer extremity of the urban development zone. By demarcating these two decentralised zones, a comparative analysis of four possible system options for the **same urban service zone** was possible as follows:

- **System option 1:** The current urban centralised wastewater management system (Figure 7.2 – areas 1, plus 2, plus 3)

- **System option 2:**

  Sub-system 2.1: A single decentralised zone with dedicated treatment plant (Figure 7.2 – area 1), and

  Sub-system 2.2: the remainder of the urban centralised system (Figure 7.2 – areas 2, plus 3).

- **System option 3:**

  Sub-system 3.1: A decentralised zone with a dedicated treatment plant (the same as sub-system 2.1),

  Sub-system 3.2: a 2nd decentralised zone with a dedicated treatment plant (Figure 7.2 – area 2), and

  Sub-system 3.3: the remainder of the urban centralised system (Figure 7.2 – area 3)

- **System option 4:**

  Sub-system 4.1: A large decentralised zone with a dedicated treatment plant (being the combination of the two smaller decentralised sub-systems 3.1 & 3.2; Figure 7.2 - areas 1, plus 2), and

  Sub-system 4.2: the remainder of the urban centralised system (the same as sub-system 3.3).

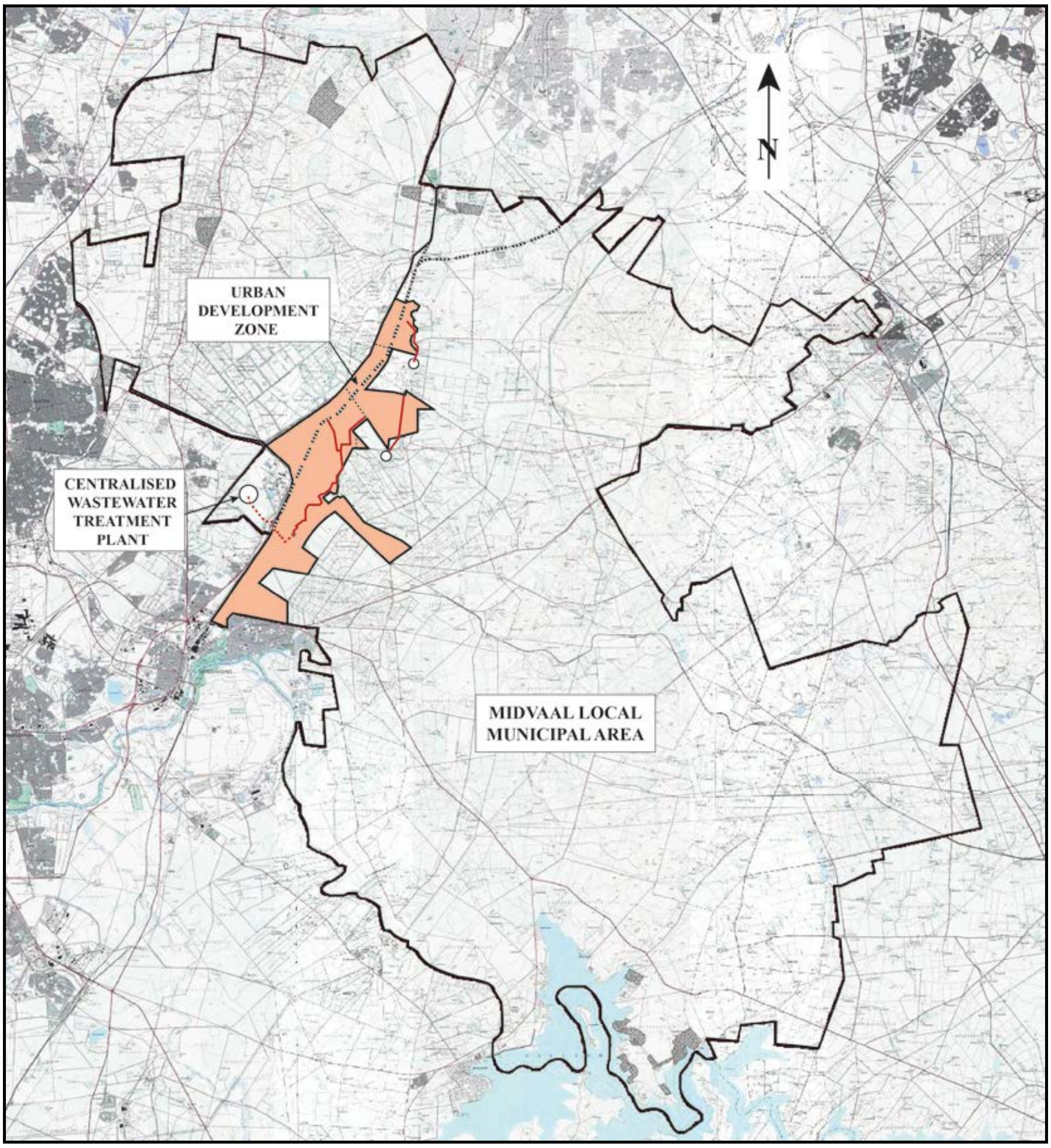


Figure 7.1 Map of the Midvaal Local Municipality area with urban spatial development zone

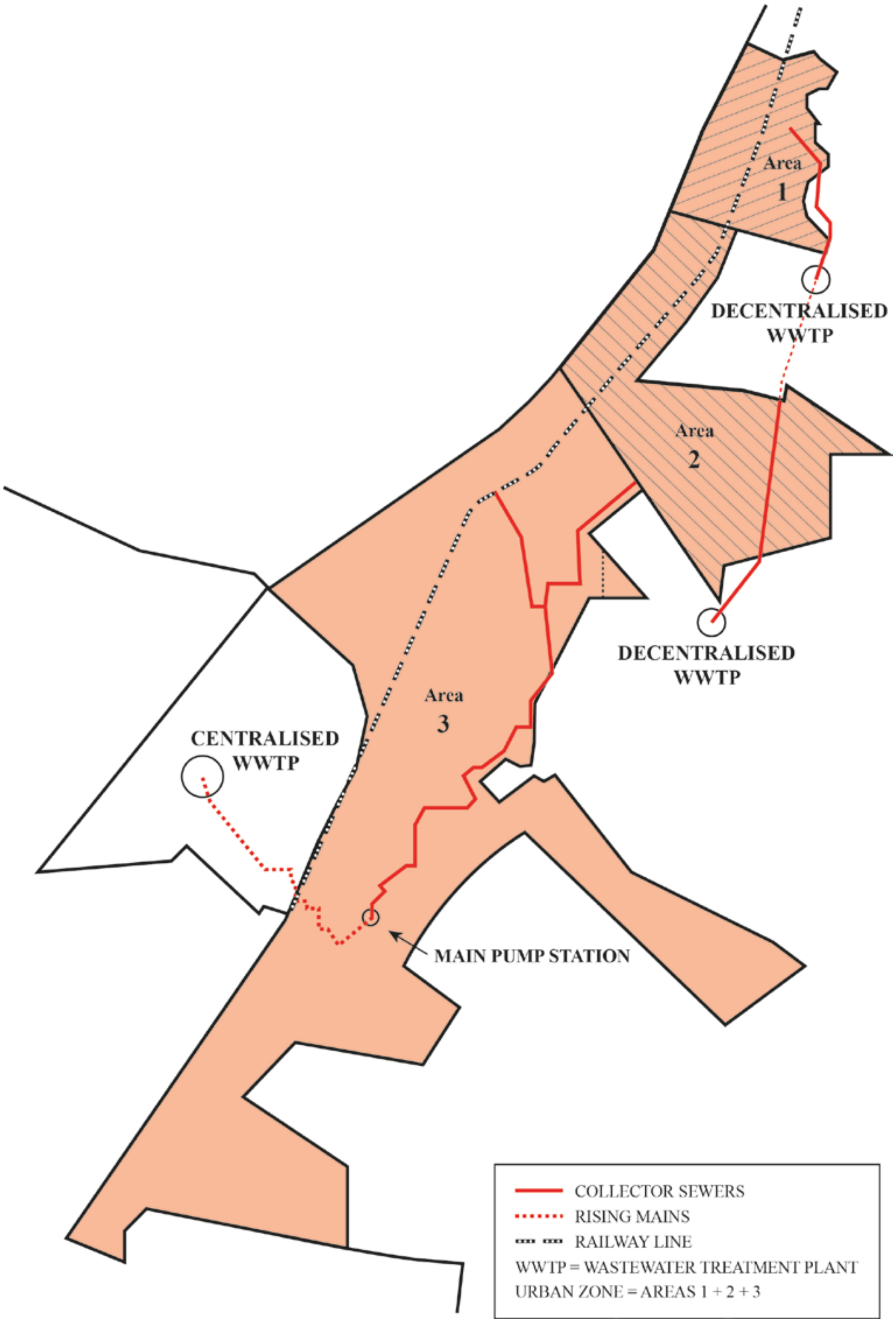


Figure 7.2 Midvaal Municipality urban spatial development area with Case Study 2 demarcated decentralised zones

7.3 WASTEWATER FLOWS

Wastewater system sewage flow estimation is based on water use being adjusted for corresponding sewer return flows. This is based on the current occupied land demand and the data made available by the Midvaal municipality consultants responsible for maintaining their infrastructure asset data (IMQS 2009/2010). The general design guidelines used for water demand by IMQS are the consumption figures as per the Guidelines for Human Settlement Planning and Design (CSIR 2000). Sewer return flows are based on an absolute average return flow factor of 60% considered by IMQS applicable for the generally larger size plots (> 2000m^2) in the Midvaal urban development zone.

A linear 3% pa growth in sewage flow was assumed for this study being equivalent to the average population growth for the Midvaal municipal area over the period 1996 to 2007 (Midvaal Local Municipality 2011). Estimating diurnal peak flows for use in treatment plant cost algorithms where necessary was done using the Harmon formula for a peak factor applied to average flows (Haestad Methods 2004). The population figures used in the Harmon equation were estimated applying a wastewater flow population equivalent of 200 litres per day to phased projected treatment flows (WISA 1988).

The required capacities for treatment plants were derived from a staged capacity versus flow balance exercise for the various system options identified. An example of the capacity/flow balances is illustrated in Figure 7.3. The remainder of the capacity balanced employed are given in Appendix C1, Figures C1.1 to C1.5.

7.4 WASTEWATER COMPOSITION CHARACTERISTICS

Pollutants considered in the research for valuing avoided pollution through treatment removal using the distance function approach are suspended solids (SS), biological oxygen demand (BOD), chemical oxygen demand (COD), nitrogen (N) and phosphorus (P). A typical domestic municipal raw wastewater was assumed for the case study with raw characteristics of a study of the South African Water Research Commission (WRC) given in Table 7.1 (Ekama *et al*. 1984).

Table 7.1 Average typical raw domestic wastewater pollutant concentrations

Pollutant concentration (mg/L)				
SS	**BOD**	**COD**	**N**	**P**
210	300	600	48	10

7.5 STAGED BALANCING OF TREATMENT CAPACITY AND FLOW

A staged approach of balancing wastewater flow was followed for provision of treatment capacity. In the case of decentralised zones where closer matching of capacity and flow can be achieved, a 5-year stage phase was assumed, while for the centralised larger extent plants with longer lead-time technology requirements a 10 year period was employed.

The staging treatment capacity/flow balancing approach used is illustrated for System option 1 in Figure 7.3.

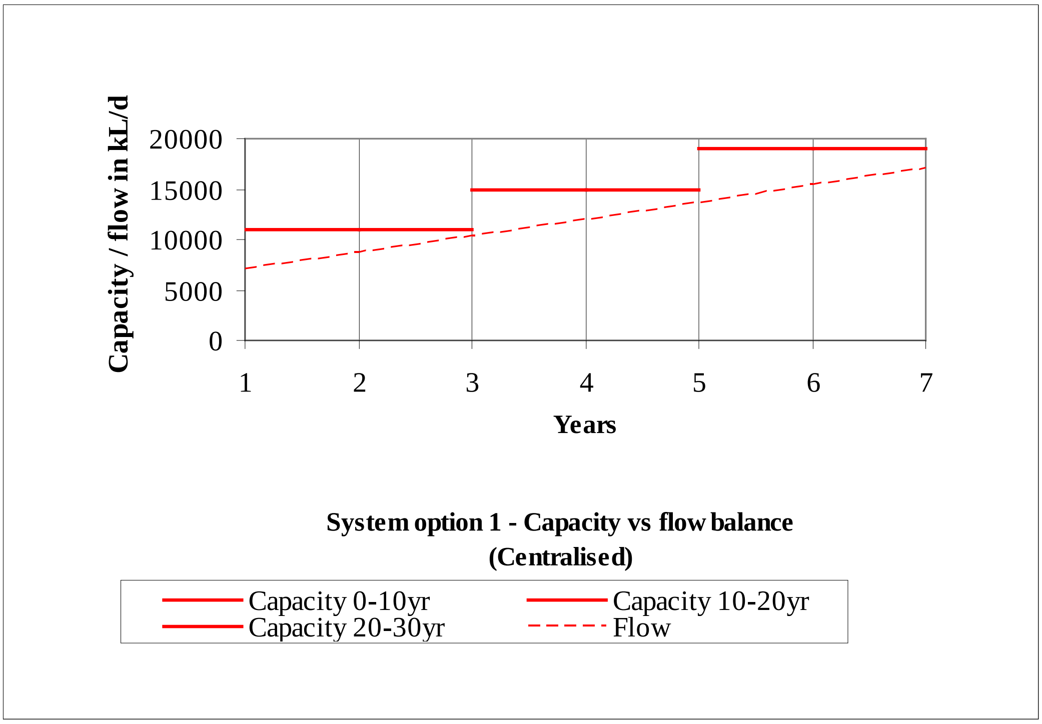


Figure 7.3 Treatment capacity/flow balance - System option 1 (fully centralised)

7.6 TREATMENT TECHNOLOGIES CONSIDERED IN CASE STUDY

The case study was based on sewered wastewater management with treatment options as follows:

- **Centralised sub-system treatment trains**

  Conventional treatment with biological nutrient removal (BNR) and sludge digestion and disposal inclusive of the following unit process:

  - Preliminary treatment (screening and grit removal);
  - Primary sedimentation;
  - Biological nutrient removal (BNR) inclusive of nitrification, denitrification and phosphate removal and final sedimentation;
  - Chlorination of final effluent;
  - Anaerobic digestion with dewatering of sludge for disposal.

- **Decentralised sub-system treatment trains**

  Membrane biological reactor and sludge digestion and disposal inclusive of the following unit processes:

  - Preliminary treatment (screening and grit removal);
  - Primary sedimentation;
  - Membrane biological reactor (MBR);
  - Chlorination of final effluent;
  - Anaerobic sludge digestion and dewatering of sludge for disposal.

MBR was opted for in the case of decentralised systems because of the high compactness of the process compared to conventional processes (footprint could be approximately 1/10th the size). Furthermore, MBR allows for higher biomass (MLSS) concentrations with a lesser quantities of sludge disposal needs ((Fane 1996). The methodology chosen for deriving life cycle system level wastewater management costs is discussed next.

7.7 WASTEWATER MANAGEMENT SYSTEM LEVEL COSTS

As revealed in the Rocky Mountain Institute (Rocky Mountain Institute 2004) research, the cost of collection networks in sewered systems is approximately 70 to 90% of the overall cost and is sufficiently high to impact the economic feasibility in system options. This emphasises the need of considering overall composite system cost (treatment and collection) in system level economic analyses. As a composite overall system cost is required the components must be compatible monetarily (being of common currency and base year) for their integration. The measures taken to achieve this in the thesis economic analysis is described in detail in section 6.4.

All costs determined for economic analyses are converted to a common 2010 year base for comparative purposes.

7.7.1 Internal costs and benefits

Cost estimation for any project should include projections of capital costs, annual operating and maintenance (O&M) costs and life cycle costs that enable the economic feasibility of various alternatives to be compared over a specific period of time.

Internal costs are made up of the sum of investment costs, operating and maintenance costs (labour, energy, chemical products and materials) and financial costs.

Apart from these capital and general O&M costs, the foregone (unavoidable) cost of having to provide upfront idle capacity with staged treatment capacity/flow balances need to be taken into account. This is of particular interest with centralised versus decentralised system option comparisons due to larger capacity and longer lead-time technology requirements normally been required for the former systems.

Internal benefits could also include the potential income of selling treated effluent and waste sludges for reuse.

7.7.2 External impacts

Any consequence of the treatment of wastewater (positive or negative, intentional or random) can be either quantitatively or qualitatively assessed. Possible externalities that according to AQUAREC (2006) could be considered in a water reuse project are listed in Table 7.2.

While some impacts have market related monetary units, certain external impacts do not have an explicit market value as corresponding markets do not exist. In these cases economic valuation methods are used, which are based on hypothetical scenarios or patterns observed in related markets.

For this case study contingent valuation by employing a production function (output distance function) approach was used to value avoided environmental pollution, public health protection and water resource conservation associated with sewered wastewater treatment.

Table 7.2 Identification and valuing of externalities (after AQUAREC 2006)

Groups	Externalities
Fresh water infrastructure	Avoids facilities for capture, storage and distribution costs of fresh water
	Avoids water purification costs
Reuse of constituents	Reuse of nutrients (nitrogen and phosphate) in agriculture
	Reuse of sludge in agriculture
	Reuse of thermal energy
Resource conservation	Increases quantity of water available
	Allows for supply augmentation in drought/shortage
	Water quality for various applications available
Public health protection	Water reuse biological risks
	Water reuse chemical risk
Environmental	Increase flow in rivers
	Avoid over-exploitation of natural water resources
	Avoids water pollution
	Allows protection of wetlands and river habitats
	Odour and noise pollution impact
	Property value impact
Social	Raising of social awareness

7.7.3 Treatment plant costs

Although methodologies for wastewater treatment cost estimation are numerous, these are not easily comparable or globally appropriate largely due to unknowns with regard to the assumptions made in their development (Joksimovic 2006, Adewumi 2010). The objective of achieving realistic and appropriate costs within the local South African context making use of the available tools presented quite a challenge and required specific measures which are described later in the study.

Costing tool selection

Application of two of the available decision making tools were considered for use for this study. The first is the South African developed *WaswarPlamo* software (Adewumi 2010) and the second the cost algorithms of Joksimovic (2006). The *WaswarPlamo* decision tool allows for economic assessment of treatment options for selected reuse applications. The software 1st introductory step assesses the potential of reuse based on input user data related to various possible applications. For this research cost estimation is required for actual flows to be treated as input which differ in principle with that used by the *WaswarPlamo* software. Due to this basic difference in input requirements its use for obtaining cost results was not further considered. However, as unit process removal efficiency is independent of input flow it was possible to make use of the *WaswarPlamo* software in determining treatment train final effluent quality. Although being of limited use in this case study for the reason mentioned, the software has the potential with varying input applications provided the input framework is adjusted to suite such inputs and this has been recommended to be explored with further research.

The algorithms developed by Joksimovic (2006) for treatment train costing, energy and land footprint determination were subsequently employed in the research using a spreadsheet approach (*Microsoft Exel)*. The methodology developed by the WRC (1981) was used to quantify sludge production. Details of both these algorithms mentioned are given in Appendix C2.

Cost estimation

The Joksimovic algorithms allow quantifying costs for various treatment train options both in terms of initial capital expense and retrofit/replacement thereof as well as the Electrical and Mechanical (EM) equipment cost components, operation and maintenance (O&M), land use footprint, energy requirements and sludge production volumes.

The methodology for deriving 2010 ZAR comparative costs employing the Joksimovic cost algorithms (in euro at base year 2006) consisted of the following:

1. Conversion of 2006 Euro costs to average June 2006 ZAR values by applying the 2006 foreign exchange rate (European Central Bank (ECB)).
2. Escalate the 2006 year base ZAR values to that for June 2010 by applying the South African Consumer Price indexes (CPI) (Statistics South Africa).

The mentioned foreign exchange and CPI escalation adjustments were made using the following equations:

$$Cost(2006\,ZAR) = Cost(2006\,Euro) \times Foreign\ \ Exc\,(Euro - ZAR)_{2006} \qquad (7.1)$$

$$Cost(2010\,ZAR) = Cost(2006\,ZAR) \times \frac{SA\,CPI_{2010}}{SA\,CPI_{2006}} \qquad (7.2)$$

where

Cost (2006 ZAR) = ZAR cost at base year 2006

Cost (2010 ZAR) = ZAR cost at base year 2010

Cost (2006 Euro) = Euro cost at base year 2006

Foreign Exchange (Euro-ZAR)$_{2006}$ = Average Foreign Exchange rate (Euro to ZAR) with base year 2006 (1 Euro = 8.2194 ZAR); (European Central Bank (ECB))

SA CPI 2006 = Average South African Consumer Price Index for 2006
= 57.41 (Statistics South Africa)

SA CPI 2010 = Average South African Consumer Price Index for 2010
= 117.1 (Statistics South Africa)

The cost of the land use footprint of the treatment facility was dealt with separately. The Joksimovic algorithms quantify the land use footprint required and the corresponding cost was determined based on a unit land value of the area concerned. For the Midvaal location the cost of unproclaimed land envisaged for the location of treatment facilities were ascertained to be about R150000 per hectare (Personal communication: Mr N de Klerk, Midvaal property appraiser, on 27 November 2011).

Allowance for sludge treatment and disposal O&M costs were based on unit annualised rates according to the United Nations-Economic and Social Commission for Western Asia (2003). As these costs are in 1998 US$, the following conversion to obtain 2010 ZAR costs were made:

$$Cost\,(1998\,ZAR) = Cost\,(1998\,US\$) \times Foreign\;\;Exc\,(US\$ - ZAR)_{1998} \qquad (7.3)$$

$$Cost\,(2010\,ZAR) = Cost\,(1998\,ZAR) \times \frac{SA\,CPI_{2010}}{SA\,CPI_{1998}} \qquad (7.4)$$

where

Cost (1998 ZAR) = ZAR cost at base year 1998

Cost (2010 ZAR) = ZAR cost at base year 2010

Cost (1998 US$) = US$ cost at base year 1998

*Foreign Ex (US$-ZAR)$_{1998}$* = Average foreign exchange rate (US$ to ZAR) with base year 1998 (1 US$ = 5.5315 ZAR) (X-rates.com).

SA CPI 1998 = South African Consumer Price Index –base year 1998
= 56.41 (Statistics South Africa).

SA CPI 2010 = South African Consumer Price Index –base year 2010
= 117.1 (Statistics South Africa).

7.7.4 Cost adjustment

In order to allow for varied unit cost related to capacity size, costs were adjusted in comparison to the prevailing 2010 South African capital treatment plant cost envelope. Based on cost data obtained from various consulting engineers in the South African water sector, this cost envelope varies between 8 to 12 million ZAR (IMQS, 2009/2010; personal communication: Mr L Naude, SSI Consulting Engineers, October 2011).

This adjustment was done using a linear approach with the highest cost factor being applied to the smallest staged capacity analysed (0.80 ML/d), and lowest cost factor being applied to the largest staged capacity (17.0 ML/d).

The cost envelope applied included the following treatment train and general cost allowances:

- Biological nutrient removal with sludge treatment and disposal (anaerobic digestion and dewatering).
- Engineering design and construction monitoring fees.

A further general item cost allowance of 25% was added to allow for site development costs and contingencies.

7.7.5 Collection network and costs

SA based cost estimates for the collection network were obtained from cost curves made available for the study by GLS Consulting Engineers derived for their projects in the Gauteng province of South Africa. These cost curves forms part of the IMQS data base compiled for the Midvaal municipality (IMQS 2009/2010). The cost curves reflect unit construction prices of gravity mains (including manholes), pump delivery (rising) mains and pump station as well as mechanical and electrical (ME) installations and are given in Appendix C3, Figures C3.1 to C3.3. A 25% adjustment was made to costs derived from the cost curves to allow for construction preliminary and general costs as well as design and construction monitoring fees.

O&M cost for the collection network was based on the expense budget of the Midvaal municipality made available for the study (Personal communication: Mr N Vermeulen, Midvaal Local Municipality: Director Engineering Services, October 2011). An extract from the municipal budget related to the sewer network is given in Appendix C10.

7.8 ECONOMIC MODELLING AT WASTEWATER MANAGEMENT SYSTEM LEVEL

The methodology for the economic analysis at system level is similar to that of the treatment plant level outlined in Chapter 6.2.

The output distance function approach (outlined in Chapter 5.10.3) and the *Matlab* model developed before (Chapter 6.5) were used for modelling the system level analysis. However, four model inputs (cost components) and six model outputs (treated effluent plus five different contaminants removed) were distinguished for the output distance function optimisation. Again model parameters were solved through an optimisation approach, but two scenarios with their related costing were considered here. The first scenario analysed the staged treatment plants only and the second scenario that of complete sewered wastewater systems (treatment plus collection networks). Shadow prices were derived for both treatment undesirable outputs (various contaminants removed) and the resulting equivalent combined environmental benefits obtained (based on an assumed observed market monetary price of 1 ZAR/m^3 for treated effluent).

7.8.1 Pollutant load removed

In the analysis maximum unit process efficiency and pollutant removal was assumed which are illustrated in Figure 7.4 for the two technology options considered in this research.

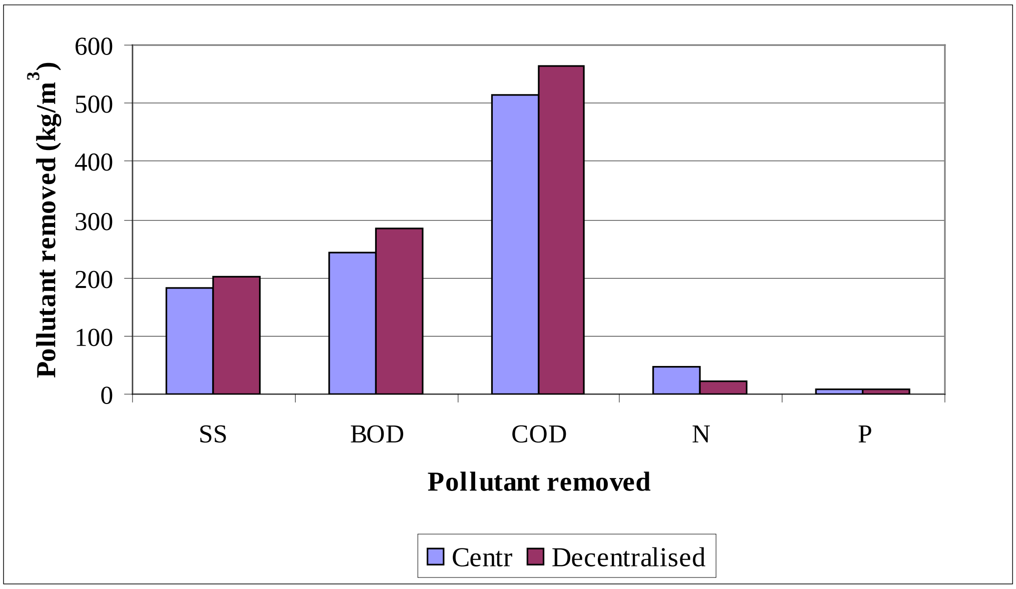


Figure 7.4 Pollutant removals by BNR (centralised) and MBR (decentralised) technologies considered in the study

7.8.2 Distance function and pollutant shadow prices

For every sub-system staged treatment capacity requirement the optimal output distance function parameters, output distance function values and shadow prices were determined using the Färe objective function and shadow price equations (Eqs 5.9 & 5.18). The composition of the translog objective function allows for any number of input cost components to be considered, but the extent thereof also determines the level of optimisation that can be achieved. With this study resources of actual cost was highly limited and analyses relied on mainly synthetic algorithm generated costs. The distance function values as shown in Appendix C6 (Tables C6.1 & C6.2) are mostly equal to unity (the optimisation objective) or very close to it. Considering the limitations of input cost data experienced, the extent of optimisation achieved here is considered sufficient for the planning level analysis done.

The contribution of pollutants to shadow prices for centralised and decentralised options is illustrated in Figure 7.5.

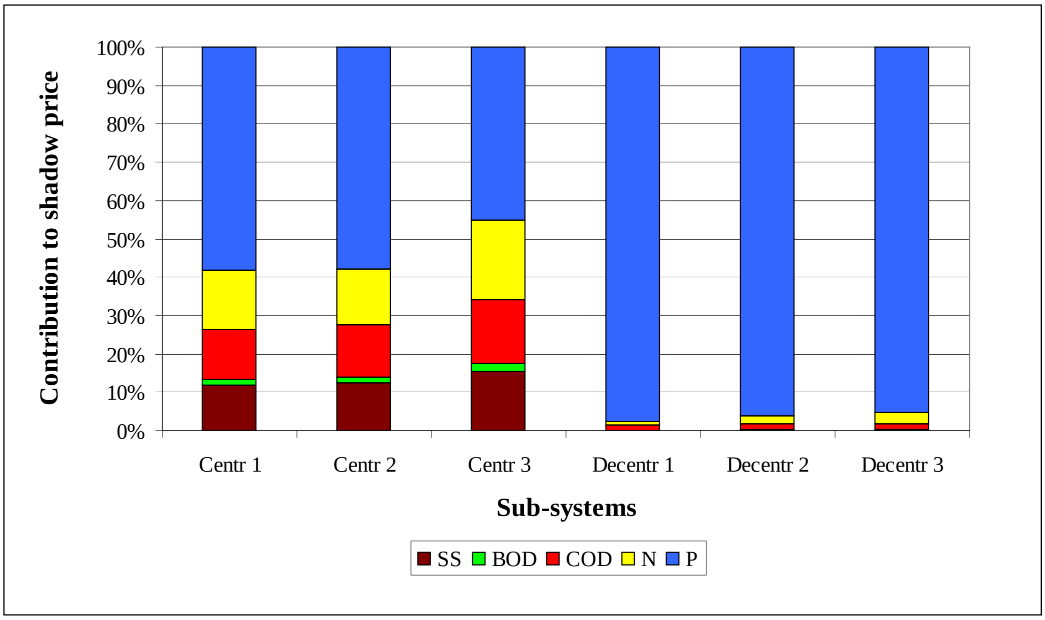


Figure 7.5 Contribution of pollutants to shadow prices for centralised and decentralised options at system level

The inverse trend between pollutant shadow price (ZAR/kg) and its load removed (kg/m^3) evident in Case Study 1, is also apparent from Figures 7.4 and 7.5, i.e. high pollutant shadow price corresponding to a low load removed and vice versa. In economic terms this amounts to a relative high marginal cost (shadow price) having to be incurred for removal of every additional unit of pollutant with low load removed and vice versa.

Furthermore the MBR technology inherent high sludge separation capabilities used in decentralised treatment compared to conventional BNR clarification is also evident in Figure 7.5.

7.8.3 Combined benefits of wastewater management

As highlighted in Case Study 1, the context here is also that of combining benefits (environmental, public health and water resource conservation). For each scenario mentioned before the combined benefits, referred to as environmental benefits (EB), was calculated using Eq (6.1). Due to the mitigation of negative impacts through avoided pollution, the negative shadow prices revert to positive values when the environmental benefits (EBs) are determined (Färe *et al*. 1993).

The combined EB values for staged capacities are given in Appendix C6, Tables C6.1 & C6.2. These EB values are based on a unity treated effluent value of 1 ZAR/m^3 as is the case with shadow prices. As established before in Case Study 1, the pollutant with lowest load removed (kg/m^3) has the highest shadow price (ZAR/kg), and vice versa.

7.9 ECONOMIC ANALYSIS

Comparing non-uniform series of expense for alternative solutions (capital and annual cost items) along a particular time line requires a mechanism of equivalence to be employed. In this study the Present Value (PV) and Equivalent Uniform Annual Cost (EUAC) principles of cost timeline discounting were used as basis of economic comparison of alternative system options.

For economic feasibility the benefits obtained by the wastewater system need to be accounted for and the basic objective is to maximise net benefits, which, in economic terms is the difference between income (benefits) and costs. This result must reflect a positive value for a project to be feasible. When calculating total benefit, it is worth including not only internal benefits, but also those from externalities and opportunity cost.

7.9.1 Methodology for determining system option PV and EUAC's for staged treatment capacity provision

The approach used for economic accounting of staged capacity/flow balance over the 30 year cash flow timeline considered is illustrated in Figure 7.6 (e.g. 10 year staged capacity/flow balance). Only differences in staged costs of providing increased capacity have to be taken into account along the cash flow time line.

All costs (both treatment facility and collector networks) and benefits of the different staged capacity/flow balances are expressed in terms of present value (PV).

Increase in services (both treatment capacity and collection networks) and related benefits are represented by the increase in PV at the point of its introduction along the cash flow time line. Each staged PV is then subsequently discounted to a present value using the appropriate present worth factor.

As illustrated in Figure 7.6, the net sub-system PV is determined by summation of the individual discounted staged PV's. The corresponding sub-system EUAC value (or annualised value) is obtained by multiplication of the net discounted PV with the appropriate uniform series present value factor.

The discounted PV and EUAC's (or annualised values) for the various sub-systems are given in Appendix C5, Tables C5.1 to C5.6.

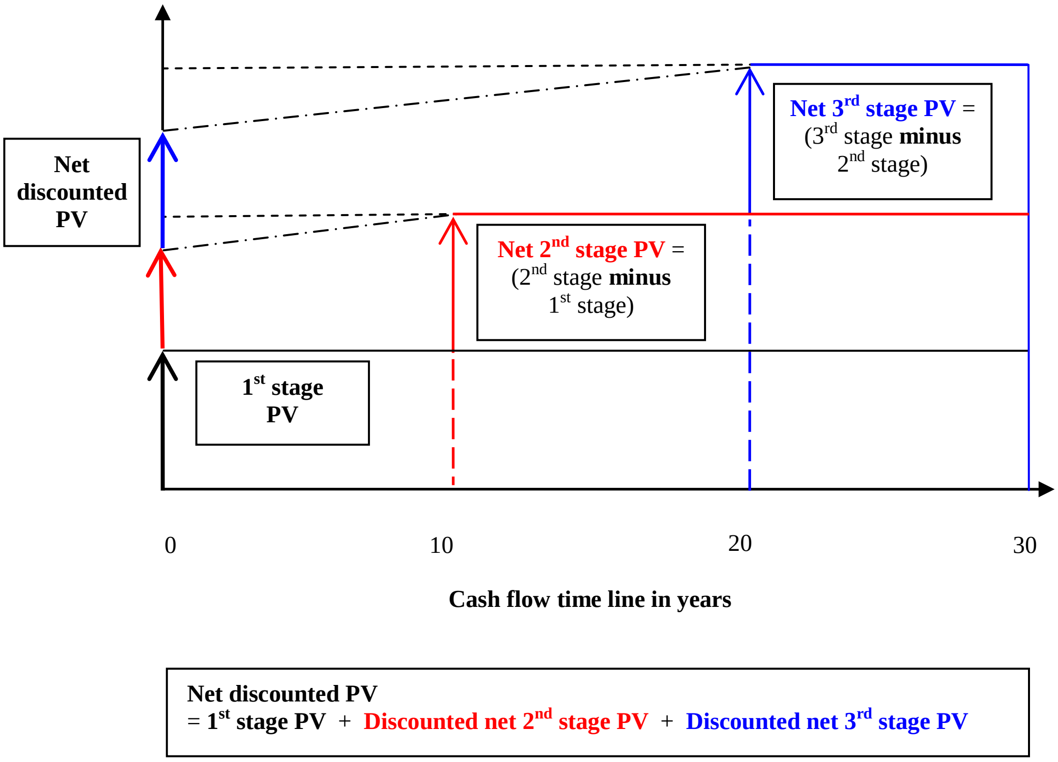


Figure 7.6 Economic accounting of staged PV's along cash flow time line

7.9.2 Economic analysis rate of return

For time line cost discounting the rate of return had to be equivalent to the basic cost of money to governmental institutions and public utility companies. The SA Reserve Bank repurchase rate (Repo rate), being the rate at which the private sector banks borrow from the reserve bank, was taken as indicator of rate of return for public type projects such as wastewater management. The Repo rate has steadily declined from 7% pa since beginning 2010 to 5.4% pa early 2011 (South African Reserve Bank). As current monetary policy tend to be anti-inflationary with a lower Repo rate level, an average value of about 6% pa for the economic analyses was considered reasonable for a basic planning study undertaken here.

7.9.3 Annualised treatment facility and collector network costs

A summary of discounted annualised costs for the various sub-system option components (treatment and collection networks) are given in Tables 7.3 and 7.4 respectively.

The overall system level annualised costs (treatment **plus** collection) are given in Table 7.5.

Table 7.3 Annualised system option treatment facility costs

System and sub-systems	**Description**	**Annualised treatment costs over analysis period in ZAR/year** (Unit annualised cost in ZAR/kL)				
		Capital	O&M	Retrofit and EM	Energy	Total
System 1	System level	-	-	-	-	**31,869,786**
	Centralised	11,600,505	761,406	18,553,726	954,150	31,869,786
		(2.07)	(0.14)	(3.32)	(0.17)	(5.69)
System 2	System level	-	-	-	-	**34,531,360**
2.1	Decentralised	1,257,228	280,635	2,897,968	174,209	4,610,040
		(2.42)	(0.54)	(5.57)	(0.33)	(8.86)
2.2	Centralised	10,220,388	697,327	18,144,015	859,589	29,921,319
		(2.00)	(0.14)	(3.55)	(0.17)	(5.86)
System 3	System level	-	-	-	-	**38,772,218**
3.1 (= 2.1)	Decentralised	-	-	-	-	-
3.2	Decentralised	3,736,977	715,416	6,538,835	544,403	11,535,630
		(2.24)	(0.43)	(3.92)	(0.33)	(6.92)
3.3	Centralised	8,379,309	590,101	13,052,559	13,052,559	22,626,549
		(2.38)	(0.17)	(3.71)	(0.17)	(6.42)
System 4	System level	-	-	-	-	**37,104,874**
4.1	Decentralised	4,839,671	896,918	8,019,033	722,704	14,478,326
		(2.21)	(0.41)	(3.67)	(0.33)	(6.62)
4.2 (= 3.3)	Centralised	-	-	-	-	-

Note:
1. See system option description (Section 2)
2. EM = Electrical & mechanical equipment

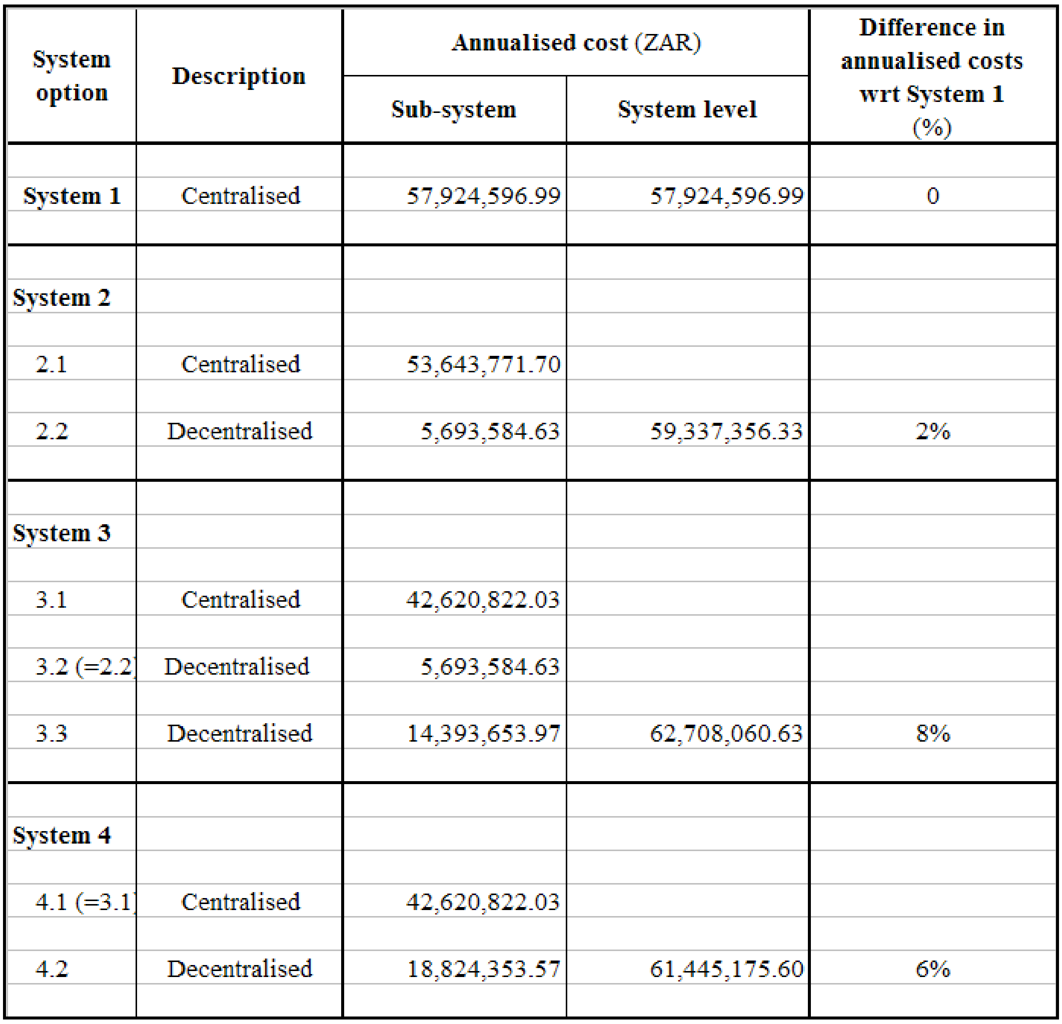
Table 7.4 Annualised system option collection network costs

System and sub-systems	**Description**	**Annualised collection costs over analysis period in ZAR/year** (Unit annualised cost in ZAR/kL)				
		Capital	O&M	Retrofit and EM	Energy	Total
System 1	System level	-	-	-	-	**26,054,811**
	Centralised	19,988,294	86,174	5,419,182	561,160	26,054,811
		(3.57)	(0.02)	(0.97)	(0.10)	(4.66)
System 2	System level	-	-	-	-	**24,805,997**
2.1	Decentralised	942,256	3,569	133,658	4,062	1,083,545
		(1.81)	(0.01)	(0.26)	(0.01)	(2.08)
2.2	Centralised	18,328,320	76,821	4,827,409	489,903	23,722,452
		(3.59	(0.02)	(0.95)	(0.10)	(4.65)
System 3	System level	-	-	-	-	**23,935,842**
3.1 (= 2.1)	Decentralised	-	-	-	-	-
3.2	Decentralised	2,479,880	10,331	364,864	2,949	2,858,024
		(1.49)	(0.01)	(0.22)	(0.002)	(1.71)
3.3	Centralised	16,042,377	57,960	3,567,447	326,490	19,994,273
		(4.55)	(0.02)	(1.01)	(0.09)	(5.68)
System 4	System level	-	-	-	-	**24,340,301**
4.1	Decentralised	3,684,933	17,648	618,655	24,792	4,346,028
		(1.68)	(0.01)	(0.28)	(0.01)	(1.99)
4.2 (= 3.3)	Centralised	-	-	-	-	-

Note:

1. See system option description (Section 2)
2. EM = Electrical & mechanical equipment

Table 7.5 Overall system level option annualised costs



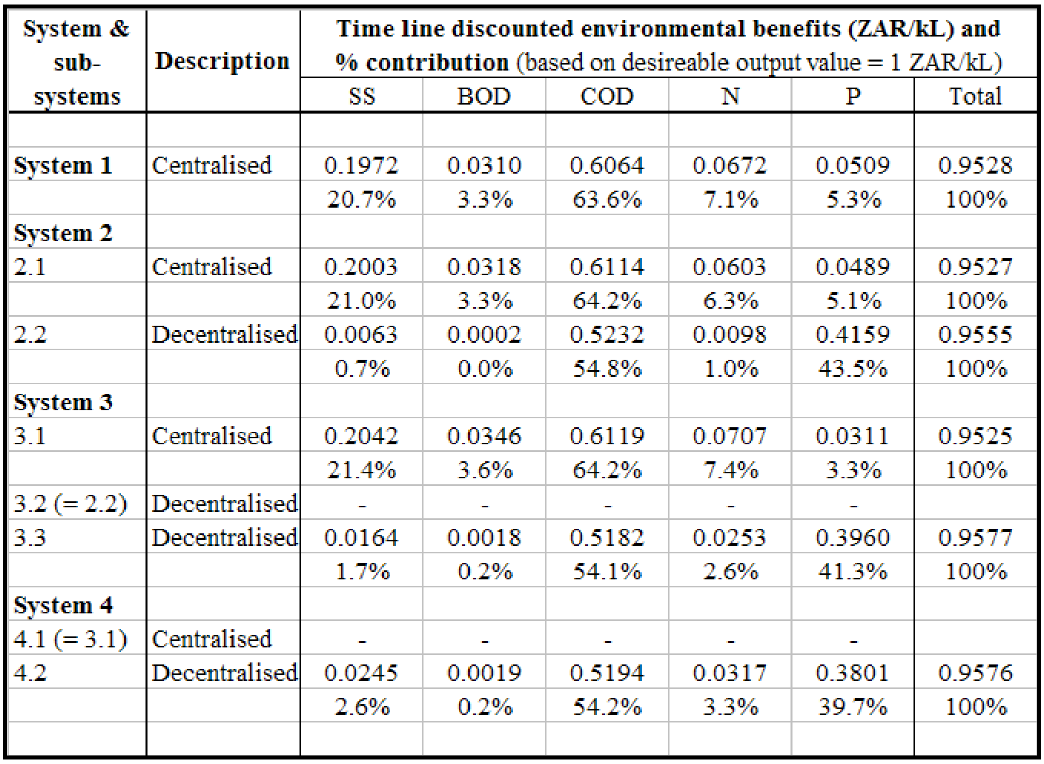
System option	Description	Annualised cost (ZAR)		Difference in annualised costs wrt System 1 (%)
		Sub-system	System level	
System 1	Centralised	57,924,596.99	57,924,596.99	0
System 2				
2.1	Centralised	53,643,771.70		
2.2	Decentralised	5,693,584.63	59,337,356.33	2%
System 3				
3.1	Centralised	42,620,822.03		
3.2 (=2.2	Decentralised	5,693,584.63		
3.3	Decentralised	14,393,653.97	62,708,060.63	8%
System 4				
4.1 (=3.1	Centralised	42,620,822.03		
4.2	Decentralised	18,824,353.57	61,445,175.60	6%

7.9.4 Discounted combined benefits

Since combined benefits are aligned with treatment capacity provision, the methodology for its present value discounting is similar to that of life cycle costs illustrated in Figure 7.6.

A summary of the discounted benefits (with assumed desirable output value of 1 ZAR/m^3) for the various system options and accompanying sub-systems are given in Tables 7.6.

Table 7.6 Discounted combined benefit values for system and sub-systems



System & sub-systems	Description	Time line discounted environmental benefits (ZAR/kL) and % contribution (based on desireable output value = 1 ZAR/kL)					
		SS	BOD	COD	N	P	Total
System 1	Centralised	0.1972	0.0310	0.6064	0.0672	0.0509	0.9528
		20.7%	3.3%	63.6%	7.1%	5.3%	100%
System 2							
2.1	Centralised	0.2003	0.0318	0.6114	0.0603	0.0489	0.9527
		21.0%	3.3%	64.2%	6.3%	5.1%	100%
2.2	Decentralised	0.0063	0.0002	0.5232	0.0098	0.4159	0.9555
		0.7%	0.0%	54.8%	1.0%	43.5%	100%
System 3							
3.1	Centralised	0.2042	0.0346	0.6119	0.0707	0.0311	0.9525
		21.4%	3.6%	64.2%	7.4%	3.3%	100%
3.2 (= 2.2)	Decentralised	-	-	-	-	-	
3.3	Decentralised	0.0164	0.0018	0.5182	0.0253	0.3960	0.9577
		1.7%	0.2%	54.1%	2.6%	41.3%	100%
System 4							
4.1 (= 3.1)	Centralised	-	-	-	-	-	
4.2	Decentralised	0.0245	0.0019	0.5194	0.0317	0.3801	0.9576
		2.6%	0.2%	54.2%	3.3%	39.7%	100%

7.9.5 Idle treatment capacity

Idle treatment capacity being provided upfront to accommodate increased flow over time has financial implications. The extent of forfeited treatment capacity for the various system options due to staged flow balances are given in Table 7.7.

Table 7.7 Staged idle treatment capacity

Sub-systems	**Idle treatment capacity of system options** (kL/d)			
	1	**2**	**3**	**4**
1.1 Centralised	3000	-	-	-
Total	**3000**			
2.1 Decentralised	-	143	-	-
2.2 Centralised		2550	-	-
Total	-	**2693**		
3.1 Decentralised	-	-	143	-
3.2 Decentralised	-	-	700	-
3.3 Centralised	-	-	1950	-
Total			**2793**	
4.1 Decentralised	-	-	-	1050
4.2 Centralised	-	-	-	1950
Total				**3000**

7.10 BREAKEVEN ECONOMIC ANALYSIS OF SYSTEM LEVEL OPTIONS

For economic viability the net benefits (total benefits less total costs) must be non-negative. The approach for calculating the minimum required fresh water rate ($FWR_{REQ}^{Environ+Reuse}$) for economic viability taking into account combined environmental benefits under varying reclamation or reuse levels is similar to that used in Case Study 1. (see Chapter 6.8).

However, with a long term period of analysis (30 years in this case) possible escalation in the fresh water tariff needs to be considered. Different escalation rates for the fresh water tariff were accounted for over the economic analysis period, being 6, 8 and 10% pa. The impact of these different tariff escalations for both treatment plant and system levels on reuse feasibility (at a 100% reuse level) are given in Figure 7.7.

The calculations for the above as well that of other reuse levels are given in Appendixes C7 (Tables C7.1 to C7.4) and C8 (Tables 8.1 to C8.4).

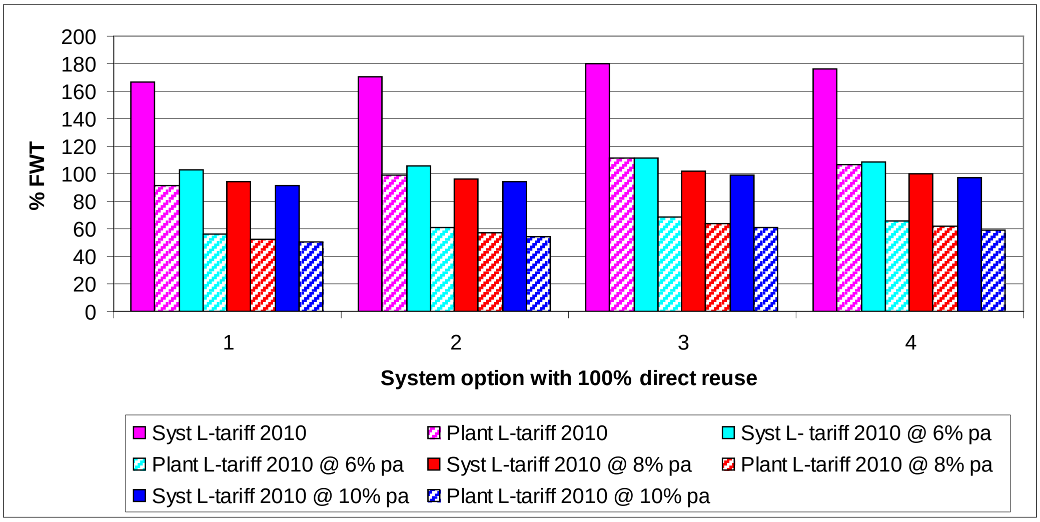


Figure 7.7 Impact of fresh water tariff escalation on system level economic breakeven reuse feasibility (for 100% effluent reuse)

7.11 MULTI-CRITERIA ANALYSIS

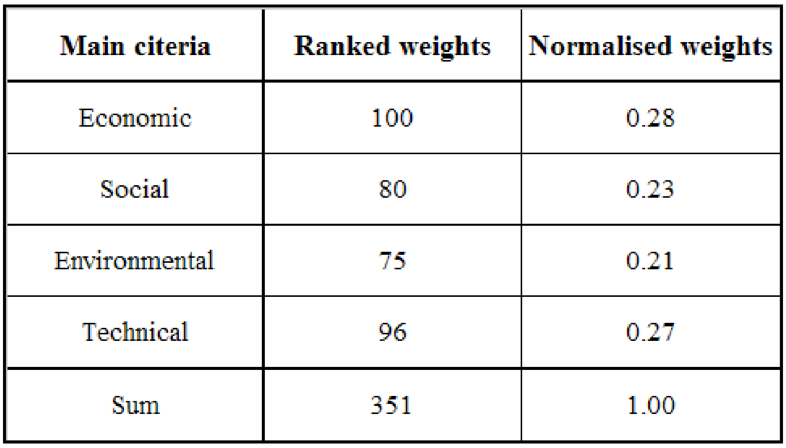
As introduced in Chapter 5, multi-criteria analyses (MCA) allow a holistic sustainable comparison of system options, taking apart from economic criteria, other aspects difficult to estimate in monetary terms such as technical, environmental and social related aspects into consideration.

For this case study a hypothetical test MCA was done based on the mostly synthetic data obtained from the economic analysis with assumed criteria weightings due to the absence of real stakeholder survey data. The assumptions made are described in the methodology used.

Criteria within four main categories of technical, economic, environmental and social were considered in this multi-criteria analysis. The selection and description of the main and sub-criteria are given in Chapter 5.17.3.

Traditionally wastewater management was viewed primarily as a technical and economic issue. However, the new paradigm and awareness of the importance of integration of environmental and social needs require that these issues with an array of other criteria to be considered in sustainability analyses.

Table 7.8 Main criteria category weightings assumed for Case Study 2



Main citeria	Ranked weights	Normalised weights
Economic	100	0.28
Social	80	0.23
Environmental	75	0.21
Technical	96	0.27
Sum	351	1.00

For the case study hypothetical MCA a ratio of the combined normalised weighting of economic and technical criteria categories in relation to that of environmental and social categories of approximately 55/45 was assumed (Table 7.8), compared to a nominal 80/20 likely to be used with a historical conventional approach. This alignment of MCA criteria in accordance with the new paradigm mentioned was considered appropriate for the South African context, taking into consideration the extent of environmental related legislation adoption and implemented to date. According to Marjanovic *et al.* (2011), South Africa's National Water Act and policy documents such as the National Water Resource Strategy are examples of policies that reflect integrated systems thinking with sustainability and equity principles firmly embedded.

Table 7.9 reflects main and sub criteria for the economics category as reference. In this instance the 1st step assumption for planning purposes was an equal contribution of life cycle costs and returns to scale for the economics category. This was based on the view that both contribute significantly as long-term economic baseline factors for feasibility assessment (Chapter 5.14.6 & 5.19). Assessment score sheets of the other MCA categories (technical, social and environmental) are given in Appendix C9, Tables C9.1 to C9.3.

Table 7.9 Main and sub-criteria for economics category

Category	Main criteria	Sub criteria	Ranking	Normalised category weight coefficients (%)	Overall Individual weight coefficients (%)
Economics	**Life cycle costs**	Capital			
		Operation & Maintenance			
		Retrofit & EM			
		Energy			
		Present Value (PV)			
		Idle capacity value			
	Financial risk exposure				
	Returns to scale				
	Willingness to pay				
	Affordability				
	Column sum				

7.11.1 System level MCA methodology

The decision making methodology at wastewater management system level is outlined in Chapter 5.15 and illustrated in Figure 5.14. Due to the hypothetical assumptions already discussed, the next step within the methodology is focused on further, referred to as “Criteria indicator scoring”.

This sub-routine is set out in Figure 7.8 and briefly described next.

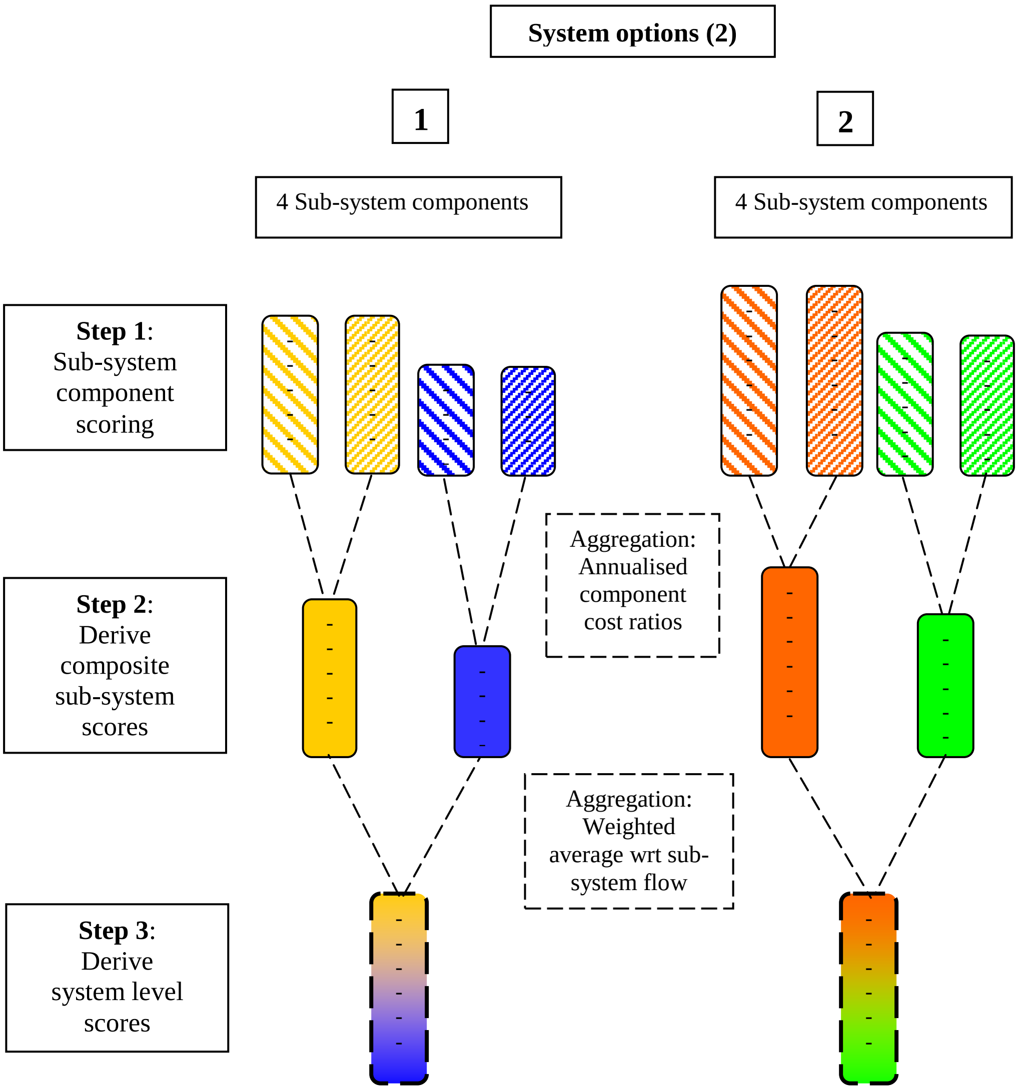


Figure 7.8 Procedure for deriving system level aggregate scores with MCA

Step 1 – Conventional scoring of criteria indicators for treatment technology and collector network options

Indicator scoring is done individually for each treatment technology option and its corresponding collector network. Due to varied extent and cost of collector networks within a centralised/ decentralised system scale, distinction of components for indicator scoring is essential. The results of sub-system treatment and collection component aggregate scores are given in Table 7.10 and illustrated in Figures 7.9a & b and 7.10a & b respectively.

Table 7.10 Sub-systems treatment and collection aggregate scores and ranking

Description	Treatment sub-systems scores [Ranking]			Collection sub-systems scores [Ranking]		
	1	**2**	**3**	**1**	**2**	**3**
Centralised	721 **[2]**	723 **[1]**	709.9 **[3]**	596.1 **[4]**	583.8 **[5]**	580.2 **[60]**
Decentralised	604.4 **[6]**	615.9 **[5]**	627.8 **[4]**	706.5 **[3]**	710.8 **[1]**	707 **[2]**

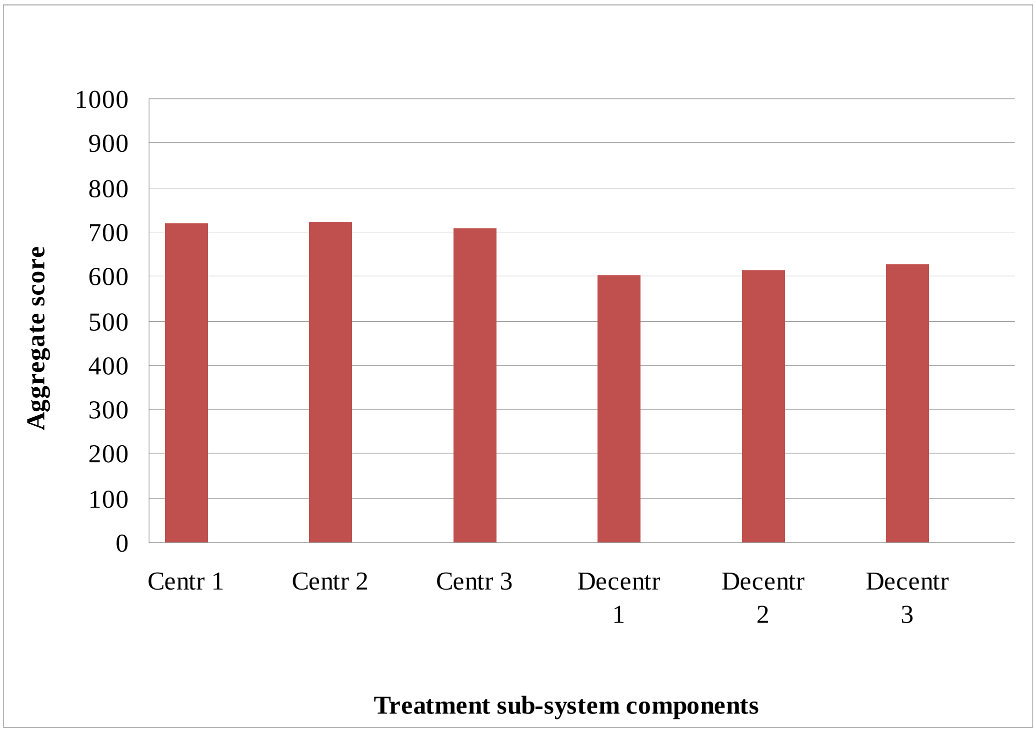


Figure 7.9a Treatment sub-system option aggregate scores

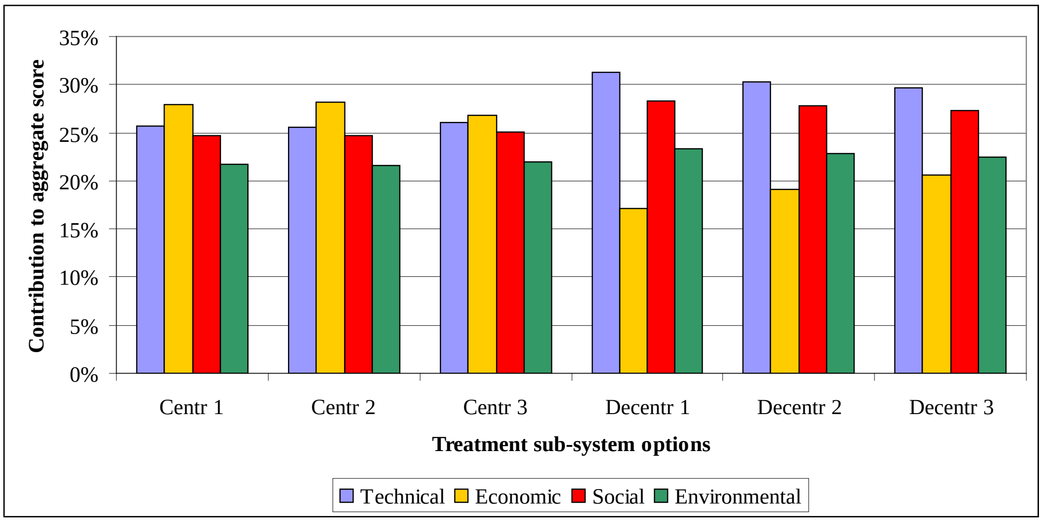


Figure 7.9b Treatment sub-system main criteria contributions to aggregate scores

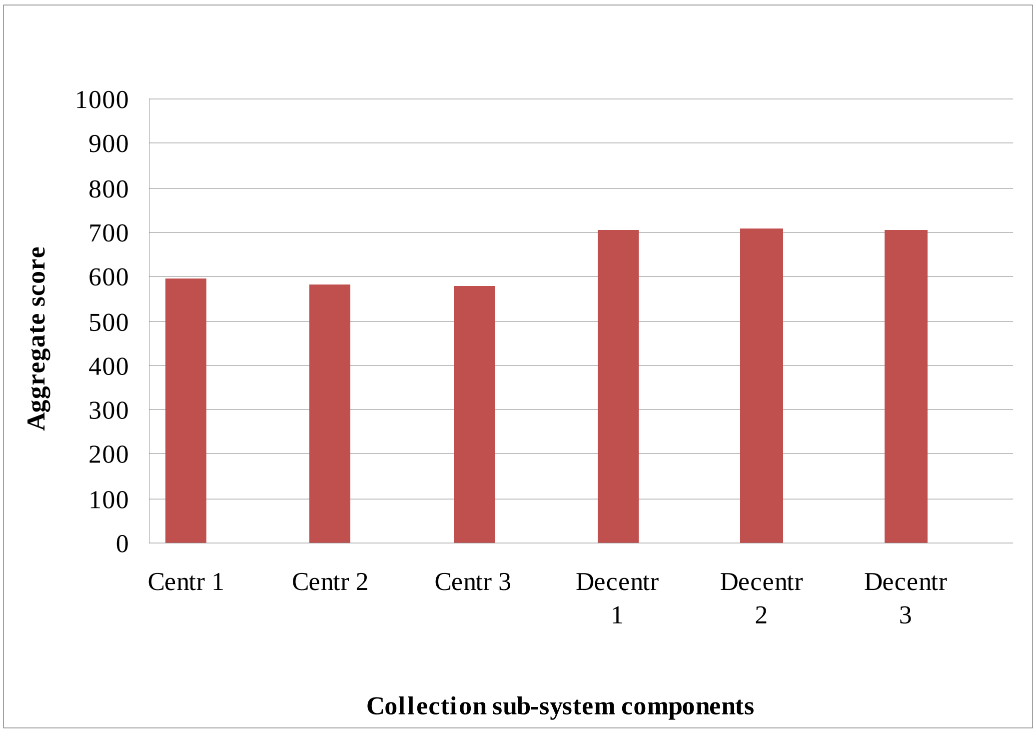


Figure 7.10a Collection sub-system option aggregate scores

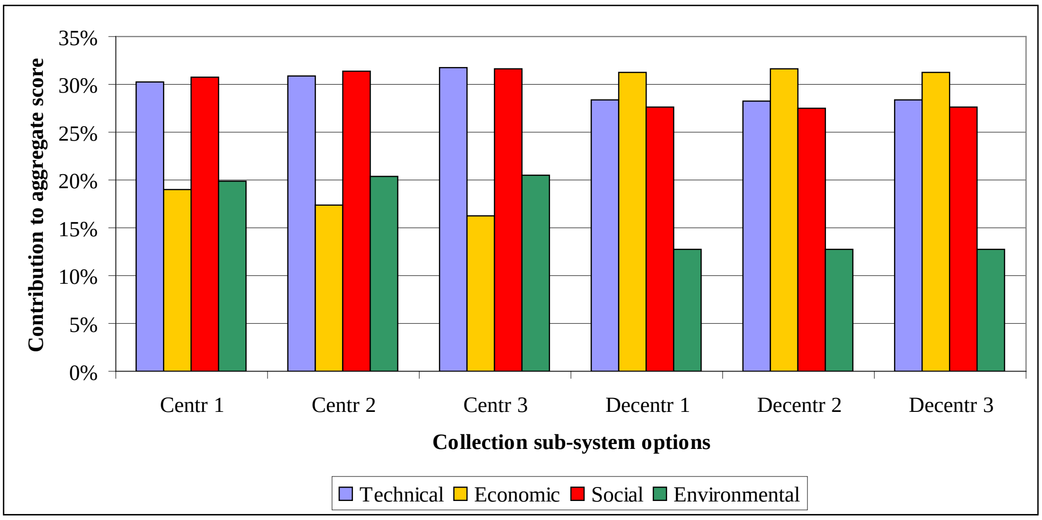


Figure 7.10b Collection sub-system main criteria contribution to aggregate scores

Step 2 – Deriving composite aggregate scores for possible sewered sub-system options

A sub-system within a sewered system context is a combination of a treatment technology and its associated collection network. Under conditions of varied system scale and multiple treatment technologies being considered, multiple sub-systems may be possible.

A composite score for each sewered sub-system option (a particular technology combined with its associated collection component) would therefore have to be obtained. Annualised cost being a measure of monetary equivalence is considered most appropriate for this purpose. The metric employed for combining the sub-system components is the treatment/collection annualised cost ratio. These ratios together with the system level component annualised costs are given in Table 7.11. Although the annualised cost ratios of the four system options considered vary from 1.22 to 1.52, an envelope analysis ratio of 1.20 to 1.65 (with intermittent values of 1.20, 1.45 and 1.65) were employed in the aggregation exercise.

Table 7.11 System level annualised treatment/collection cost ratios derived with the economic analysis

Item	System options			
	1	2	3	4
Annualised cost (ZAR):				
Treatment	31,869,786	34,531,360	38,772,218	37,104,874
Collection	26,054,811	24,805,997	23,935,842	24,340,301
Annualised treatment/ collection cost ratios	1.223	1.392	1.619	1.524

Step 3 – Deriving system level scores

The number and description of sub-systems considered in this study is outlined in section 2. As the same service area applies to each system level option, total wastewater flow is common to all. System level aggregate scores were derived by weighted averages of contributing sub-systems wrt wastewater flow throughput.

The case study system option total scores and their ranking for the three annualised treatment/collection cost ratios considered are given in Table 7.12 and illustrated in Figure 7.11.

Step 4 – Index for sustainability

The overall MCA results for both technology and system levels can be expressed as percentages of the highest possible aggregate scores. Tables 7.10 and 7.12 shows scores obtained for the various sub-system components (treatment **and** collection) and sub-systems (treatment **plus** collection). By expressing the particular aggregate scores as percentages of the highest possible aggregate score, a measure of the sustainability and their comparison with specified levels of acceptance can be evaluated. As the highest possible aggregate score is 1000, sustainability level for treatment and collection components, sewered sub-systems and system level options can be derived from scores given in Table 7.10 (Figures 7.9a & 7.10a) and Table 7.12 (Figure 7.11) respectively.

Table 7.12 Aggregate scores and ranking of case study system level options for three annualised treatment/collection cost ratios

Annualised Treatment/Collection cost ratio	**System level options aggregate scores** **[Ranking]** (% difference wrt option ranked 1)			
	Option 1 (Fully centralised)	**Option 2** (1× S_decentralised + rem centralised)	**Option 3** (2× S_decentralised + rem centralised)	**Option 4** (1× L_decentralised + rem centralised)
1.20	600.92 **[1]** (0)	596.56 **[2]** (-0.73%)	593.84 **[4]** (-1.18%)	596.34 **[3]** (-1,09%)
1.45	606.71 **[1]** (0)	602.04 **[2]** (-0.77%)	598.76 **[3]** (-1.31%)	595.96 **[4]** (-1.77%)
1.65	610.56 **[1]** (0)	605.68 **[2]** (-0.80%)	600.37 **[3]** (-1.67%)	597.37 **[4]** (-2.16%)

Note: 1 × S_decentralised = single small decentralised zone
2 × S_decentralised = two small decentralised zones
1 × L_decentralised = single large decentralised zone

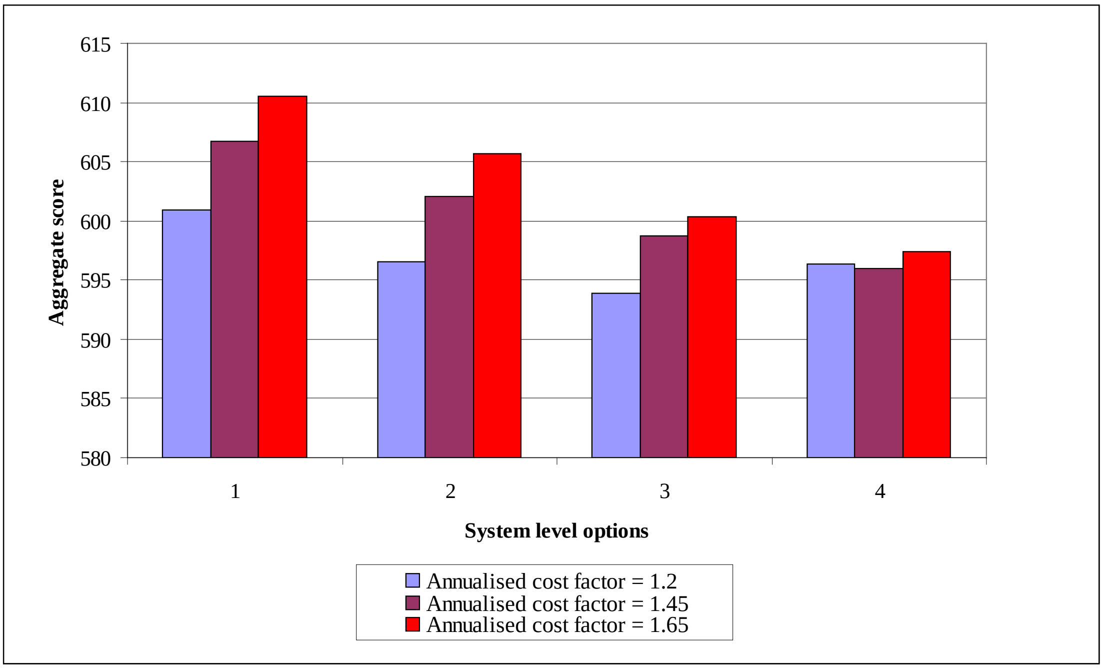


Figure 7.11 System level options aggregate scores

7.12 CONCLUSIONS

The first part of section 12 covers the economic analysis only, while the second part considers the MCA done.

7.12.1 Economic related aspects

The annualised costs of the four system level options considered are given in Table 7.5. It is evident that the fully centralised system option (option 1) has the lowest EUAC's (and PV's). The second lowest is option 2 (single smaller decentralised zone and the remainder of the centralised zone), followed by option 4 (large single decentralised zone with remainder of the centralised zone) and finally option 3 (two separate smaller decentralised zones with the remainder of the centralised zone). The increase in EUAC's (and PV's also) of the mentioned system options (compared to that of the fully centralised system option) is **2, 6 and 8%** respectively.

Although the economic analysis indicates the fully centralised option as being most favourable, the difference in costs between it and the other mixed scale system options (centralised combined with decentralised) has to be seen in proper perspective. Considering that all costs derived for the economic analysis allows for approximately a 15% contingency, relative economic differences here are marginal and it can be concluded that in an economic sense the different options are virtually equal.

Another important result from the economic analysis is the contribution of the collection network component to overall sewered system costs. The literature points out that this cost contribution is significant and up to between 70 to 90% (Rocky Mountain Institute 2004). The contribution of about 61 to 63% for the centralised sub-systems in the case study compares well with that mentioned in the literature. For the three decentralised zones the collector network cost contribution varies between 35 to 41 % which is substantially less than that for fully or partially centralised zones. Collector network increased returns to scale (economy of scale) of smaller decentralised systems is evident in this study and correspond with the finding in literature (RMI 2004).

The marginal differences between system options in the economic analysis emphasises the need for an MCA to explore feasibility of alternatives over a wider range of issues than economics as such, taking into account also those aspects not readily monetised in the technical, social and environmental domains.

The following conclusions can be drawn from the economic breakeven viability analysis for 100% reuse levels illustrated in Figure 7.7:

1. Should treatment cost be considered only, generally all system options require a reuse tariff less or equal to the FWT_{2010} (50 to 100%), except with option 3 where the FWT is exceeded (110%) for breakeven feasibility. When escalation of the FWT is considered (6 to 10% pa) the required breakeven reuse tariff reduces significantly to about 50 to 70%. This last comparison is the more appropriate due to the longer term view of FWT's being a economic sound approach for wastewater management.
2. With a system level consideration the picture however is completely different. Based on the current FWT_{2010} all options require a reuse tariff far in excess of a 100% full FWT (170 to 180%) for feasibility. The picture improves should the longer term projected escalated FWT be considered. For a FWT escalated at 6% pa all system options are close to the full escalated FWT (100 to 110%), while at 8 and 10% the required reuse tariff decreases to about 90 to 100% of FWT. It is interesting to note that the lowest breakeven reuse tariff applies to the options with larger centralised scale being attributed to economy of scale effects. Furthermore, the optimal system level breakeven feasibility is achieved at approximately an 8% pa escalation in FWT.

As with Case Study 1, the minimum value derived for treated effluent (compared to the current fresh water tariff) should serve as a benchmark indicator value for achieving economic viability for a particular system scenario. However, the benchmark value needs to be adjusted for any distribution costs of treated effluent to potential consumers. Should an integrated approach for costing be followed with distribution as part of the reuse system, the additional distribution costs will contribute towards an increased total cost of water reclamation and reuse. With this inclusive higher system input cost (collection, treatment and distribution) as a basis and similar pollutant removal load, shadow prices are expected to decrease due to a relative decline in facility/system economic efficiency. For economic breakeven viability, the likely reduction in shadow prices will require higher treated effluent tariffs and reuse levels compared to those excluding such distribution costs.

In this study the extent of upfront staged treatment capacity in excess of flow throughput (idle foregone capacity) for the various system options are given in Table 7.7. It is evident that smaller idle capacities are possible with decentralised sub-systems due to closer matching of flow and shorter staged periods compared to the centralised generally longer lead-time technology requirements. However, at system level the accumulative difference is a maximum of approximately 10% compared to that of the option with the highest idle capacity and not of great significance.

Provision of idle capacity and corresponding increased system/facility input costs, also has a negative impact on treatment plant efficiency with regard to expected lower levels of pollutant load removal efficiency. At best, even if a similar pollutant removal was possible, the higher costs inputs are expected to result in lower shadow prices and likely to have a similar economic impact as distribution costs mentioned before.

It would be more prudent to ensure that such idle treatment capacity be of the smallest practically possible increments in order to, not only avoid large additional expense and corresponding financial burden (high tariffs for capital expenditure together with financing cost of such expenditure) but also the negative impact on process efficiency and lower plant economic viability. Apart from alleviating under-capacity problems as such, flexible smaller scale phased capacity provision achieves improved financial benefits due to avoided expense towards large underutilised over-built capacity. All of this is suggesting that a move towards decentralised systems would be advantageous economically.

It is evident from the discussion that decentralised wastewater systems, as opposed to centralised ones, would present positive advantages in regard to some of the aspects mentioned. The generally closer location of decentralised wastewater systems to waste source as well as potential users of treated effluent would contribute to reducing distribution and associated costs. In addition, such systems being of smaller scale result in better amenability for smaller increments of treatment capacity. Furthermore, it also contributes to improved plant economy as discussed previously and a more competitive tariff of treated effluent for reuse or reclamation.

However, decentralised system may have a disadvantage in the case of large volume users such as industries and large landscape irrigational use, since extensive distribution systems from a large number of source points are needed to make the required volume available. As large volume use may be the most cost efficient applications of reuse, careful consideration need be given to the distribution cost component in finding an optimal management system.

Apart from the system related economic aspects mentioned, another aspect that will greatly affect and ultimately determine the value of treated effluent is obviously the market supply-demand forces.

7.12.2 MCA related aspects

From the treatment and collection sub-system aggregate scores and ranking obtained the following conclusions can be reached:

Treatment scores of all three centralised sub-system options are higher than that of the three decentralised ones. This is mainly due to the impact of economic related indicators being consistently higher for centralised sub-systems (improved treatment economy of scale wrt decentralised) and overshadows high values of decentralised sub-systems for technical, social and environmental indicators. In a treatment sense centralised sub-systems are therefore ranked higher than the decentralised ones.

Collection scores of all three decentralised sub-system options are higher than those of the three centralised ones. This is again mainly due to the impact of economic related indicators being consistently higher in the case of decentralised sub-systems (lower collection diseconomy of scale wrt centralised) exceeding high technical and social scores of centralised sub-systems.

The above comments also apply to relative sustainability levels, i.e. centralised treatment is more sustainable than decentralised and decentralised collection is more sustainable than centralised.

From Figure 7.9 it is evident that the MCA ranking of system level options for the three annualised treatment/collection cost ratios is different with increased cost ratio.

For an annualised cost factor of 1.2, option 1 is ranked highest followed by option 2, option 4 and then option 3. When the annualised cost factor is 1.45 the ranking of options 3 and 4 switched places. This ranking then remained for an increased annualised cost factor of 1.65.

Considering the mixed system scales for the lowest annualised cost factor scenario (equals 1.2), single oppose to multiple decentralised zones appear to be more advantageous for the particular locality studied. Here option 2 and 4 (both consisting of single small and large decentralised zones respectively) have preferential ranking to that of option 3 (multiple smaller decentralised zones). For the annualised cost factor scenarios of 1.45 and 1.65 the preferential mixed system scale is different.

It can thus be concluded that an optimum system scale do exist for a particular service area and that pure systems per say is not necessarily the most sustainable management solution. Also for urban development fully centralised systems do not necessarily provide the most sustainable solution for wastewater management.

The average percentage difference from option ranked 1 to 4 is only approximately 1.8% (taken at annualised cost ratio level 1.45). This order of magnitude is considered marginal and not of any significant magnitude that would necessarily point towards an optimal solution for making a choice among the system options. The importance of stakeholder participation and selection of criteria and appropriate weighting in MCAs is evident and crucial to achieve optimal solutions in accordance with stakeholders localised needs and preferences.

When comparing the results of the economic analysis and that of the MCA interesting aspects emerge.

For a sub-system annualised cost factor of 1.2 the ranking of system level options based on economics alone (from lowest to highest annualised cost) compared to that of the MCA are the same. Option 1 is ranked highest, followed by option 2, option 4 and lowest option 3. In the case of the economic analysis the difference in these system options is 2, 6 and 8% respectively, while for the MCA the differences reduced to approximately 0.8, 1.3 and 1.8%. The MCA has therefore narrowed down the economically based differences between system options bringing them closer when an inclusive holistic approach inclusive of economic, environmental, social and technical non-monetary factors for sustainability assessment is taken.

For the two higher annualised sub-system cost ratios (1.45 & 1.65) the MCA ranking changed for options 3 and 4 (ranked 3rd and 4th respectively). As the two cost ratios apply to these two options as such, their direct role of determining the ranking order is obvious (Table 7.11).

However, the analysis done is based on a particular main criteria weighting and a completely different result would emerge should other weightings be considered. The outcome would thus depend on the preferred weighting of criteria determined in consultation and in collaboration with role players and interested parties such as decision makers and specialists within the water sector for a particular project. As the particular exercise here is based on mostly synthetic (and not necessarily real data and costs) this part of the MCA was not pursued any further here.

From the view of optimal solutions for wastewater treatment being one primarily driven by meeting stakeholder needs, a two-stage MCA approach could be considered. The first stage will cover the main criteria categories of social, environmental and technical, while the second would assess economic criteria and feasibility. This two-stage MCA approach has been tested at treatment level by Musiyarira *et al.* (2011), but need to be explored further at wastewater management system level and is recommended for future research.

7.12.3 Other aspects

With economic internalisation of combined benefits (environmental, public health and water resource conservation) a more holistic and objective assessment of economic viability of wastewater management at system level is possible. The case study showed that the approach of distance function valuing of externalised benefits in sustainability assessment can be employed at both treatment and overall system levels. However, the necessity of incorporating the economics into a holistic MCA is essential for finding optimal solutions and assisting with decision-making.

A need do however exist for finding an acceptable mechanism to positively contribute to wastewater management system sustainability by benefit realisation into actual cash flows of treatment systems/facilities. As the combined benefits are not localised necessarily but extend beyond their service areas it can be considered of regional and even national interest. Introduction of a suitable mechanism with a regional or national base is essential for future sustainability of these systems/facilities or in other words achieving national or regional goals in wastewater management system level analysis is a must. Although treatment level analysis are of value, but caution should be exercised not to interpret findings at such level beyond that being justified.

The concept of an environmental pollution mitigation allowance in the form of a direct government subsidy or tax rebate could be a possible option to consider. This allowance could be related to the environmental and ecological sensitivity of the particular catchment where effluent disposal takes place. For example, where special regulatory effluent standards have to be introduced for this purpose, the marginal cost of increased contaminant removal to avoid undesired negative impacts that could not be tolerated, could be part of such an allowance. In addition, where reuse or reclamation of treated effluent is practised an equivalent marginal cost for fresh water mobilisation could be incorporated into the allowance. For proper regulation and management of such allowances it would have to be incorporated into the permitting process of every treatment facility with the explicit incorporation of the allowance conditions being strictly administered by the regulating authority.

The USA approach used for achieving environmental standards of tradable permitted allowances also needs mention. This system was originally developed for polluting power generation industries. Researchers have proved that under competitive markets permit-trading provides a suitable alternative to regulatory schemes and could achieve the given environmental standards at relatively lower cost (Coggins and Smith, 1993, Coggins and Swinton, 1996).

CHAPTER 8

CONCLUDING REMARKS

8.1 THESIS SUMMARY

Due to the growth in urban populations globally and the increased demand for and the concomitant pressure exerted on finite fresh water resources, exploration of unconventional resources such as rain water harvesting, desalination and wastewater reuse to supplement dwindling natural fresh water resources are receiving great interest. As the segmented approach of conventional water management with a mainly supply-side approach is under pressure and not able to efficiently manage and ensure societal requirements of resource conservation and environmental protection, **a new paradigm for wastewater management is essential. For sustainable use of the environment wastewater intrinsic value recovery must be an integral part of the equation of balancing natural-unconventional resource use within the environmental, social and economic constraints.**

The research explores wastewater intrinsic value recovery by reuse within this sustainability balancing equation. A methodology is proposed for deriving a monetary indicator equivalent for wastewater reuse. The methodology internalises negative environmental impact externalities and applies Lagrangian optimisation of a treatment level production function (output distance function) for deriving marginal prices of contaminant removal subsequently used as measure of total environmental benefits. Furthermore, the developed methodology includes the economic assessment of wastewater intrinsic value recovery (or beneficiation) for the wastewater continuum inclusive of both wastewater treatment and wastewater management system levels.

8.2 CONCLUSIONS

Wastewater beneficiation or intrinsic value recovery is achieved through the three different pathways of reclamation, reuse and recycle. Each of these pathways or combinations thereof has different social, environmental and economic repercussions and their application is location specific. The potential of wastewater beneficiation also depends on the particular wastewater management scale. For onsite wastewater beneficiations the potential is highest for onsite plants, but becomes less efficient at higher levels of block and cluster scales. However, offsite wastewater beneficiation would be feasible at cluster scale already with higher efficiency likely at central and regional scale levels.

For the most sustainable wastewater management solution, optimisation has to be sought at system level with integration of intrinsic value recovery (or beneficiation). However, such system level optimisation analyses does require adequate and appropriate data for the service area considered. In the case of South Africa obtaining the necessary data is very difficult as in many instances at best sparse data are available for such levels of investigation. However, synthetic data can be developed using algorithms to fill caps but has to be done with caution to ensure that such data is appropriate to the locality investigated. The limitation therefore of system level analyses and optimisation is at data base level and not as a result of inadequate techniques or methodology for analysis purposes.

- The European Union (EU), as reference to developed nations, follows a dual approach for effluent disposal/reuse. According to the EU urban wastewater directive, secondary treatment is stipulated as the minimum effluent treatment level treatment for systems serving populations in excess of 2000. Where effluent is disposed to receiving waters within sensitive areas (i.e. areas with potential high ecological and environmental risk) treatment has to be to tertiary level. This dual approach is based on a prescribed technology view that does not align primarily with that of a *treatment towards a reuse objective* required for achieving sustainable wastewater management. Such an objective ensures selection of treatment processes that best utilise wastewater as resource, potentially converting waste to a useful product such as biogas, fertiliser, etc.

> In this manner negative impact on the environment is reduced and effluent reuse can be optimised (Nhapi and Gijzen, 2005). The methodology developed in this research should be incorporated into all wastewater management decision-making frameworks as it does ensure sustainable wastewater management.

With reuse of wastewater, virtual water components are positively impacted and water footprints reduced. In the research five points of intervention were identified for reducing water footprints, which in principle amount to reduction of water withdrawals through multiple use of water withdrawn by reuse. Although both imports and exports increase the water footprint (WF), high virtual water (VW) containing product imports should be stimulated when import prices do not account for the full cost of VW contained therein, as in effect it would potentially subsidise domestic users economically. Similarly, the export of high VW containing products should be avoided as this would subsidise the importing country in the event of subsidised water.

These notions emphasises the importance of market related water pricing for accounting the real value of VW contained in products of a country's exports to achieve the best economic return in both single and multiple water withdrawal use of exports.

The methodology developed could also be modified to include additional benefits of multiple water use as well as benefits that could occur indirectly through a reduction of negative virtual water export streams (negative export streams refer to subsidised water included as virtual water in exported products) for which the real cost of water are not taken into account.

The possibility exist for obtaining additional benefits from wastewater intrinsic value recovery through use of reclaimed water for the enhancement of less renewable resources (e.g. groundwater) with significant positive economic potential oppose to discharge to renewable surface waters (rivers and natural reservoirs*).* This aspect however needs further, analysis and evaluation and is listed as recommended further research.

Even though the virtual water concept would be beneficial for various types of water use related assessment, its assumption of a single withdrawal for production of goods from the natural water cycle component, direct application in the case of wastewater management is considered limited due to multiple water use through reuse. **The incorporation of multiple water usage into the virtual water concept is included in the issues for further research in this section**.

The quantifying of the impact of reuse on increased water availability for urban water supply systems allows making a link of reuse level to equivalent resource conservation benefits (being potentially equivalent to the increased supply), for inclusion into an integrated management system level analysis. **The simplified water balance model with single system loss factor used, result in unrealistic values of potential increased availability as independent network-specific and consumer-end losses not being quantified, nor the various loss types/components of these two parts**. Although, in the research the simplified model was revised to include network-specific and consumer-end losses, these were not refined to include the various components thereof. **To achieve improved model representation as close as possible to the urban water supply systems in practise, the further model refinements should be done and is recommended for further research**.

8.3 LIMITATIONS OF THE STUDY

The methodology developed for intrinsic value recovery applies to both wastewater treatment and integrated wastewater management system levels. However, in the case study for system level analysis (Case Study 2) synthetic data was mostly relied on due to extended system related real data not being available. It would be preferable to use real data for decision making at this level and any synthetic data derived must be used with caution having checks and balances to ensure data is appropriate for the locality considered.

A hypothetical MCA assessment was done in the absence of survey data for stakeholder inputs. Although the essential stakeholder participation MCA component (selection and final choice of sustainability criteria and weighting) was not assessed, the decision-making methodology developed incorporates this function for comprehensive alternative wastewater management solutions sustainability assessment.

With Case study 1, the one-year cost for treatment plants available allowed analysis and derivation of marginal cost for a single one-year period only. With the longer term approach associated with wastewater systems generally, assessment of multiple annual cost cycles (that incorporate changes in cost and plant process performance over time) is necessary for obtaining more realistic longer term monetary equivalents (shadow prices) for intrinsic value recovery, feasibility analyses and management systems optimisation. Further cycles of treatment level data should be obtained for longer term sensitivity analyse of these factors mentioned.

An inverse relationship between contaminant shadow price and contaminant removed for a particular cost and cost cycle at both treatment and management system levels were identified in the research, i.e. a high shadow price corresponds to a low removal and vice versa. The relationship of contaminant shadow price vs. contaminant removed and related cost factor aspects requires further exploration mathematically and statistically to allow derivation of shadow price envelopes (and corresponding environmental benefits) of different wastewater treatment trains for use in systems optimisation with wastewater management systems planning.

The contaminant shadow price versus contaminant removed relationship established in the research was extended to consider treatment plant environmental benefits and corresponding plant effluent suitability for agricultural use. **The direct relationship between plant environmental benefit and effluent constituent content fraction established, allowed a ranking for suitability of plant (or plant effluent) for agricultural reuse**.

The agricultural suitability ranking done was limited to natural fertiliser constituents (nutrients N and P) and could be extended with further research to include other constituents in wastewater generally beneficial for soil fertility stabilisation.

As the output distance function algorithm is a function of the plant costs and contaminants removed in a particular time cycle, with shadow prices in turn derived from the algorithm optimal value, variations in any of these three factors will affect the unique relationship between contaminant shadow prices and load removed of a particular plant.

8.4 RECOMMENDED FURTHER RESEARCH

The following aspects are recommended for consideration in future research:

1. **Shadow prices evaluation over multiple time periods for both treatment and collection components to allow assessment of the impacts of changes in costs and process efficiencies over time on shadow prices and monetary equivalents for total environmental benefits.**

2. **The inverse relationship established between contaminant shadow price and contaminant removed at treatment level be explored further by considering multiple time periods and development of expressions for equating the contaminant shadow price vs. contaminant removed relationship based on a mathematical and statistical analyses and comparison of such relationship for various treatment trains to apply in wastewater management system planning and optimisation.**

3. **The relationship established between large plant environmental benefit and high remaining contaminant effluent fraction and the associated potential benefit for agricultural use be researched further. The focus of the role of nutrients (N and P) be explored further to not only include benefits of comparative use of natural and artificial fertilisers but also constituents present in wastewater that would contribute to soil fertility and stabilisation in agriculture generally and the ranking of treatment plants (and their effluent) for suitability in agriculture or horticulture.**

4. **Modification of the developed methodology developed to include additional benefits of multiple water use as well as indirect benefits of reduction of negative virtual water export streams (exports for which real cost of water not taken into account).**

5. **Ways of adjustment of the base of virtual water (VW) from single withdrawal from the natural water cycle and the water footprint to incorporate multiple water use by reuse.**
6. **The impact of reuse on increased water availability for urban water supply systems and incorporating a network-specific and consumer-end related system losses differentiation and the relevant contributing loss types/ components thereof. The link between reuse level and corresponding increased supply allow for assessment of equivalent resource conservation benefits for inclusion into an integrated management system level analysis.**
7. **Adoption of the methodology to analyse the economic impacts associated with wastewater reclamation, reuse and recycling in principle and perusal of questions regarding the economic effects of choices between these intrinsic value recovery or a combination thereof and analysis of economic performance differences between surface and ground water reclamation strategies within an integrated management system analysis.**
8. **Consider returns to scale in treatment and collection systems for urban sewered systems within a South African context (analogous to the Clark study done in Australia referred to in this research).**
9. **Application of the decision-making methodology developed to consider system management sustainability over the full extent of the centralised-decentralised wastewater continuum, accounting for various mixed system scale scenario's as well as the scope of technologies appropriate within a South African context.**
10. **Comparison of a single (all domains considered together) and a two-staged sustainability assessment approach. The first stage covering sustainability based on social, environmental and technical aspects, while the second consists of an economic analysis of the options indentified and ranking for decision making. This could be considered both at treatment and wastewater management system level scenarios.**

11. **Amendment of the South African developed *Waswarplamo* decision tool (primarily developed for treatment sustainability assessment for various reuse applications) to also allow application of the tool in instances where treatment options for user quantified wastewater treatment input volumes must be considered.**

The economic distance function assessment methodology proposed is considered a needed and appropriate tool for incorporating monetary equivalents for environmental benefit externalities and wastewater intrinsic value recovery (or beneficiation) consideration in wastewater management systems planning and optimisation. The methodology and extensions proposed allows for expression of environmental benefits and wastewater beneficiation in monetary equivalents. This allows wastewater treatment systems to be considered in improved equivalent economic terms and wastewater beneficiation as a prerequisite for sustainable water management to be included in the sustainability balancing equation of natural-unconventional resource use and environmental, social and economic constraints, aimed for.

REFERENCES

Adewumi, J.R. 2010. *A Decision Support System for Assessing the Feasibility of Implementing Dual Water Reticulation Systems in South Africa*. University of the Witwatersrand, Johannesburg, South Africa.

Aigner, D.J. & Chu, S.F. 1968. “On Estimating the Industry Production Function”, *The American Economic Review,* vol. 58, no. 4, pp. 826–839.

Al-Jayyousi, O.R. 2003. “Greywater reuse: towards sustainable water management”, *Desalination,* vol. 156, no. 1–3, pp. 181–192.

Allan, J.A. 1998. “Virtual Water: A Strategic Resource Global Solutions to Regional Deficits”, *Ground Water,* vol. 36, no. 4, pp. 545–546.

Anderson, J. 2003. “The Environmental Benefits of Water Recycling and Reuse”, *Water Science and Technology,* vol. 3, no. 4, pp. 1–10.

Asano, T. 2002. “Water from (Waste)Water – The Dependable Water Resource”, *Water Science and Technology,* vol. 3, no. 4, pp. 1–10.

Ashton, P.J. 2002. “Avoiding Conflicts over Africa’s Water Resources”, *Ambio,* vol. 31, no. 3, pp. 236–242.

AQUAREC. 2006. *Aquarec Project - Integrated Concepts for Reuse of Upgraded Wastewater Handbook on feasibility studies for water reuse systems,* AQUAREC.

Austin, L.M., Duncker, L.C., Matsebe, G.N., Phasha, M.C. & Cloete, T.E. 2005. *Ecological Sanitation – literature review*. WRC, South Africa.

Balkema, A.J., Preisig, H.A, Otterpohl, R. and F.J.D. Lambert. 2002. "Indicators for the sustainability assessment of wastewater treatment systems", *Urban Water* vol 4, pp. 153–161.

Beck, M.B., Chen, J., Saul, A.J. & Butler, D. 1994. “Urban drainage in the 21st century: Assessment of new technology on the basis of global material flows”, *Wat. Sci. Tech.,* vol. 30, no. 2, pp. 1–12.

Beck, M.B. & Cummings, R.G. 1996. “Wastewater infrastructure: Challenges for the Sustainable City in the New Millennium”, *Habitat International*, vol. 20, no. 3, pp. 405–420.

Belton,V.,Stewart,T.J. 2002. *Multi criteria decision analysis: An integrated approach.* 1st edn. Springer.

Birol, E., Karousakis, K. & Koundouri, P. 2006. “Using economic valuation techniques to inform water resources management: A survey and critical appraisal of available techniques and an application”, *Science of The Total Environment,* vol. 365, no. 1–3, pp. 105–122.

Brown, D., Dillard, J. & Scott Marshall, R. 2006. *Triple Bottom Line: A Business metaphor for a Social Construct*. Department of Business Economics: Universitat Autonoma de Barcelona, Spain.

Burian, S.J., Nix, S.J., Pitt, R.E. & Durrans, S.R. 2000. “Urban Wastewater Management in the United States: Past, Present, and Future”, *Journal of Urban Technology,* vol. 7, no. 3, pp. 33.

Burton, S., Cohen, B., Harrison, S., Pather-Elias, S., Stafford, W., van Hille, R. & von Blottnitz, H. 2009. *Energy from Wastewater – A Feasibility study*. WRC, South Africa.

Capital Regional District (CRD) 2007. *Discussion Paper No. 6: Core Area and West Shore Sewage Treatment – Triple Bottom Line Analysis*. Capital Regional District, Vancouver, Canada.

Chambers, R.G., Chung, Y. & Fare, R. 1998. “Profit, Directional Distance Functions, and Nerlovian Efficiency”, *Journal of Optimization Theory and Application,* vol. 98, no. 2, pp. 351–364.

Chapagain, A.K. & Hoekstra, A.Y. 2004a. *Water Footprints of Nations. Volume 1: Main Report*, UNESCO-IHE. Value of Water Research Series No. 16, Delft, The Netherlands.

Chapagain, A.K. & Hoekstra, A.Y. 2004b. *Water Footprints of Nations. Volume 2: Appendices*, UNESCO-IHE. Value of Water Research Series No. 16, Delft, The Netherlands.

Chen, J. & Beck, M.B. 1997. “Towards designing sustainable urban wastewater infrastructures: A screening analysis”, *Water Science and Technology,* vol. 35, no. 9, pp. 99–112.

Chen, R. & Wang, X.C. 2009. “Cost-benefit evaluation of a decentralized water system for wastewater reuse and environmental protection”, *Water Science and Technology,* vol. 59, no. 8, pp. 1515–1522.

Christova-Boal, D., Eden, R.E. & McFarlane, S. 1996. “An investigation into greywater reuse for urban residential properties”, *Desalination,* vol. 106, no. 1–3, pp. 391–397.

Coggins, J.S. & Smith, V.H. 1993. “Some Welfare Effects of Emission Allowance Trading in a Twice-Regulated Industry”, *Journal of Environmental Economics and Management,* vol. 25, no. 1, pp. 275–297.

Coggins, J.S. & Swinton, J.R. 1996. “The Price of Pollution: A Dual Approach to Valuing SO2 Allowances”, *Journal of Environmental Economics and Management,* vol. 30, no. 1, pp. 58–72.

Cornel, P. & Schaum, C. 2009. “Phosphorus recovery from wastewater: needs, technologies and costs”, *Water Science & Technology,* vol. 59, no. 6, pp. 1069–1076.

CSIR 2000. “Chapter 9: Water supply” in *Guidelines for Human Settlement Planning and design.* CSIR, Pretoria, South Africa.

Dinesh, N., Dandy, G.C. 2003. “A decision support system for municipal wastewater reclamation and reuse”, *Water Science & Technology: Water Supply,* vol. 3, no. 3, pp. 1-8.

Dixon, A., Butler, D. & Fewkes, A. 1999. “Water Saving Potential of Domestic Water Reuse Systems using Greywater and Rainwater in combination”, *Water Science and Technology,* vol. 39, no. 5, pp. 25–32.

DNHPD – Department of National Health and Population Development 1978, *Guide: Permissible utilisation and disposal of treated sewage effluent.* Pretoria, South Africa.

Dolnicar, S. & Shafer, A.I. 2009. “Desalinated versus recycled water: Public Perceptions and Profiles of the Accepters”, *Journal of Environmental Management,* vol. 90, pp. 888–900.

DWAF - Department of Water Affairs and Forestry. 1996. *South African Water Quality Guidelines (Volumes 1 to 8).* DAWF, Pretoria, South Africa.

Ekama, G.A., v R Marais, G., Siebritz, I.P., Pitman, A.R., Keay, G.F.P., Buchan, L. & Gerber, A.S.M. 1984. *Theory, Design and Operation of Nutrient Removal Activated Sludge Processes*. Water Research Commission, Pretoria, South Africa.

Eriksson, E., Auffarth, K., Henze, M. & Ledin, A. 2002. “Characteristics of grey wastewater”, *Urban Water,* vol. 4, no. 1, pp. 85–104.

European Central Bank (ECB), *Euro foreign exchange reference rates*. Available: http://www.ecb.int/stats/exchange/eurofxref/html/index.en.html [2012, 2/23/2012].

Falkenmark, M. 1989. “The Massive Water Scarcity Now Threatening Africa: Why Isn’t It Being Addressed?”, *Ambio,* vol. 18, no. 2, pp. 112–118.

Fane, A.G. 1996. “Membranes for water production and wastewater reuse”, *Desalination,* vol. 106, pp. 1–9.

Färe, R., Grosskopf, S., Lovell, C.A.K. & Yaisawarng, S. 1993. “Derivation of Shadow Prices for Undesirable Outputs: A Distance Function Approach”, *The review of economics and statistics,* vol. 75, no. 2, pp. 374–380.

Färe, R., Grosskopf, S., Noh, D. & Weber, W. 2005. “Characteristics of a polluting technology: theory and practice”, *Journal of Econometrics,* vol. 126, no. 2, pp. 469–492.

Farrell, M.J. 1957. “The Measurement of Productive Efficiency”, *Journal of the Royal Statistical Society.Series A (General),* vol. 120, no. 3, pp. 253–290.

Feachem, R.G., Bradley, D.J., Garelick, H. & Mara, D.D. 1983. *Sanitation and disease: health aspects of excreta and wastewater management. World Bank Studies in Water Supply and Sanitation 3*. John Wiley & Sons.

Foxon, T.J., McIlkenny, G., Gilmour, D., Oltean-Dumbrava, C., Souter, N., Ashley, R., Butler, D., Pearson, P., Jowitt, P. & Moir, J. 2002. “Sustainability Criteria for Decision Support in the UK Water Industry”, *Journal of Environmental Planning and Management,* vol. 45, no. 2, pp. 285-301.

Fricker, A. 1998. “Measuring up to sustainability”, *Futures,* vol. 30, no. 4, pp. 367–375.

Fuller, S. & Petersen, S. 1996. *NIST Handbook 135. LIFE-CYCLE COSTING MANUAL for the Federal Energy Management Program*. US Department of Commerce, Washington USA.

Gijzen, H.J. 2001. “Anaerobes, aerobes and phototrophs A winning team for wastewater management”, *Water Science and Technology,* vol. 44, no. 8, pp. 123–132.

Gijzen, H.J. 1998. “Sustainable Wastewater Management via Re-use: Turning Waste into Wealth”, *Proc. AGUA98 – Water and Sustainability July 1998 Cali Columbia*. ed. M.e.a. Garcia, Cinara Institute Universidad Del Valle, Cali Columbia, pp. 211.

Gijzen, H.J. & Siebel, M.A. 2002. *Application of Cleaner production concepts in urban water management*. IHE, Delft, The Netherlands.

Grobicki, A. & Cohen, B. 1999. *Water Reclamation for direct reuse in Urban and Industrial applications in South Africa and its projected impact upon water demand*. WRC.

Haarhoff, J. & van der Merwe, B. 1996. “Twenty-five years of Wastewater Reclamation in Windhoek Namibia”, *Water Science and Technology,* vol. 33, no. 10, pp. 25–35.

Haestad Methods. 2004. “Dry Weather Wastewater Flows” in *Wastewater Collection Systems Modeling and Design*. ed. B. T.E.. 1st edn. Haestad Methods Inc., USA, pp. 173–201.

Harremoës, P. 2002. “Water ethics – a substitute for over-regulation of a scarce resource”, *Water Science and Technology,* vol. 45, no. 8, pp. 113–124.

Harremoës, P. 1999. “Water as a transport medium for waste out of towns”, *Water Science and Technology,* vol. 39, no. 5, pp. 1–8.

Harremoës, P. 1997. “Integrated water and waste management”, *Water Science and Technology,* vol. 35, no. 9, pp. 11–20.

Heinonen-Tanski, H. & van Wijk-Sijbesma, C. 2005. “Human excreta for plant production”, *Bioresource technology,* vol. 96, no. 4, pp. 403–411.

Henze, M. & Ledin, A. 2001. “Part II: Waste and wastewater characteristics and its collection. Section 4 Types, characteristics and quantities of classic, combined domestic wastewaters” in *Decentralized Saniation and Reuse – Concepts , Systems and Implementation*. eds. P. Lens, G. Zeeman & G. Lettinga. IWA Publishing, pp. 55–72.

Hermanowicz, S.W. & Asano, T. 1999. “Abel Wolman’s “The Metabolism of cities” revisited: A case for water recycling and reuse”, *Water Science and Technology,* vol. 40, no. 4–5, pp. 29–36.

Hermanowicz, S.W. 2005. *Sustainability in Water Resources Management: Changes in Meaning and Perception.* [Homepage of University of California Berkeley: Water Resources Center Archives]. [Online]. Available: http://escholarship.org/uc/item/9h48p02k#page-1 [2011, 1/4/2011].

Hernández-Sancho, F. & Sala-Garrido, R. 2009. “Technical efficiency and cost analysis in wastewater treatment processes: A DEA approach”, *Desalination,* vol. 249, no. 1, pp. 230–234.

Hoekstra, A.Y. 2003. “Part 1: Global studies. Virtual water: An introduction”, *Proceedings of the International Expert Meeting on Virtual Water Trade Value of Water Research Report Series No. 12*. ed. A.Y. Hoekstra, UNESCO-IHE Institute for Water Education, Delft, The Netherlands.

Hoekstra, A.Y. & Hung, P.Q. 2002. *Virtual water trade: A quantification of virtual water flows between nations in relation to international crop trade*. UNESCO-IHE. Value of Water Research Series No. 11, Delft, The Netherlands.

Ilemobade, A.A., Adewumi, J.R. & van Zyl, J.E. 2009. *Assessment of the feasibility of using a dual water reticulation system in South Africa*. WRC, South Africa.

IMQS 2009/2010. *Infrastructure management system and data base for Midvaal Local Municipality*. IMQS, Cape Town South Africa.

Jacobsen, S.E. 1972. “On Shephard’s duality theorem”, *Journal of Economic Theory,* vol. 4, no. 3, pp. 458–464.

Jeppesen, B. 1996. “Domestic greywater re-use: Australia’s challenge for the future”, *Desalination,* vol. 106, no. 1–3, pp. 311–315.

Joksimovic, D. 2006. *Decision Support System for Planning of Integrated Water Reuse Projects*. University of Exeter, UK.

Joubert, A., Stewart, T. 2004. *Guidelines for the use of multi criteria decision analysis in the implementation of the National Water Act*. WRC, Pretoria South Africa.

Lancaster, K.J. 1966. “A New Approach to Consumer Theory”, *The Journal of Political Economy,* vol. 74, no. 2, pp. 132–157.

Larsen, T.A. & Boller, M.A. 2001. “Part III: Technological aspects of DESAR: A Concepts of and technologies for DESAR. Section 20 Perspectives of nutrient recovery in DESAR concepts” in *Decentralized Saniation and Reuse – Concepts, Systems and Implementation*. eds. P. Lens, G. Zeeman & G. Lettinga. IWA Publishing, pp. 387–410.

Larsen, T.A. & Gujer, W. 1996. “Seperate Management of Anthrogenic Nutrient Solutions (Human urine)”, *Water Science & Technology,* vol. 34, no. 3–4, pp. 87–94.

Lazarova, V., Hills, S. & Birks, R. 2003. “Using recycled water for non-potable, urban uses: a review with particular reference to toilet flushing”, *Water Science & Technology: Water Supply,* vol. 3, no. 4, pp. 69–77.

Lennartsson, M., Kvarnström, E., Lundberg, T., Buenfil, J., Sawyer, R. 2009. *Comparing Sanitation Systems using Sustainability Criteria*. Stockholm Environment Institute (SEI), Stockholm Sweden.

Lettinga, G., Lens, P. & Zeeman, G. 2001. “Part 1: The DESAR concept for environmental protection. Section 1 Environmental Protection Technologies for Sustaibable Development” in *Decentralized Saniation and Reuse – Concepts, Systems and Implementation*. eds. P. Lens, G. Zeeman & G. Lettinga. IWA Publishing, pp. 1–10.

Li, F., Wichmann, K. & Otterpohl, R. 2009. “Evaluation of appropriate technologies for grey water treatments and reuses”, *Water Science & Technology,* vol. 59, no. 2, pp. 249–260.

Loetscher, T., Keller, J. 2002. “A decision support system for selecting sanitation systems in developing countries”, *Socio-economic planning sciences,* vol. 36, no. 4, pp. 267-290.

Marjanovic, P., Musiyarira, H. ,Reynders, C. 2009. *Technical Report to Gauteng Department of Local Government & Housing – Investigate the efficient management of peri-urban, farming and isolated areas wastewater through the application of an integrated wastewater management approach*. Wits Commercial Enterprise (Pty) Ltd. University of the Witwatersrand, Johannesburg, South Africa.

Marjanovic, P., Musiyarira, H. & Reynders, C. 2011. “Managing Water Resources in Developing Countries: South Africa as an example for Policy and Regulation”, *Journal of Serbian Water Pollution Control Society: Water Research and Management*, vol. 1, no. 3, pp. 9–24.

Massoud, M.A., Tarhini, A. & Nasr, J.A. 2009. “Decentralized approaches to wastewater treatment and management: Applicability in developing countries”, *Journal of environmental management,* vol. 90, no. 1, pp. 652-659.

Midvaal Local Municipality. 2011. *Integrated Development Plan (IDP)*. Midvaal Local Municipality.

McGhee, T.J. 1991. “Chapter 18 Characteristics of Wastewater” in *Water Supply and Sewerage*. eds. B.J. Clark & D.A. Damstra. 6th edn. McGraw-Hill Inc., pp. 373–386.

Meehl, G.A., Stocker, T.F., Collins, W.D., Friedlingstein, P., Gaye, A.T., Gregory, J.M., Kitoh, A., Knutti, R., Murphy, J.M., Noda, A., Raper, S.C.B., Watterson, I.G., Weaver, A.J. & Zhao, Z.C. 2007. “Chapter 10 Global Climate Projections” in *Climate Change 2007: The Physical Science Basis Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. eds. S. Solomon, D. Qin, M. Manning, et al. http://www.ipcc.ch/publications_and_data/ar4/wg1/en/contents.html edn. Cambridge University Press, Cambridge, United Kingdom and New York, USA., pp. 747–845.

Melin, T., Jefferson, B., Bixio, D., Thoeye, C., De Wilde, W., De Koning, J., van der Graaf, J. & Wintgens, T. 2006. “Membrane bioreactor technology for wastewater treatment and reuse”, *Desalination,* vol. 187, pp. 271–282.

Middleton, B.J. & Bailey, A.K. 2008. *Water Resources of South Africa, 2005 Study (WR2005)*. WRC, South Africa.

Molinos-Senante, M., Hernández-Sancho, F. & Sala-Garrido, R. 2010. “Economic feasibility study for wastewater treatment: A cost-benefit analysis”, *Science of The Total Environment,* vol. 408, no. 20, pp. 4396–4402.

Munda, G., Nijkamp, P. & Rietveld, P. 1994. “Qualitative multicriteria evaluation for environmental management”, *Ecological Economics*, vol. 10, no. 2, pp. 97-112.

Musiyarira, H., Reynders, C., Marjanovic, P. 2011. “Decision Making Support in Wastewater Management: Comparative Analysis of Techniques and Tools used in Centralized and Decentralized System Layouts”, *1st Climate Change, Economic Development, Environmental and People Conference.* Educons University, Novi Sad, Serbia, 14–16 September 2011.

Nancarrow, B.E., Leviston, Z., Po, M., Porer, N.B. & Tucker, D.I. 2008. “What drives communities’ decisions and behaviours in the reuse of wastewater”, *Water Science & Technology,* vol. 57, no. 4, pp. 485–491.

Nhapi, I. & Gijzen, H.J. 2005. “A 3-Step Strategic Approach to Sustainable Wastewater Management”, *Water SA,* vol. 31, no. 1, pp. 133–140.

Niemczynomicz, L. 2001. “Part II: Waste and wastewater characteristics and its collection. Section 7 The urban sanitation dilemma” in *Decentralized Saniation and Reuse – Concepts, Systems and Implementation*. eds. P. Lens, G. Zeeman & G. Lettinga. IWA Publishing, pp. 116–129.

O’Donnell, C.J. & Coelli, T.J. 2005. “A Bayesian approach to imposing curvature on distance functions”. *Journal of Econometrics.* vol. 126. no. 2. pp. 493–523.

Panebianco. S. & Pahl-Wostl. C. 2006. “Modelling socio-technical transformations in wastewater treatment—A methodological proposal”, *Technovation,* vol. 26, no. 9, pp. 1090–1100.

Pearce, D.W. & Turner, R.K. 1989. *Economics of Natural Resources and the Environment*, No Edition Stated edn. The Johns Hopkins University Press.

Rand Water South Africa. 2010. *Sales and Custumer Services – Tariffs*. Available: http://www.randwater.co.za/SalesAndCustomerServices/Tariffs/Forms/AllItems.aspx [2011, 1/31/2011].

Reig-Martínez, E., Picazo-Tadeo, A. & Hernández-Sancho, F. 2001. “The calculation of shadow prices for industrial wastes using distance functions: An analysis for Spanish ceramic pavements firms”, *International Journal of Production Economics*, vol. 69, no. 3, pp. 277–285.

Renault, D. 2003. “Part 1: Global studies. Value of virtual water in food: Principles and virtues”, *Proceedings of the International Expert Meeting on Virtual Water Trade Value of Water Research Report Series No. 12*. ed. A.Y. Hoekstra, UNESCO-IHE Institute for Water Education, Delft, The Netherlands.

ReVelle, C., McGarity, A.E. 1997. *Design and operation of civil and environmental engineering systems.* Wiley, New York.

Reynders, C.C., Musiyarira, H. & Marjanovic, P. 2010. “Development of a Decision Support System for Sustainable Wastewater Management in smaller South African municipalities”, *11th WaterNET/WARFSA/GWP-SA Symposium 2010*, 27–28 October 2010.

Rocky Mountain Institute. 2004. *Valuing Decentralized Wastewater Technologies. A Catalog of Benefits, Costs, and Economic Analysis Techniques*. Rocky Mountain Insitute, Snowmass CO 81654 USA.

Schultze-Rettmer, R. 1991. “The Simultaneous Chemical Precipitation of Ammonium and Phosphate in the form of Magnesium-ammonium-phosphate”, *Water Science & Technology,* vol. 23, no. Kyoto, pp. 659–667.

Shephard, R.W. 1970. *Theory of cost and production functions, (Princeton studies in mathematical economics).* Princeton University Press.

Shiklomanov, I.A. 2000. “Appraisal and Assessment of World Water Resources”. *Water International,* vol. 25, no. 1, pp. 11.

Simpson, J.M. 1999. “Changing community attitudes to potable reuse in South-East Queensland”, *Water Science & Technology,* vol. 40, no. 4–5, pp. 59–66.

South African Reserve Bank. *Selected historical exchange rates and other interest rates – South African Reserve Bank*. Available: http://www.resbank.co.za/Research/Rates/Pages/SelectedHistoricalExchangeAndInterestRates.aspx [2012, 2/25/2012].

Statistics South Africa. *Consumer Price Indexes (CPI)* . Available: http://www.statssa.gov.za/keyindicators/cpi.asp [2012, 2/23/2012].

Tchobanoglous, G., Burton, F.L. & Stensel, D.H. 2004. *Wastewater Engineering Treatment And Reuse.* 4th edn. McGraw-Hill, New York.

Tchobanoglous, G. 1991. “Chapter 3 Wastewater Characteristics” in *Wastewater Engineering Treatment Disposal Reuse*. eds. B.J. Clark & J.M. Morriss. 3rd edn. McGraw-Hill Inc., , pp. 47–119.

Tchobanoglous, G. 1991a. “Chapter 11 Advanced Wastewater Treatment” in *Wastewater Engineering Treatment Disposal Reuse*. eds. B.J. Clark & J.M. Morriss. 3rd edn. McGraw-Hill Inc., pp. 663–756.

Tchobanoglous, G. 1991b. “Chapter 16 Wastewater Reclamation and Reuse” in *Wastewater Engineering Treatment Disposal Reuse*. eds. B.J. Clark & J.M. Morriss. 3rd edn. McGraw-Hill Inc., pp. 1137–1193.

Tchobanoglous, G. 1991c. “Chapter 8 Biological Unit Processes” in *Wastewater Engineering Treatment Disposal Reuse*. eds. B.J. Clark & J.M. Morriss. 3rd edn. McGraw-Hill Inc., pp. 359–444.

Tchobanoglous, G. 1981. “Chapter 3: Wastewater Flows and Measurement” in *Wastewater Engineering: Collection and Pumping of Wastewater*. ed. G. Tchobanoglous, McGraw-Hill, pp. 60–99.

Tchobanoglous, G. & Burton, F.L. 1991. “Chapter 10 Design of Facilities for the Biological Treatment of Wastewater” in *Wastewater Engineering Treatment Disposal Reuse*. eds. B.J. Clark & J.M. Morriss. 3rd edn. McGraw-Hill Inc., pp. 529–662.

Törnqvist, R., Norström, A., Kärrman, E. & Malmqvist, P. 2008. “A framework for planning of sustainable water and sanitation systems in peri-urban areas”, *Water Science & Technology,* vol. 58, no. 3, pp. 563–570.

Turton, A.R. 2010. *Is water the new oil?*. March/April 2010 edn. South African Water Research Commission (WRC), South Africa.

Turton, A.R. 1998. “The monopolization of access to a critical natural resource: The case of water in South Africa”, *14th International Congress of Anthropological and Ethnological Sciences Symposium on Resource Management and through Indigenous Socio-cultural Practises and MEWREW Occasional Paper No. 8.* School of Oriental and African Sciences (SOAS), Water Issues Study Group, University of London.

UNEP/GEC. 2004. *Water and Wastewater Reuse – An Environmentally sound approach for Sustainable Urban Water Management*. United Nations Environmental Programme (UNEP). The Hague, The Netherlands.

UNESCO-IHE (SWITCH). 2006. *Sustainable Water Management Improves Tomorrow’s Cities Health project*. UNESCO-IHE Insitute for Water Education, Delft, Netherlands.

UN-ESCWA. 2003. *Wastewater Treatment Technologies: A General Review*. United Nations, New York USA.

United Nations. 2010. *The Millenium Development Goals Report 2010*. Available: http://www.un.org/millenniumgoals/reports.shtml [2011].

United Nations. 2009. *Department of Economic and Social Affairs; Population Division World Urbanization Prospects, the 2009 Revision*. Available: http://esa.un.org/unpd/wup/index.htm [2011, 1/3/2011].

United Nations. 2008. *Department of Economic and Social Affairs; Population Division World Population Prospects, the 2008 Revision*. Available: http://esa.un.org/unpd/wpp2008/index.htm [2011, 1/3/2011].

US EPA. 1981. *Construction costs for municipal conveyance systems: 1973-1979*. US EPA. Washington, USA.

US EPA. 1999. *Innovative Urban Wet-Weather Flow Management Systems; Chapter 10: Cost Analysis and Financing of Urban Water Infrastructure*. US EPA, Washington, USA.

United States Environmental Protection Agency (US EPA). 2004. *2004 Guidelines for Water Reuse*. US EPA, USA.

US National Research Council. 1998a. “1 Reclaiming Wastewater: An Overview” in *Issues in potable reuse: the viability of augmenting drinking water supplies with reclaimed water*. ed. D.A. Dobbs. Academy Press, Washington, D.C., pp. 14–44.

US National Research Council. 1998b. “2 Chemical Contaminants in Reuse Systems” in *Issues in potable reuse: the viability of augmenting drinking water supplies with reclaimed water,* ed. D.A. Dobbs. Academy Press, Washington, D.C., pp. 45–71.

US National Research Council. 1998c. “3 Microbial Contaminants in Reuse Systems” in *Issues in potable reuse: the viability of augmenting drinking water supplies with reclaimed water*. ed. D.A. Dobbs. Academy Press, Washington, D.C., pp. 45–71.

Van der Vleuten-Balkema, A.J. 2003. *Sustainable Wastewater Treatment, developing a methodology and selecting promising systems*. Technische Universiteit Eindhoven.

Van Ha, N., Kant, S. & Maclaren, V. 2008. “Shadow prices of environmental outputs and production efficiency of household-level paper recycling units in Vietnam”, *Ecological Economics,* vol. 65, no. 1, pp. 98–110.

Van Lier, J.B. & Lettinga, G. 1999. “Appropriate Technologies for Effective Management of Industrial and Domestic Waste Waters: The decentralised Approach”, *Water Science and Technology*, vol. 40, no. 7, pp. 171–183.

Van Rooyen, J.A. & Versfeld, D.B. 2010. *Integrated Water Resource Planning for South Africa: A Situation Analysis 2010*. Department Water Affairs: Republic of South Africa, South Africa.

Van Zyl, H.J., van Zyl, J.E., Guestyn, l., llemobade, A. & Buckle, J.S. 2007. *Water consumption levels in selected South African cities*. WRC, South Africa.

Varian, H.R. 1992. *Microeconomic Analysis.* Third edn. W.W. Norton & Company Ltd, Castle House, 75/76 Wells Street, London W1T 3QT.

Vernick, A.S. & Walker, E.C. 1981. *Handbook of Wastewater Treatment Processes.* MARCEL DEKKER INC., New York USA.

WHO. 2003. *Domestic Water Quantity, Service Level and Health*. World Health Organisation, Geneva, Switzerland.

WHO/UNEP. 2006a. *Guidelines for the safe use of wastewater, excreta and greywater Volume 1, Policy and regulatory aspects*. WHO, Geneva, Switzerland.

WHO/UNEP. 2006b. *Guidelines for the safe use of wastewater, excreta and greywater Volume 2, Wastewater use in agriculture*. WHO, Geneva, Switzerland.

WHO/UNEP. 2006c. *Guidelines for the safe use of wastewater, excreta and greywater Volume 3, Wastewater and excreta use in aquaculture*. WHO, Geneva, Switzerland.

WHO/UNEP. 2006d. *Guidelines for the safe use of wastewater, excreta and greywater Volume 4, Excreta and greywater use in agriculture*. WHO, Geneva, Switzerland.

Wilderer, P.A. 2001. “Part 1: The DESAR concept for environmental protection. Section 3 Decentalized versus centralized wastewater management” in *Decentralized Saniation and Reuse – Concepts*, *Systems and Implementation*. eds. P. Lens, G. Zeeman & G. Lettinga. IWA Publishing, pp. 39–54.

WISA. 1988. *Manual on the Design of Small Sewage Works*. The Water Institute of Southern Africa, Halfway House South Africa.

X-rates.com, *Monthly Exchange Rate Average (American Dollar, South African Rand) 1998 – x-rates* . Available: http://www.x-rates.com/d/USD/ZAR/hist1998.html [2012, 2/23/2012].

APPENDICES

APPENDIX A1

WORLD POPULATION VALUES USED FOR WATER RESOURCE AVAILABILITY CALCULATION

(derived from UN Department of Economic and Social Affairs, Population Division: World Urbanization Prospects, the 2009 Revision)

Continent	**UN populations in 1000s**			
	2000	**2010**	**2020**	**2030**
Europe	726568	732759	732950	723373
Northern-America (North & Central America + Caribbean)	492475	547086	598715	624411
South-America	347407	393221	430212	458052
Africa **(North-Africa)**	819462 (179525)	1033043 (212921)	1276369 (247564)	1524187 (277351)
Asia	3698296	4166741	4596256	4916701
Oceania	31160	35838	40329	44572
The World	6115368	6908688	7674833	8308895

APPENDIX A2

WATER CROWDING INDEX (WCI) FOR AFRICAN COUNTRIES AND REGIONS

(after Falkenmark 1989)

Africa regions and countries	**Water Crowding Index (initially water competition level)** (people/million m^3/year)		
	1982	**2000**	**2025**
Eastern Africa	312	593	1195
Burundi	1200	1900	3100
Ethiopia	290	510	970
Kenya	480	1000	2200
Rwanda	810	1680	3500
Somalia	430	600	1100
Tanzania	250	520	1100
Uganda	210	410	790
Middle/central Africa	22	37	69
Angola	47	84	160
Central African Republic	17	27	48
Chad	120	190	340
Congo	2	3	6
Equatorial Guinea	13	19	31
Gabon	7	10	20
United Rep. of Cameroon	33	54	94
Zaire	30	51	100
Northern Africa	341	551	870
Algeria	650	1100	1900
Egypt	460	690	1000
Libya	460	870	1600
Morocco	680	1100	1900
Sudan	120	200	330
Tunisia	1500	2100	3000
Southern Africa*	169	319	634
Botswana	96	210	450
Lesotho	350	560	1000
Malawi	730	1300	2600
Mozambique	190	380	690
Namibia	120	260	480
Zambia	60	120	250
Zimbabwe	350	660	1400
* South Africa excluded in study (data not made available at the time of study)			

APPENDIX A2 (continued)

Africa regions/countries	**Water Crowding Index** **(initially water competition level)** (people/million m^3/year)		
	1982	**2000**	**2025**
Western Africa	109	200	394
Benin	250	420	810
Burkina Faso	260	380	700
Gambia	400	560	940
Ghana	180	310	540
Guinea	23	35	62
Guinea–Bissau	19	40	70
Ivory Coast	64	120	210
Liberia	9	15	29
Mali	110	200	340
Mauretania	86	150	290
Niger	130	220	430
Nigeria	270	530	1100
Senegal	170	290	540
Sierra Leone	23	30	49
Togo	330	550	1100

APPENDIX A3

NUMBER OF AFRICAN COUNTRIES PER WCI'S SCARCITY LEVELS

(derived from Falkenmark 1989)

WCI levels, with associated management issues (persons / million m^3 / year)	**African regions –number of countries**					**Whole of Africa**
	Eastern	**Central**	**Northern**	**Southern**	**Western**	
Less than 100 – (well watered):						
2000	0	7	0	2	6	15
2025	5	5	0	0	4	9
100 to 600 – (moderate problems):						
2000	5	1	3	4	9	22
2025	0	3	1	3	6	13
600 to 1000 – (water stressed):						
2000	1	0	2	1	0	4
2025	2	0	0	2	3	7
1000 to 2000 – (chronic shortages):						
2000	1	0	1	0	0	2
2025	2	0	4	1	2	9
Beyond 2000 – (water barrier):						
2000	0	0	0	0	0	0
2025	3	0	1	1	0	5

APPENDIX A4

BELLAGIO PRINCIPLES

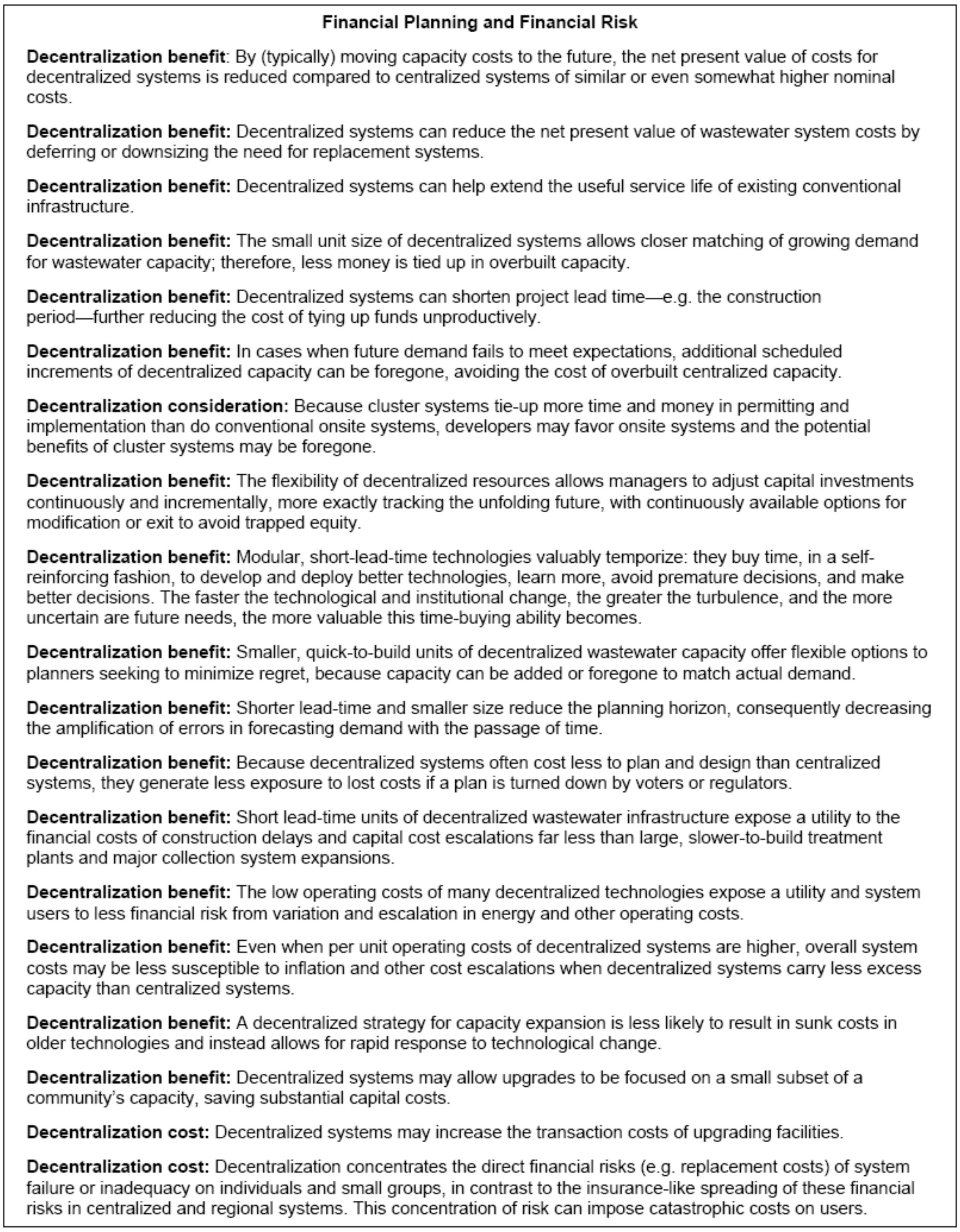
The Bellagio Principles were drawn up by the Environmental Sanitation Working Group of the Water Supply and Sanitation Collaborative Council (WSSCC) and endorsed by the Council during its 5th Global Forum in November 2000 in Iguacu, Brazil.

1) Human dignity, quality of life and environmental security at the household level should be at the centre of the new approach, which should be responsive and accountable to needs and demands in the local and national setting:
    - Solutions should be tailored to the full spectrum of social, economic, health and environmental concerns;
    - The household and community environment should be protected;
    - The economic opportunities of waste recovery and use should be harnessed.
2) In line with governance principles, decision-making should involve participation of all stakeholders, especially the consumers and providers of services:
    - Decision-making at all levels should be based on informed choices;
    - Incentives for provision and consumption of services and facilities should be consistent with the overall goal and objective;
    - Rights of consumer and providers should be balanced by responsibilities to the wider human community and environment.
3) Waste should be considered a resource, and its management should be holistic and form part of integrated water resources, nutrient flow and waste management:
    - Inputs should be reduced so as to promote efficiency and water and environmental security;
    - Exports of waste should be minimised to promote efficiency and reduce the spread of pollution;
    - Wastewater should be recycled and added to the water budget.
4) The domain in which environmental sanitation problems are resolved should be kept to the minimum practical size (household, community, town, district, catchment, city) and wastes diluted as little as possible:
    - Waste should be managed as close as possible to the source;
    - Water should be minimally used to transport waste;
    - Additional technologies for waste sanitisation and reuse should be developed.

APPENDIX A5

BENEFITS OF DECENTRALISED WASTEWATER SYSTEMS

(after Rocky Mountain Institute 2004)



Financial Planning and Financial Risk

Decentralization benefit: By (typically) moving capacity costs to the future, the net present value of costs for decentralized systems is reduced compared to centralized systems of similar or even somewhat higher nominal costs.

Decentralization benefit: Decentralized systems can reduce the net present value of wastewater system costs by deferring or downsizing the need for replacement systems.

Decentralization benefit: Decentralized systems can help extend the useful service life of existing conventional infrastructure.

Decentralization benefit: The small unit size of decentralized systems allows closer matching of growing demand for wastewater capacity; therefore, less money is tied up in overbuilt capacity.

Decentralization benefit: Decentralized systems can shorten project lead time—e.g. the construction period—further reducing the cost of tying up funds unproductively.

Decentralization benefit: In cases when future demand fails to meet expectations, additional scheduled increments of decentralized capacity can be foregone, avoiding the cost of overbuilt centralized capacity.

Decentralization consideration: Because cluster systems tie-up more time and money in permitting and implementation than do conventional onsite systems, developers may favor onsite systems and the potential benefits of cluster systems may be foregone.

Decentralization benefit: The flexibility of decentralized resources allows managers to adjust capital investments continuously and incrementally, more exactly tracking the unfolding future, with continuously available options for modification or exit to avoid trapped equity.

Decentralization benefit: Modular, short-lead-time technologies valuably temporize: they buy time, in a self-reinforcing fashion, to develop and deploy better technologies, learn more, avoid premature decisions, and make better decisions. The faster the technological and institutional change, the greater the turbulence, and the more uncertain are future needs, the more valuable this time-buying ability becomes.

Decentralization benefit: Smaller, quick-to-build units of decentralized wastewater capacity offer flexible options to planners seeking to minimize regret, because capacity can be added or foregone to match actual demand.

Decentralization benefit: Shorter lead-time and smaller size reduce the planning horizon, consequently decreasing the amplification of errors in forecasting demand with the passage of time.

Decentralization benefit: Because decentralized systems often cost less to plan and design than centralized systems, they generate less exposure to lost costs if a plan is turned down by voters or regulators.

Decentralization benefit: Short lead-time units of decentralized wastewater infrastructure expose a utility to the financial costs of construction delays and capital cost escalations far less than large, slower-to-build treatment plants and major collection system expansions.

Decentralization benefit: The low operating costs of many decentralized technologies expose a utility and system users to less financial risk from variation and escalation in energy and other operating costs.

Decentralization benefit: Even when per unit operating costs of decentralized systems are higher, overall system costs may be less susceptible to inflation and other cost escalations when decentralized systems carry less excess capacity than centralized systems.

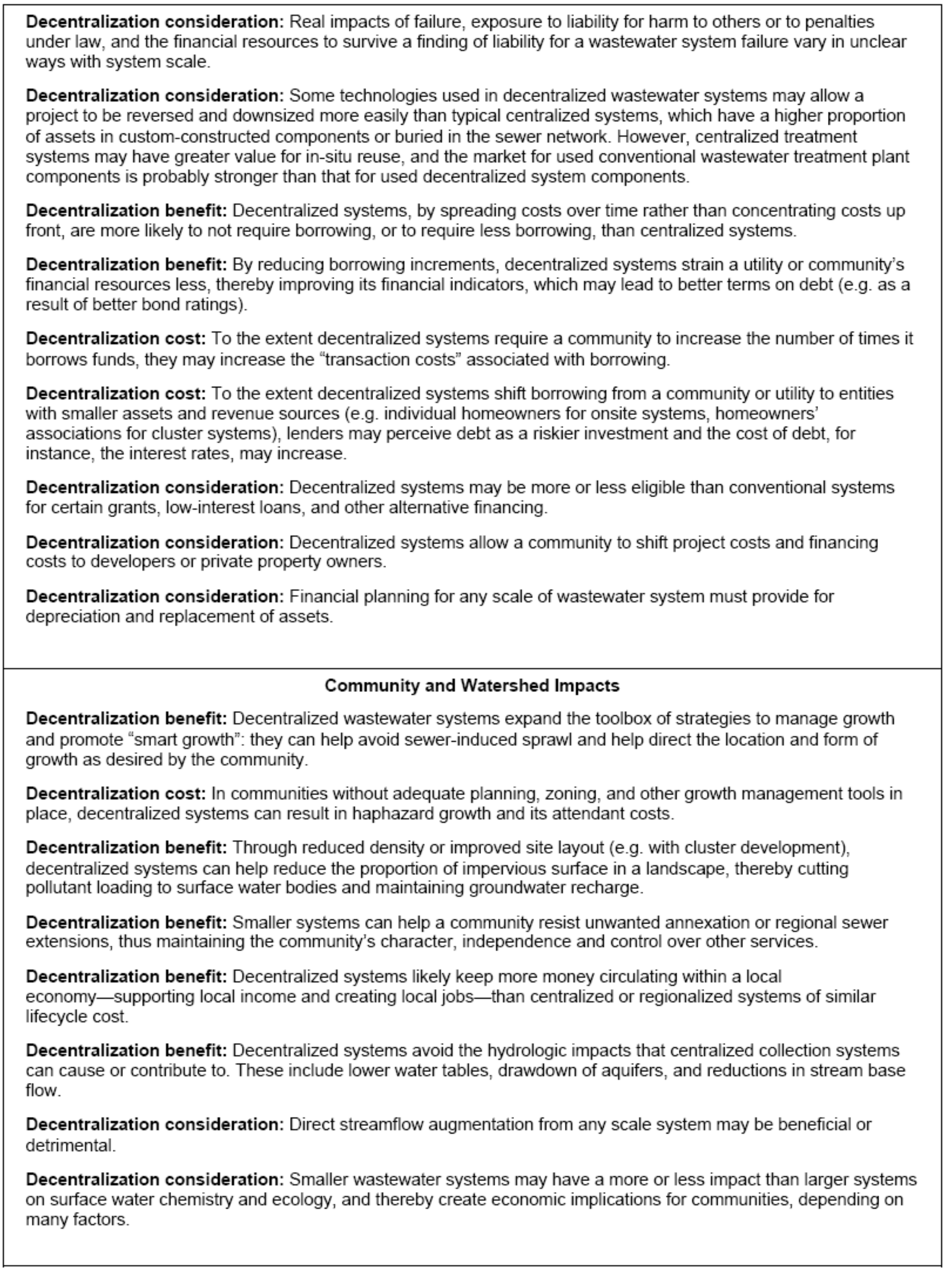
Decentralization benefit: A decentralized strategy for capacity expansion is less likely to result in sunk costs in older technologies and instead allows for rapid response to technological change.

Decentralization benefit: Decentralized systems may allow upgrades to be focused on a small subset of a community's capacity, saving substantial capital costs.

Decentralization cost: Decentralized systems may increase the transaction costs of upgrading facilities.

Decentralization cost: Decentralization concentrates the direct financial risks (e.g. replacement costs) of system failure or inadequacy on individuals and small groups, in contrast to the insurance-like spreading of these financial risks in centralized and regional systems. This concentration of risk can impose catastrophic costs on users.

APPENDIX A5 (continued)



Decentralization consideration: Real impacts of failure, exposure to liability for harm to others or to penalties under law, and the financial resources to survive a finding of liability for a wastewater system failure vary in unclear ways with system scale.

Decentralization consideration: Some technologies used in decentralized wastewater systems may allow a project to be reversed and downsized more easily than typical centralized systems, which have a higher proportion of assets in custom-constructed components or buried in the sewer network. However, centralized treatment systems may have greater value for in-situ reuse, and the market for used conventional wastewater treatment plant components is probably stronger than that for used decentralized system components.

Decentralization benefit: Decentralized systems, by spreading costs over time rather than concentrating costs up front, are more likely to not require borrowing, or to require less borrowing, than centralized systems.

Decentralization benefit: By reducing borrowing increments, decentralized systems strain a utility or community's financial resources less, thereby improving its financial indicators, which may lead to better terms on debt (e.g. as a result of better bond ratings).

Decentralization cost: To the extent decentralized systems require a community to increase the number of times it borrows funds, they may increase the "transaction costs" associated with borrowing.

Decentralization cost: To the extent decentralized systems shift borrowing from a community or utility to entities with smaller assets and revenue sources (e.g. individual homeowners for onsite systems, homeowners' associations for cluster systems), lenders may perceive debt as a riskier investment and the cost of debt, for instance, the interest rates, may increase.

Decentralization consideration: Decentralized systems may be more or less eligible than conventional systems for certain grants, low-interest loans, and other alternative financing.

Decentralization consideration: Decentralized systems allow a community to shift project costs and financing costs to developers or private property owners.

Decentralization consideration: Financial planning for any scale of wastewater system must provide for depreciation and replacement of assets.

Community and Watershed Impacts

Decentralization benefit: Decentralized wastewater systems expand the toolbox of strategies to manage growth and promote "smart growth": they can help avoid sewer-induced sprawl and help direct the location and form of growth as desired by the community.

Decentralization cost: In communities without adequate planning, zoning, and other growth management tools in place, decentralized systems can result in haphazard growth and its attendant costs.

Decentralization benefit: Through reduced density or improved site layout (e.g. with cluster development), decentralized systems can help reduce the proportion of impervious surface in a landscape, thereby cutting pollutant loading to surface water bodies and maintaining groundwater recharge.

Decentralization benefit: Smaller systems can help a community resist unwanted annexation or regional sewer extensions, thus maintaining the community's character, independence and control over other services.

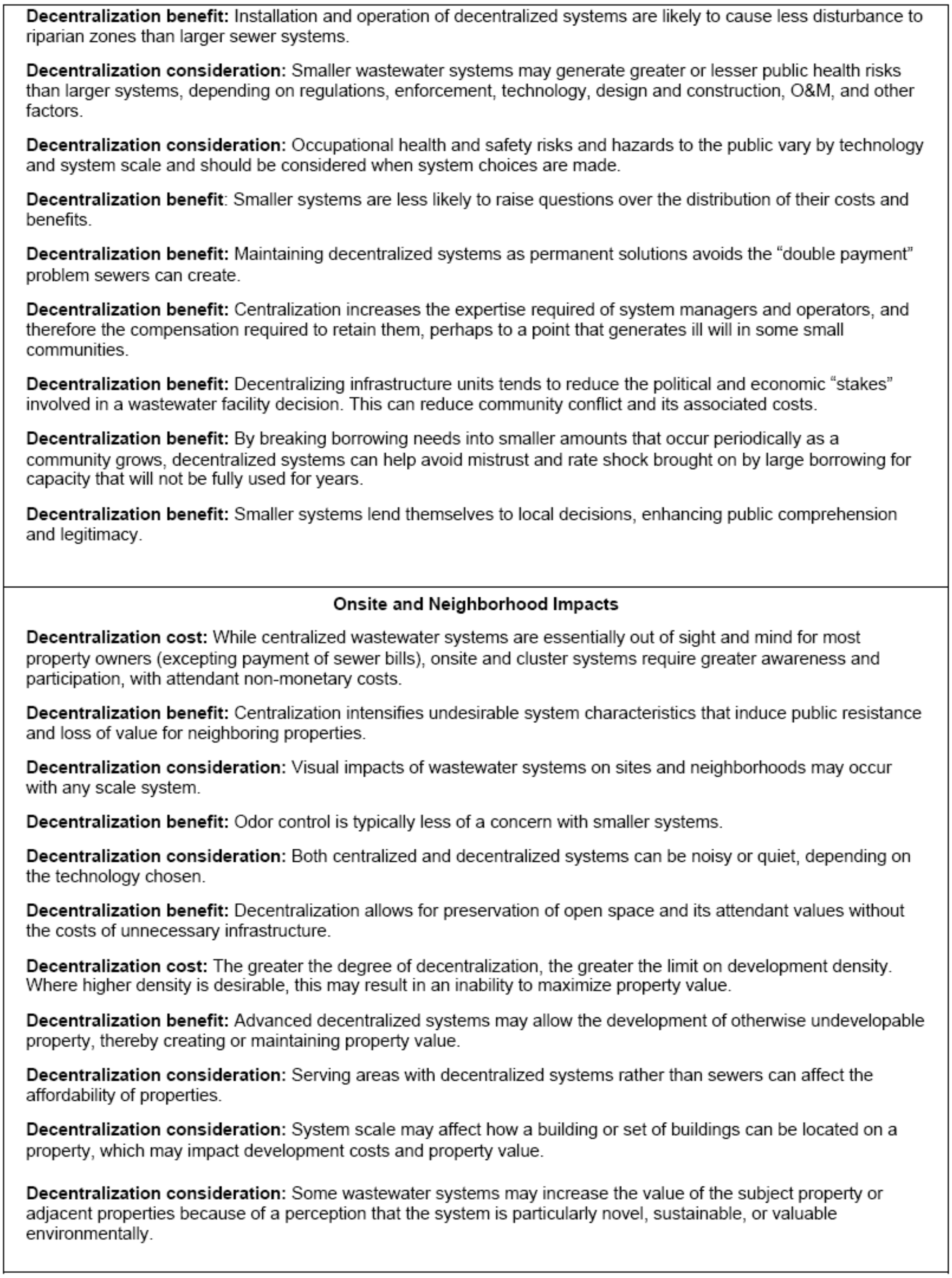
Decentralization benefit: Decentralized systems likely keep more money circulating within a local economy—supporting local income and creating local jobs—than centralized or regionalized systems of similar lifecycle cost.

Decentralization benefit: Decentralized systems avoid the hydrologic impacts that centralized collection systems can cause or contribute to. These include lower water tables, drawdown of aquifers, and reductions in stream base flow.

Decentralization consideration: Direct streamflow augmentation from any scale system may be beneficial or detrimental.

Decentralization consideration: Smaller wastewater systems may have a more or less impact than larger systems on surface water chemistry and ecology, and thereby create economic implications for communities, depending on many factors.

APPENDIX A5 (continued)



Decentralization benefit: Installation and operation of decentralized systems are likely to cause less disturbance to riparian zones than larger sewer systems.

Decentralization consideration: Smaller wastewater systems may generate greater or lesser public health risks than larger systems, depending on regulations, enforcement, technology, design and construction, O&M, and other factors.

Decentralization consideration: Occupational health and safety risks and hazards to the public vary by technology and system scale and should be considered when system choices are made.

Decentralization benefit: Smaller systems are less likely to raise questions over the distribution of their costs and benefits.

Decentralization benefit: Maintaining decentralized systems as permanent solutions avoids the "double payment" problem sewers can create.

Decentralization benefit: Centralization increases the expertise required of system managers and operators, and therefore the compensation required to retain them, perhaps to a point that generates ill will in some small communities.

Decentralization benefit: Decentralizing infrastructure units tends to reduce the political and economic "stakes" involved in a wastewater facility decision. This can reduce community conflict and its associated costs.

Decentralization benefit: By breaking borrowing needs into smaller amounts that occur periodically as a community grows, decentralized systems can help avoid mistrust and rate shock brought on by large borrowing for capacity that will not be fully used for years.

Decentralization benefit: Smaller systems lend themselves to local decisions, enhancing public comprehension and legitimacy.

Onsite and Neighborhood Impacts

Decentralization cost: While centralized wastewater systems are essentially out of sight and mind for most property owners (excepting payment of sewer bills), onsite and cluster systems require greater awareness and participation, with attendant non-monetary costs.

Decentralization benefit: Centralization intensifies undesirable system characteristics that induce public resistance and loss of value for neighboring properties.

Decentralization consideration: Visual impacts of wastewater systems on sites and neighborhoods may occur with any scale system.

Decentralization benefit: Odor control is typically less of a concern with smaller systems.

Decentralization consideration: Both centralized and decentralized systems can be noisy or quiet, depending on the technology chosen.

Decentralization benefit: Decentralization allows for preservation of open space and its attendant values without the costs of unnecessary infrastructure.

Decentralization cost: The greater the degree of decentralization, the greater the limit on development density. Where higher density is desirable, this may result in an inability to maximize property value.

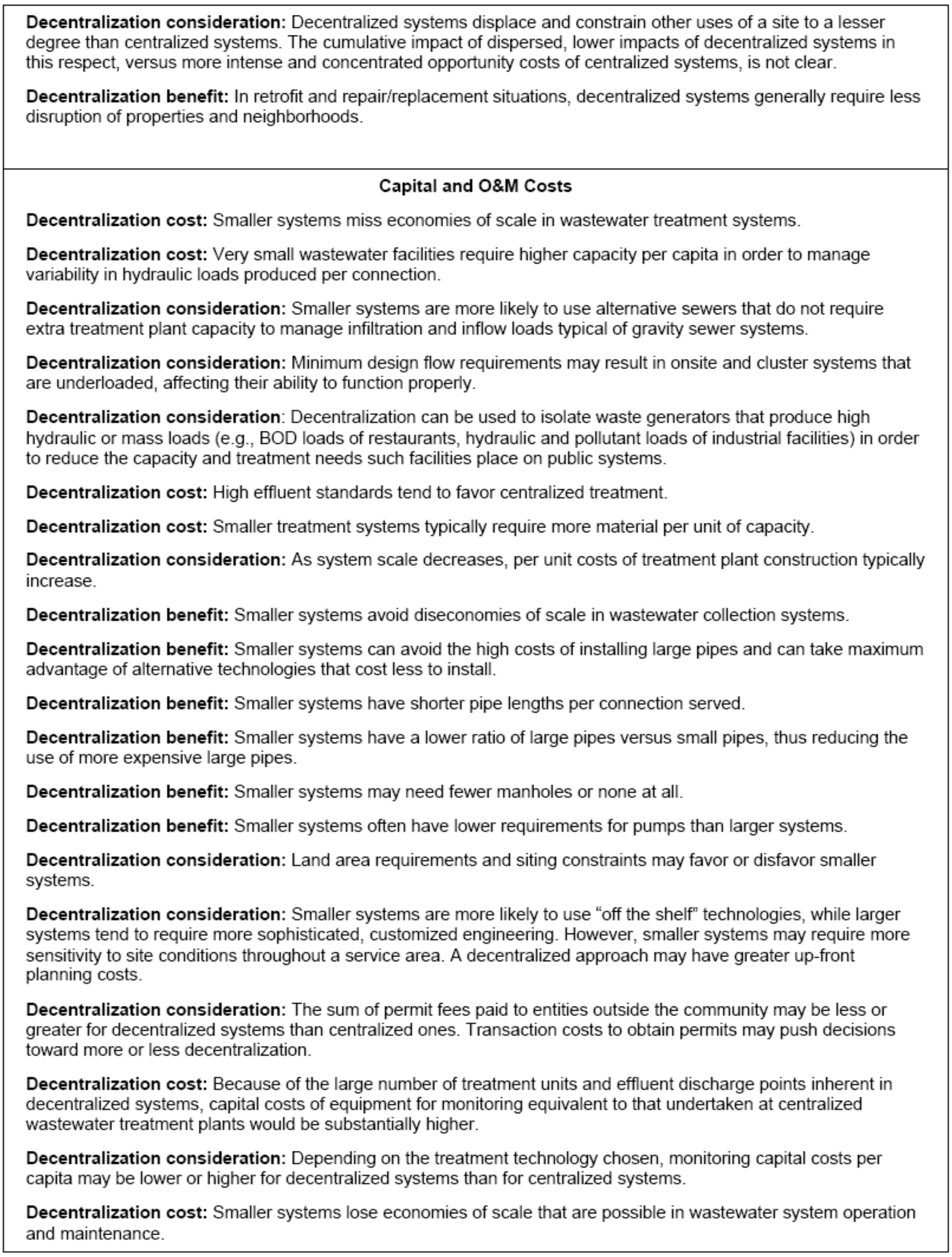
Decentralization benefit: Advanced decentralized systems may allow the development of otherwise undevelopable property, thereby creating or maintaining property value.

Decentralization consideration: Serving areas with decentralized systems rather than sewers can affect the affordability of properties.

Decentralization consideration: System scale may affect how a building or set of buildings can be located on a property, which may impact development costs and property value.

Decentralization consideration: Some wastewater systems may increase the value of the subject property or adjacent properties because of a perception that the system is particularly novel, sustainable, or valuable environmentally.

APPENDIX A5 (continued)



Decentralization consideration: Decentralized systems displace and constrain other uses of a site to a lesser degree than centralized systems. The cumulative impact of dispersed, lower impacts of decentralized systems in this respect, versus more intense and concentrated opportunity costs of centralized systems, is not clear.

Decentralization benefit: In retrofit and repair/replacement situations, decentralized systems generally require less disruption of properties and neighborhoods.

Capital and O&M Costs

Decentralization cost: Smaller systems miss economies of scale in wastewater treatment systems.

Decentralization cost: Very small wastewater facilities require higher capacity per capita in order to manage variability in hydraulic loads produced per connection.

Decentralization consideration: Smaller systems are more likely to use alternative sewers that do not require extra treatment plant capacity to manage infiltration and inflow loads typical of gravity sewer systems.

Decentralization consideration: Minimum design flow requirements may result in onsite and cluster systems that are underloaded, affecting their ability to function properly.

Decentralization consideration: Decentralization can be used to isolate waste generators that produce high hydraulic or mass loads (e.g., BOD loads of restaurants, hydraulic and pollutant loads of industrial facilities) in order to reduce the capacity and treatment needs such facilities place on public systems.

Decentralization cost: High effluent standards tend to favor centralized treatment.

Decentralization cost: Smaller treatment systems typically require more material per unit of capacity.

Decentralization consideration: As system scale decreases, per unit costs of treatment plant construction typically increase.

Decentralization benefit: Smaller systems avoid diseconomies of scale in wastewater collection systems.

Decentralization benefit: Smaller systems can avoid the high costs of installing large pipes and can take maximum advantage of alternative technologies that cost less to install.

Decentralization benefit: Smaller systems have shorter pipe lengths per connection served.

Decentralization benefit: Smaller systems have a lower ratio of large pipes versus small pipes, thus reducing the use of more expensive large pipes.

Decentralization benefit: Smaller systems may need fewer manholes or none at all.

Decentralization benefit: Smaller systems often have lower requirements for pumps than larger systems.

Decentralization consideration: Land area requirements and siting constraints may favor or disfavor smaller systems.

Decentralization consideration: Smaller systems are more likely to use “off the shelf” technologies, while larger systems tend to require more sophisticated, customized engineering. However, smaller systems may require more sensitivity to site conditions throughout a service area. A decentralized approach may have greater up-front planning costs.

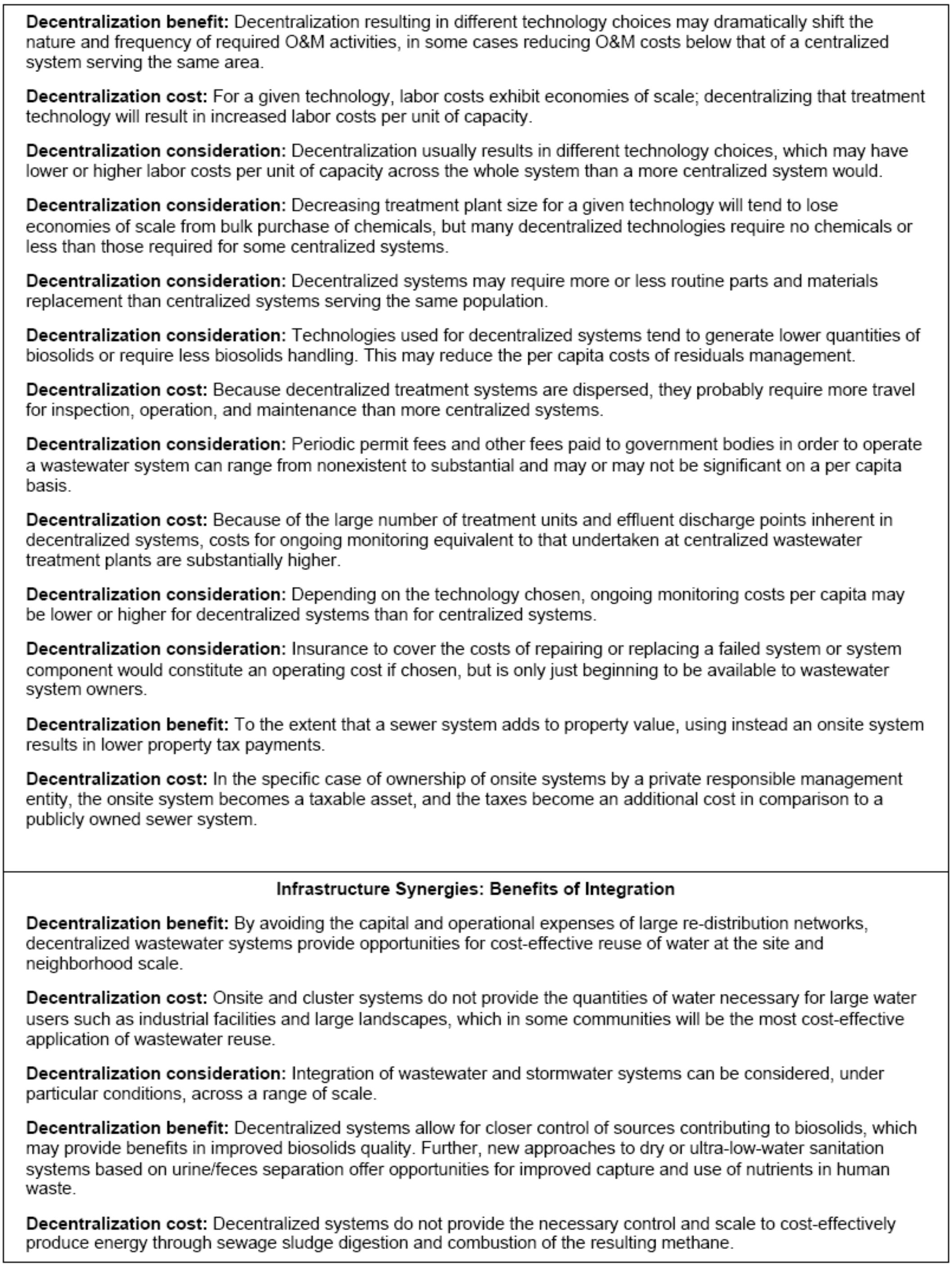
Decentralization consideration: The sum of permit fees paid to entities outside the community may be less or greater for decentralized systems than centralized ones. Transaction costs to obtain permits may push decisions toward more or less decentralization.

Decentralization cost: Because of the large number of treatment units and effluent discharge points inherent in decentralized systems, capital costs of equipment for monitoring equivalent to that undertaken at centralized wastewater treatment plants would be substantially higher.

Decentralization consideration: Depending on the treatment technology chosen, monitoring capital costs per capita may be lower or higher for decentralized systems than for centralized systems.

Decentralization cost: Smaller systems lose economies of scale that are possible in wastewater system operation and maintenance.

APPENDIX A5 (continued)



Decentralization benefit: Decentralization resulting in different technology choices may dramatically shift the nature and frequency of required O&M activities, in some cases reducing O&M costs below that of a centralized system serving the same area.

Decentralization cost: For a given technology, labor costs exhibit economies of scale; decentralizing that treatment technology will result in increased labor costs per unit of capacity.

Decentralization consideration: Decentralization usually results in different technology choices, which may have lower or higher labor costs per unit of capacity across the whole system than a more centralized system would.

Decentralization consideration: Decreasing treatment plant size for a given technology will tend to lose economies of scale from bulk purchase of chemicals, but many decentralized technologies require no chemicals or less than those required for some centralized systems.

Decentralization consideration: Decentralized systems may require more or less routine parts and materials replacement than centralized systems serving the same population.

Decentralization consideration: Technologies used for decentralized systems tend to generate lower quantities of biosolids or require less biosolids handling. This may reduce the per capita costs of residuals management.

Decentralization cost: Because decentralized treatment systems are dispersed, they probably require more travel for inspection, operation, and maintenance than more centralized systems.

Decentralization consideration: Periodic permit fees and other fees paid to government bodies in order to operate a wastewater system can range from nonexistent to substantial and may or may not be significant on a per capita basis.

Decentralization cost: Because of the large number of treatment units and effluent discharge points inherent in decentralized systems, costs for ongoing monitoring equivalent to that undertaken at centralized wastewater treatment plants are substantially higher.

Decentralization consideration: Depending on the technology chosen, ongoing monitoring costs per capita may be lower or higher for decentralized systems than for centralized systems.

Decentralization consideration: Insurance to cover the costs of repairing or replacing a failed system or system component would constitute an operating cost if chosen, but is only just beginning to be available to wastewater system owners.

Decentralization benefit: To the extent that a sewer system adds to property value, using instead an onsite system results in lower property tax payments.

Decentralization cost: In the specific case of ownership of onsite systems by a private responsible management entity, the onsite system becomes a taxable asset, and the taxes become an additional cost in comparison to a publicly owned sewer system.

Infrastructure Synergies: Benefits of Integration

Decentralization benefit: By avoiding the capital and operational expenses of large re-distribution networks, decentralized wastewater systems provide opportunities for cost-effective reuse of water at the site and neighborhood scale.

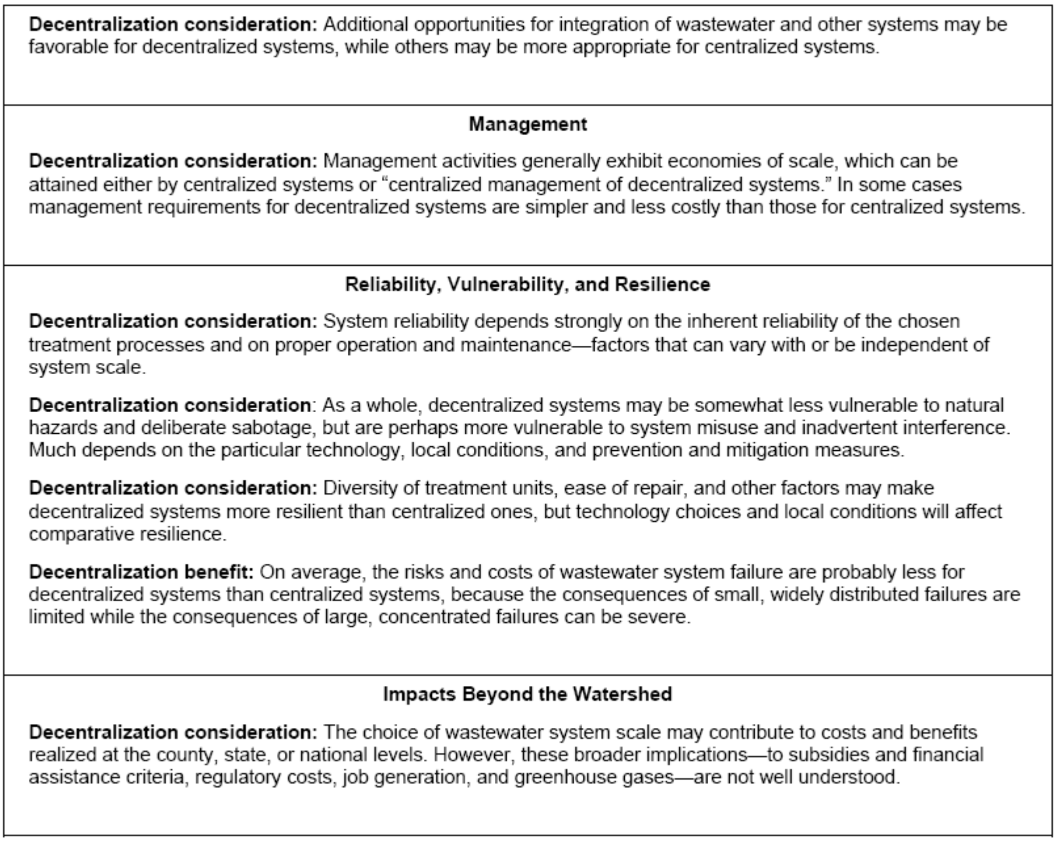
Decentralization cost: Onsite and cluster systems do not provide the quantities of water necessary for large water users such as industrial facilities and large landscapes, which in some communities will be the most cost-effective application of wastewater reuse.

Decentralization consideration: Integration of wastewater and stormwater systems can be considered, under particular conditions, across a range of scale.

Decentralization benefit: Decentralized systems allow for closer control of sources contributing to biosolids, which may provide benefits in improved biosolids quality. Further, new approaches to dry or ultra-low-water sanitation systems based on urine/feces separation offer opportunities for improved capture and use of nutrients in human waste.

Decentralization cost: Decentralized systems do not provide the necessary control and scale to cost-effectively produce energy through sewage sludge digestion and combustion of the resulting methane.

APPENDIX A5 (continued)



Decentralization consideration: Additional opportunities for integration of wastewater and other systems may be favorable for decentralized systems, while others may be more appropriate for centralized systems.

Management

Decentralization consideration: Management activities generally exhibit economies of scale, which can be attained either by centralized systems or “centralized management of decentralized systems.” In some cases management requirements for decentralized systems are simpler and less costly than those for centralized systems.

Reliability, Vulnerability, and Resilience

Decentralization consideration: System reliability depends strongly on the inherent reliability of the chosen treatment processes and on proper operation and maintenance—factors that can vary with or be independent of system scale.

Decentralization consideration: As a whole, decentralized systems may be somewhat less vulnerable to natural hazards and deliberate sabotage, but are perhaps more vulnerable to system misuse and inadvertent interference. Much depends on the particular technology, local conditions, and prevention and mitigation measures.

Decentralization consideration: Diversity of treatment units, ease of repair, and other factors may make decentralized systems more resilient than centralized ones, but technology choices and local conditions will affect comparative resilience.

Decentralization benefit: On average, the risks and costs of wastewater system failure are probably less for decentralized systems than centralized systems, because the consequences of small, widely distributed failures are limited while the consequences of large, concentrated failures can be severe.

Impacts Beyond the Watershed

Decentralization consideration: The choice of wastewater system scale may contribute to costs and benefits realized at the county, state, or national levels. However, these broader implications—to subsidies and financial assistance criteria, regulatory costs, job generation, and greenhouse gases—are not well understood.

APPENDIX A6

QUANTITATIVE AND QUALITATIVE IMPACTS OF REUSE ON SURFACE WATER RESOURCES (RIVERS)

(derived from Grobicki & Cohen 1999)

1. Same resource (river) for supply abstraction and wastewater effluent discharge

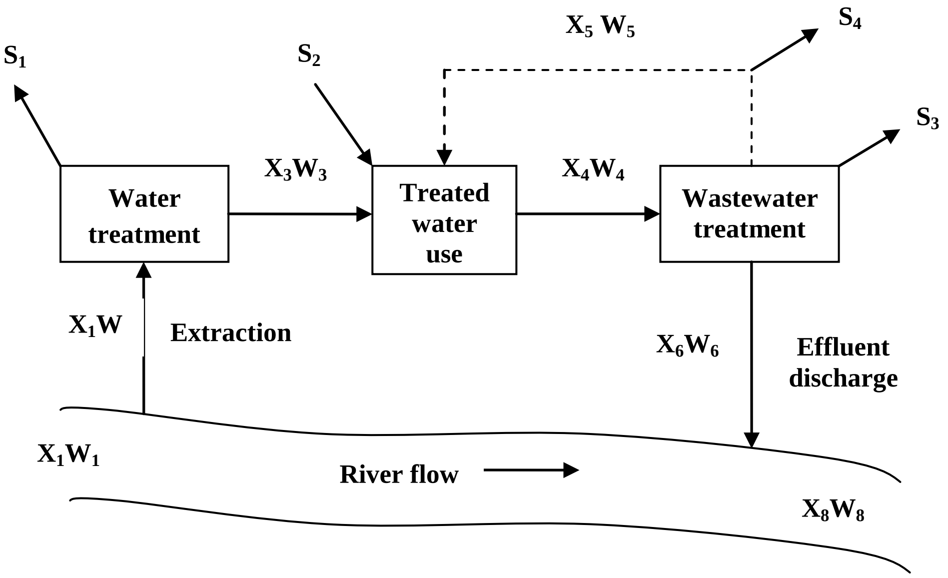


Figure A6(a)

1.1 River flow volume consideration

Figure A6(a) shows a simple water system with water removed from a river, treated and used and the remaining fraction is conveyed to wastewater treatment plant, treated and the effluent discharged into the same river. The flow in the river is reduced by the extracted stream W_2. A fraction is consumed and the remainder returned to the river as stream W_6. While with some reuse the stream discharged to the river will decrease, a lower extraction from the river would also result. Provided the amount of water reused is equivalent to that which would have been withdrawn from the river to meet this demand, reuse will imply no overall change to flow in the river.

In practise, a large amount of water is lost in all steps given in figure A5. With a reuse step introduced, the new infrastructure of treatment, transport and storage would result in lower losses compared to the single supply system. In a reuse step the total water abstracted W_2 is reduced by the amount recycled plus the reduction of water losses in the dual system. As W_6 is reduced only by the amount reused, the net overall abstraction from the source decreases, resulting in a net increase in river flow with reuse compared to non-reuse.

1.2 River TDS quality consideration

In Figure A6(a) let W represent the stream flow (l/hr) and X be the TDS concentration (g/l). XW represent the mass flow rate of TDS (g/hr). The S term represent TDS addition to or removal from water (g/hr).

(i) S_1 is removal TDS during fresh water treatment.
(ii) S_2 is the addition of TDS resulting from normal water use, e.g. domestic use.
(iii) S_3 is the removal of TDS during wastewater treatment in order to meet the receiving water body discharge requirements.
(iv) S_4 is TDS removed from the wastewater effluent intended for reuse to meet quality requirements of the user. This quality will depend on the reuse application.

The total quantity of TDS returned to the river in the stream W_6 for a reuse scenario will depend on the value of S_4. As mentioned before, reuse implies a reduction in stream W_2 and hence an increase in W_7.

Consider total TDS balance over the whole system:

$$X_8W_8 = X_1W_1 - (S_1 + S_4) + S_2 - S_3$$

Consider the effect of a reuse scenario on the right hand side of this equation, assuming initially that losses remain constant:

(i) X_1W_1 will not change
(ii) S_2, the TDS during use, and S_3, the TDS removed in treatment of wastewater, will be unaffected vs. the non-reuse scenario.
(iii) S_1 will drop by a value ΔS_1, since less fresh water is being treated.

(iv) S_4 is between zero and the value by which S_1 has changed (ΔS_1), depending on the quality requirements of the reuse user.

Where S_4 is less than ΔS_1 (i.e. the quality of reclaimed water used is lower than that of potable) a reduction in X_8W_8 is demonstrated, while treatment of reclaimed water to potable standards, and $S_4 = \Delta S_1$ will imply no change in X_8W_8.

Since it was demonstrated that a reuse scenario (with constant system losses) implies no change in river flow, reuse in this case also results in no change or a lowering in TDS loadings in the river downstream of the effluent discharge point.

To check the calculation, a balance is done over the system excluding the river:

$$X_6W_6 = X_1W_2 - (S_1 + S_4) + S_2 - S_3$$

Thus reuse compared to a non-reuse scenario implies:

(i) A reduction in W_2 and hence in X_1W_2,

(ii) A reduction in S_1, ΔS_1, which is the equivalent of the reduction in X_1W_2,

(iii) No change in S_2 and S_3 as discussed above,

(iv) A reduction in W_6,

(v) S_4 is between zero and ΔS_1, depending on quality requirements in reuse application.

Thus X_6W_6 either remains unchanged (where $S_4 = 0$, $\Delta X_1W_2 = \Delta S_1$ and thus X_6W_6 is unaffected) or decreases by a value of up to ΔX_1W_2 (when $S_4 = S_1$). Hence $\Delta X_1W_2 \leq \Delta X_6W_6 \leq 0$.

Now,

$$X_8W_8 = X_1W_1 - X_1W_2 + X_6W_6$$

With reuse compared to non-reuse, X_1W_1 remains unchanged, X_1W_2 decreases and X_6W_6 either remains the same (where $\Delta X_1W_2 = \Delta X_6W_6$) or decreases (when $\Delta X_1W_2 < \Delta X_6W_6$) up to a value of ΔX_1W_2 when $\Delta X_6W_6 = 0$.

These results thus confirm the mass balance done over the river system as a whole.

(i) X_1W_1, S_2 and S_3 do not change,
(ii) The terms X_1W_2 and S_1 are reduced,
(iii) The term X_6W_6 remains unchanged.

Hence the total TDS load X_8W_8 increases. It is necessary, however, to consider the total water flow to see how the TDS concentrations in the final stream X_8 changes. It was proven earlier that reuse does not change total stream flow W_2 compared to a non-use scenario. As the total TDS load has increased while the stream flow have not, therefore X_8 has increased. This applies to rivers equally regardless of whether the wastewater effluent being added to dilute flow in the river, or whether the river flow dilutes effluent discharged.

2. Different rivers for supply abstraction and wastewater effluent discharge

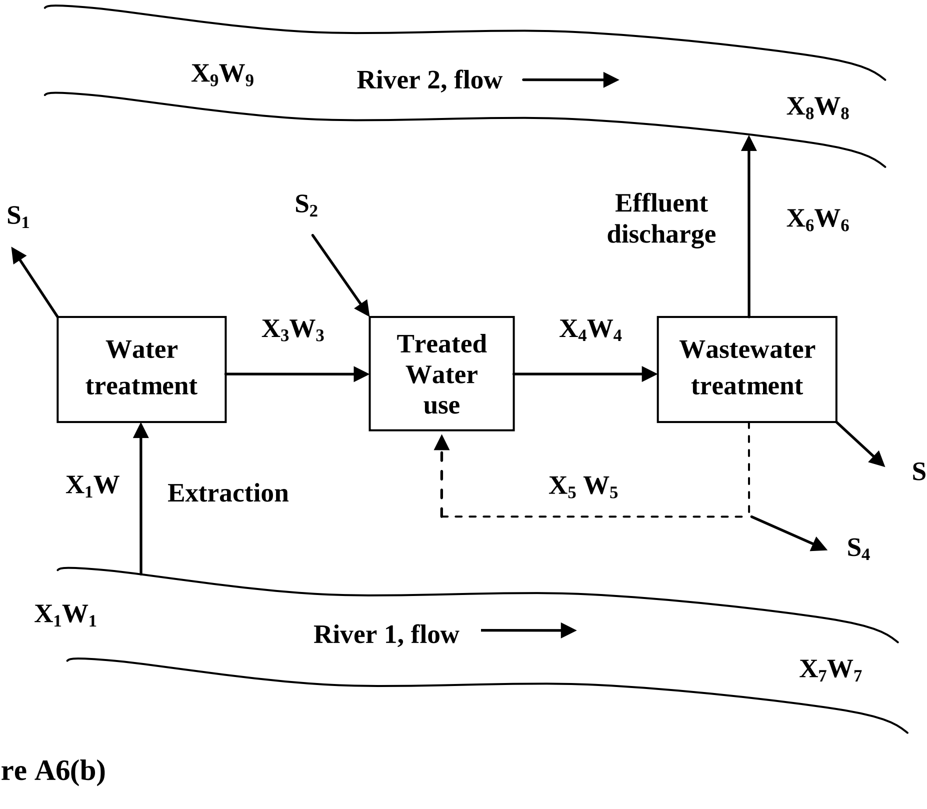


Figure A6(b)

2.1 River flow volume consideration

Figure A6(b) illustrates a situation of inter-basin transfers where supplies are extracted from “river 1”, while the discharge of effluent takes place to “river 2”. Reuse here implies a reduction in effluent return to “river 2” (W_6). Reuse results in a reduction in demand for fresh water, W_2 and hence an increase of flow in “river 1” takes place. The reduction of flow in “river 2” due to reuse need evaluation in each case specifically as it would make less flow available for users downstream from the discharge point. Once again new infrastructure for reuse purposes may imply lower system losses and hence the reduction in W_6 may be less than the reduction in W_1.

2.2 River TDS quality consideration

As illustrated in figure A6(b), no discharge takes place to “river 1” and its TDS concentration is therefore not influenced by reuse.

The TDS mass balance for “river 2” is:

$$X_8 W_8 = X_9 W_9 + X_6 W_6$$

When reuse is introduced, then

(i) W6 reduces,
(ii) X9W9 remains unchanged.

Considering a mass balance over the water use and wastewater treatment steps alone, then

$$X_6 W_6 = X_3 W_3 + S_2 - S_3 - S_4$$

In a reuse where S_2 and S_3 remain unchanged, X_3W_3 will decrease as the requirement for fresh water reduces. The value of S_4 would be between zero and the change in X_3W_3. Therefore, regardless of the value of S_4, X_6W_6 reduces. The total TDS in “river 2” (X_8W_8) thus also reduces with a reuse scenario.

APPENDIX A7

SIMPLIFIED WATER BALANCE MODEL FOR DETERMINING INCREASED SUPPLY OF A URBAN WATER SYSTEM THROUGH REUSE

(after Grobicki, Cohen 1999)

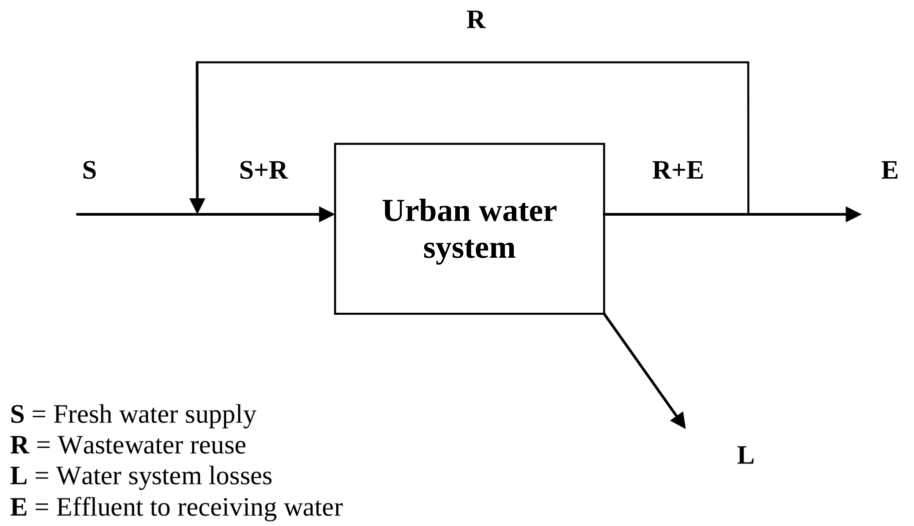


Figure A7 Simplified water balance of urban water supply system with reuse

A water balance over the whole water system gives:

$$S = E + L \tag{1}$$

A water balance over the urban water system itself gives:

$$S + R = E + R + L \tag{2}$$

By considering various levels of system losses (L) as a ratio of the total water supply to the urban water system the results in table A5 are obtained.

APPENDIX A7 (continued)

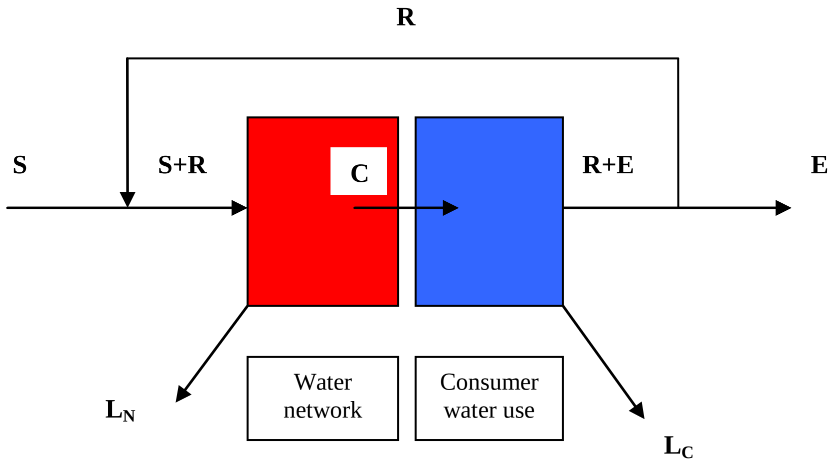
CALCULATION OF ADDITIONAL SUPPLY AVAILABILITY THROUGH REUSE

Table A7

Assumed water system loss (%)	**Loss as fraction of total supply**	**Water balance over urban water system** (Substitute L into eq. (2), figure A6)	**Increase in supply through reuse (%)**
20	$L = 0.2(S+R)$	$S+R = 0.2S + 1.2R + E$ $with\ max\ reuse, E = 0$ $R = 4S$	400
35	$L = 0.35(S+R)$	$S+R = 0.35S + 1.35R + E$ $with\ max\ reuse, E = 0$ $R = 1.86S$	186
50	$L = 0.50(S+R)$	$S+R = 0.50S + 1.50R + E$ $with\ max\ reuse, E = 0$ $R = S$	100
65	$L = 0.65(S+R)$	$S+R = 0.65S + 1.65R + E$ $with\ max\ reuse, E = 0$ $R = 0.54S$	54

APPENDIX A8

REVISED WATER BALANCE MODEL FOR URBAN WATER SUPPLY WITH REUSE, DIFFERENTIATING BETWEEN URBAN NETWORK AND CONSUMER-END RELATED LOSSES



S = Fresh water supply
R = Wastewater reuse
L_N = Different water network losses
L_C = Different consumer type losses
C = Different consumer type water use
E = Final effluent to receiving waters body

Figure A8 Network-consumer differentiated urban water supply system with reuse

Considering water balance over the whole water system in Figure A8 gives:

$$S = E + (L_N + L_C) \tag{A7.1}$$

A water balance over the urban water network gives:

$$S + R = L_N + C \tag{A7.2}$$

A water balance over the consumer area gives:

$$C = L_C + R + E \tag{A7.3}$$

A water balance over both the water network and consumer area gives:

$$S + R = (L_N + L_C) + R + E \tag{A7.4}$$

Scenario considered:

1) Urban network losses = 20% of total supply.

2) Return flow to urban wastewater system as fraction of consumption = 70%.

For condition 1) $L_N = 0.2(S+R)$

For condition 2) $L_C = 0.3C$

$$R+E = 0.7C$$

Substitute 1) and 2) into Eq A7.4

$$S+R = 0.2(S+R)+0.3\left(\frac{R+E}{0.7}\right)+R+E$$

$$S+R = 0.2S+0.2R+0.43R+0.43E+R+E$$

$$0.8S = 0.63R+1.43E$$

For full reuse (E = 0), then

$$R = \frac{0.8}{0.63}S = 1.26S$$

Therefore with reuse the increase in water supply is 126%.

APPENDIX B1

WASTEWATER TREATMENT PLANT CONTAMINANT DATA AND DERIVED MONTHLY LOADS REMOVED

Jul-09	**Ave Flow (ML/d)**	**Monthly Flow (ML)**	Influent COD (mg/l)	Effluent COD (mg/l)	**COD removed** (kg/month)	Influent SS (mg/l)	Effluent SS (mg/l)	**SS removed** (kg/month)
Plant 1	0.57	17.67	910.00	97.00	14366	325.00	60.00	4683
Plant 2	83.73	2595.63	894.00	50.00	2190712	309.00	11.00	773498
Plant 3	57.50	1782.50	846.00	84.00	1358265	341.00	30.00	554358
Plant 4	29.10	902.10	453.00	78.00	338288	131.00	27.00	93818
Plant 5	8.47	262.57	528.00	88.00	115531	185.00	24.00	42274
Plant 6	10.99	340.69	397.00	39.00	121967	193.00	10.00	62346
Plant 7	23.69	734.39	918.00	52.00	635982	333.00	20.00	229864
Plant 8	86.96	2695.76	496.00	40.39	1228215	170.24	10.00	431969
Plant 9	146.77	4549.87	787.00	35.00	3421502	343.00	10.00	1515107

Jul-09	**Ave Flow (ML/d)**	**Monthly Flow (ML)**	Influent N (mg/l)	Effluent N (mg/l)	**N removed** (kg/month)	Influent PO4 (mg/l)	Effluent PO4 (mg/l)	**PO4 removed** (kg/month)
Plant 1	0.57	17.67	37.60	15.70	387	5.60	0.20	95
Plant 2	83.73	2595.63	36.20	6.30	77609	8.90	2.50	16612
Plant 3	57.50	1782.50	14.00	8.30	10160	4.50	0.40	7308
Plant 4	29.10	902.10	10.60	1.00	8660	2.70	0.60	1894
Plant 5	8.47	262.57	20.40	1.40	4989	3.80	2.40	368
Plant 6	10.99	340.69	25.60	11.80	4702	7.90	0.90	2385
Plant 7	23.69	734.39	33.40	4.40	21297	7.50	0.70	4994
Plant 8	86.96	2695.76	21.63	7.89	37040	4.04	1.13	7845
Plant 9	146.77	4549.87	19.90	3.00	76893	6.00	0.60	24569

APPENDIX B1 (continued)

Aug-09	**Ave Flow (ML/d)**	**Monthly Flow (ML)**	Influent COD (mg/l)	Effluent COD (mg/l)	**COD removed (kg/month)**	Influent SS (mg/l)	Effluent SS (mg/l)	**SS removed (kg/month)**
Plant 1	0.55	17.05	1040.00	85.00	16283	452.00	51.00	6837
Plant 2	82.00	2542.00	1163.00	48.00	2834330	437.00	13.00	1077808
Plant 3	54.21	1680.51	967.00	71.00	1505737	361.00	21.00	571373
Plant 4	32.10	995.10	493.00	81.00	409981	168.00	29.00	138319
Plant 5	9.17	284.27	725.00	64.00	187902	190.00	29.00	45767
Plant 6	12.93	400.83	448.00	36.00	165142	175.00	15.00	64133
Plant 7	26.78	830.18	898.00	51.00	703162	330.00	23.00	254865
Plant 8	93.87	2909.97	564.73	63.50	1458564	185.77	20.15	481949
Plant 9	125.42	3888.02	939.00	41.00	3491442	334.00	14.00	1244166

Aug-09	**Ave Flow (ML/d)**	**Monthly Flow (ML)**	Influent N (mg/l)	Effluent N (mg/l)	**N removed (kg/month)**	Influent PO4 (mg/l)	Effluent PO4 (mg/l)	**PO4 removed (kg/month)**
Plant 1	0.55	17.05	42.10	23.70	314	7.00	0.80	106
Plant 2	82.00	2542.00	34.40	6.90	69905	9.90	3.10	17286
Plant 3	54.21	1680.51	19.60	7.10	21006	5.90	0.10	9747
Plant 4	32.10	995.10	13.70	6.90	6767	2.50	0.60	1891
Plant 5	9.17	284.27	21.80	1.10	5884	5.60	0.70	1393
Plant 6	12.93	400.83	29.10	11.20	7175	5.40	0.40	2004
Plant 7	26.78	830.18	32.00	6.50	21170	6.90	1.00	4898
Plant 8	93.87	2909.97	22.97	9.75	38470	4.17	1.66	7304
Plant 9	125.42	3888.02	19.20	2.10	66485	6.30	1.10	20218

APPENDIX B1 (continued)

Sep-09	**Ave Flow (ML/d)**	**Monthly Flow (ML)**	Influent COD (mg/l)	Effluent COD (mg/l)	**COD removed** (kg/month)	Influent SS (mg/l)	Effluent SS (mg/l)	**SS removed** (kg/month)
Plant 1	0.55	16.50	1111.00	59.00	17358	485.00	34.00	7442
Plant 2	81.28	2438.40	1091.00	52.00	2533498	448.00	14.00	1058266
Plant 3	48.77	1463.10	981.00	62.00	1344589	429.00	20.00	598408
Plant 4	31.52	945.60	641.00	86.00	524808	162.00	34.00	121037
Plant 5	9.30	279.00	730.00	74.00	183024	224.00	35.00	52731
Plant 6	15.09	452.70	420.00	37.00	173384	148.00	15.00	60209
Plant 7	31.15	934.50	1001.00	42.00	896186	338.00	20.00	297171
Plant 8	97.06	2911.80	600.80	56.00	1586349	187.55	17.62	494802
Plant 9	131.22	3936.60	1125.00	36.00	4286957	389.00	15.00	1472288

Sep-09	**Ave Flow (ML/d)**	**Monthly Flow (ML)**	Influent N (mg/l)	Effluent N (mg/l)	**N removed** (kg/month)	Influent PO4 (mg/l)	Effluent PO4 (mg/l)	**PO4 removed** (kg/month)
Plant 1	0.55	16.50	46.00	24.50	355	7.20	1.70	94
Plant 2	81.28	2438.40	32.90	9.70	56571	8.40	3.30	12850
Plant 3	48.77	1463.10	19.20	3.30	23263	6.60	0.20	9676
Plant 4	31.52	945.60	15.10	7.40	7281	2.70	0.80	1857
Plant 5	9.30	279.00	26.30	2.50	6640	3.80	0.80	865
Plant 6	15.09	452.70	24.60	6.60	8149	4.70	0.60	1918
Plant 7	31.15	934.50	35.30	6.80	26633	7.30	1.00	6084
Plant 8	97.06	2911.80	21.40	9.95	33340	3.96	1.17	8395
Plant 9	131.22	3936.60	21.70	3.60	71252	6.30	0.70	22780

APPENDIX B1 (continued)

Oct-09	**Ave Flow (ML/d)**	**Monthly Flow (ML)**	Influent COD (mg/l)	Effluent COD (mg/l)	**COD removed** (kg/month)	Influent SS (mg/l)	Effluent SS (mg/l)	**SS removed** kg/month
Plant 1	0.57	17.67	1153.00	78.00	18995	471.00	27.00	7845
Plant 2	79.69	2470.39	793.00	50.00	1835500	267.00	10.00	634890
Plant 3	63.20	1959.20	858.00	46.00	1590870	344.00	10.00	654373
Plant 4	37.82	1172.42	538.00	93.00	521727	140.00	28.00	131311
Plant 5	8.82	273.42	1009.00	63.00	258655	242.00	23.00	59879
Plant 6	15.97	495.07	501.00	32.00	232188	191.00	15.00	87132
Plant 7	29.34	909.54	1171.00	38.00	1030509	312.00	15.00	270133
Plant 8	105.70	3276.70	608.25	53.64	1817291	168.09	11.45	513262
Plant 9	166.12	5149.72	1126.00	43.00	5577147	320.00	11.00	1591263

Oct-09	**Ave Flow (ML/d)**	**Monthly Flow (ML)**	Influent N (mg/l)	Effluent N (mg/l)	**N removed** (kg/month)	Influent PO4 (mg/l)	Effluent PO4 (mg/l)	**PO4 removed** kg/month
Plant 1	0.57	17.67	38.80	26.20	223	7.60	1.60	106
Plant 2	79.69	2470.39	34.10	4.50	73124	7.90	2.00	14575
Plant 3	63.20	1959.20	18.20	1.10	33502	3.60	0.10	6857
Plant 4	37.82	1172.42	11.90	8.20	4338	1.50	0.80	821
Plant 5	8.82	273.42	24.40	2.80	5906	5.60	0.50	1394
Plant 6	15.97	495.07	26.10	6.90	9505	5.00	1.40	1782
Plant 7	29.34	909.54	39.60	4.20	32198	7.60	0.60	6367
Plant 8	105.70	3276.70	21.65	8.72	42368	3.91	1.52	7831
Plant 9	166.12	5149.72	19.50	4.30	78276	5.20	0.70	23174

APPENDIX B1 (continued)

Nov-09	Ave Flow (ML/d)	Monthly Flow (ML)	Influent COD (mg/l)	Effluent COD (mg/l)	COD removed (kg/month)	Influent SS (mg/l)	Effluent SS (mg/l)	SS removed (kg/month)
Plant 1	0.55	16.50	995.00	60.00	15428	491.00	36.00	7508
Plant 2	81.28	2438.40	1131.00	40.00	2660294	430.00	10.00	1024128
Plant 3	48.77	1463.10	817.00	42.00	1133903	370.00	13.00	522327
Plant 4	31.52	945.60	467.00	70.00	375403	113.00	26.00	82267
Plant 5	9.30	279.00	572.00	48.00	146196	186.00	24.00	45198
Plant 6	15.09	452.70	339.00	21.00	143959	132.00	10.00	55229
Plant 7	31.15	934.50	1077.00	31.00	977487	363.00	16.00	324272
Plant 8	97.06	2911.80	524.00	43.00	1400576	157.00	11.00	425123
Plant 9	131.22	3936.60	817.00	41.00	3054802	277.00	11.00	1047136

Nov-09	Ave Flow (ML/d)	Monthly Flow (ML)	Influent N (mg/l)	Effluent N (mg/l)	N removed (kg/month)	Influent PO4 (mg/l)	Effluent PO4 (mg/l)	PO4 removed (kg/month)
Plant 1	0.55	16.50	25.60	19.90	94	8.40	0.80	130
Plant 2	81.28	2438.40	33.20	2.10	75834	7.70	2.80	12346
Plant 3	48.77	1463.10	15.80	0.70	22093	4.00	0.10	5896
Plant 4	31.52	945.60	8.80	3.00	5484	1.00	0.30	684
Plant 5	9.30	279.00	19.20	3.10	4492	4.40	0.20	1211
Plant 6	15.09	452.70	20.50	1.30	8692	4.10	0.70	1590
Plant 7	31.15	934.50	40.80	3.50	34857	8.30	0.40	7629
Plant 8	97.06	2911.80	18.00	7.30	31156	3.40	1.50	5717
Plant 9	131.22	3936.60	14.90	7.30	29918	4.70	0.90	15458

APPENDIX B1 (continued)

Dec-09	**Ave Flow (ML/d)**	**Monthly Flow (ML)**	Influent COD (mg/l)	Effluent COD (mg/l)	**COD removed** (kg/month)	Influent SS (mg/l)	Effluent SS (mg/l)	**SS removed** (kg/month)
Plant 1	0.82	25.42	1233.00	81.00	29284	673.00	27.00	16421
Plant 2	80.46	2494.26	1063.00	48.00	2531674	440.00	10.00	1072532
Plant 3	59.86	1855.66	2396.00	50.00	4353378	1041.00	10.00	1913185
Plant 4	48.66	1508.46	551.00	73.00	721044	124.00	23.00	152354
Plant 5	14.69	455.39	624.00	74.00	250465	181.00	23.00	71952
Plant 6	16.89	523.59	346.00	24.00	168596	110.00	11.00	51835
Plant 7	30.37	941.47	902.00	32.00	819079	283.00	10.00	257021
Plant 8	140.10	4343.10	506.00	55.00	1958738	137.00	10.00	551574
Plant 9	178.90	5545.90	736.00	41.00	3854401	250.00	10.00	1331016

Dec-09	**Ave Flow (Ml/d)**	**Monthly Flow (ML)**	Influent N (mg/l)	Effluent N (mg/l)	**N removed** (kg/month)	Influent PO4 (mg/l)	Effluent PO4 (mg/l)	**PO4 removed** (kg/month)
Plant 1	0.82	25.42	34.00	21.70	313	10.10	0.20	252
Plant 2	80.46	2494.26	33.30	3.10	75327	8.10	2.50	13968
Plant 3	59.86	1855.66	13.10	0.60	23196	6.00	0.10	10948
Plant 4	48.66	1508.46	10.60	3.60	10559	1.90	0.30	2414
Plant 5	14.69	455.39	15.40	3.40	5465	4.30	0.40	1776
Plant 6	16.89	523.59	18.00	3.10	7801	4.30	0.60	1937
Plant 7	30.37	941.47	37.40	2.20	33140	7.50	0.30	6779
Plant 8	140.10	4343.10	18.00	8.40	41694	3.80	2.60	5212
Plant 9	178.90	5545.90	16.60	6.90	53795	4.50	0.80	20520

APPENDIX B1 (continued)

Jan-10	Ave Flow (ML/d)	Monthly Flow (ML)	Influent COD (mg/l)	Effluent COD (mg/l)	COD removed (kg/month)	Influent SS (mg/l)	Effluent SS (mg/l)	SS removed (kg/month)
Plant 1	0.93	28.83	548.00	25.00	15078	224.00	12.00	6112
Plant 2	128.99	3998.69	793.00	31.00	3047002	343.00	10.00	1331564
Plant 3	85.61	2653.91	718.00	36.00	1809967	316.00	10.00	812096
Plant 4	60.63	1879.53	305.00	38.00	501835	84.00	16.00	127808
Plant 5	13.89	430.59	607.00	45.00	241992	138.00	20.00	50810
Plant 6	22.31	691.61	180.00	19.00	111349	83.00	10.00	50488
Plant 7	32.58	1009.98	549.00	21.00	533269	199.00	10.00	190886
Plant 8	181.89	5638.59	279.00	39.90	1348187	94.98	15.05	450692
Plant 9	261.34	8101.54	381.00	23.00	2900351	164.00	10.00	1247637

Jan-10	Ave Flow (ML/d)	Monthly Flow (ML)	Influent N (mg/l)	Effluent N (mg/l)	N removed (kg/month)	Influent PO4 (mg/l)	Effluent PO4 (mg/l)	PO4 removed (kg/month)
Plant 1	0.93	28.83	21.50	2.30	554	3.50	0.20	95
Plant 2	128.99	3998.69	25.90	1.10	99168	5.70	2.30	13596
Plant 3	85.61	2653.91	7.40	0.70	17781	3.60	0.20	9023
Plant 4	60.63	1879.53	7.50	1.50	11277	0.90	0.10	1504
Plant 5	13.89	430.59	15.30	2.90	5339	4.10	0.20	1679
Plant 6	22.31	691.61	13.60	1.20	8576	2.60	0.90	1176
Plant 7	32.58	1009.98	19.70	2.00	17877	4.40	0.50	3939
Plant 8	181.89	5638.59	12.39	6.87	31125	2.53	1.62	5131
Plant 9	261.34	8101.54	11.30	1.30	81015	3.40	1.40	16203

APPENDIX B1 (continued)

Feb-10	**Ave Flow (ML/d)**	**Monthly Flow (ML)**	Influent COD (mg/l)	Effluent COD (mg/l)	**COD removed** (kg/month)	Influent SS (mg/l)	Effluent SS (mg/l)	**SS removed** (kg/month)
Plant 1	0.86	24.08	1056.00	33.00	24634	577.00	24.00	13316
Plant 2	89.04	2493.12	1194.00	22.00	2921937	407.00	10.00	989769
Plant 3	83.64	2341.92	572.00	39.00	1248243	250.00	10.00	562061
Plant 4	52.37	1466.36	353.00	52.00	441374	87.00	16.00	104112
Plant 5	15.50	434.00	519.00	39.00	208320	143.00	16.00	55118
Plant 6	16.00	448.00	273.00	22.00	112448	117.00	14.00	46144
Plant 7	30.69	859.32	579.00	25.00	476063	251.00	10.00	207096
Plant 8	162.04	4537.12	502.16	40.50	2094607	188.69	11.61	803433
Plant 9	231.66	6486.48	415.00	38.00	2445403	155.00	10.00	940540

Feb-10	**Ave Flow (ML/d)**	**Monthly Flow (ML)**	Influent N (mg/l)	Effluent N (mg/l)	**N removed** (kg/month)	Influent PO4 (mg/l)	Effluent PO4 (mg/l)	**PO4 removed** (kg/month)
Plant 1	0.86	24.08	24.90	3.90	506	6.70	0.30	154
Plant 2	89.04	2493.12	29.60	0.50	72550	6.40	0.80	13961
Plant 3	83.64	2341.92	11.50	0.70	25293	2.90	0.20	6323
Plant 4	52.37	1466.36	10.20	2.80	10851	1.20	0.40	1173
Plant 5	15.50	434.00	13.50	1.10	5382	3.20	0.70	1085
Plant 6	16.00	448.00	12.10	1.80	4614	2.30	1.70	269
Plant 7	30.69	859.32	21.60	1.00	17702	5.80	0.90	4211
Plant 8	162.04	4537.12	16.39	6.30	45780	3.21	1.51	7713
Plant 9	231.66	6486.48	13.10	2.50	68757	3.40	0.80	16865

APPENDIX B1 (continued)

Mar-10	**Ave Flow (ML/d)**	**Monthly Flow (ML)**	Influent COD (mg/l)	Effluent COD (mg/l)	**COD removed** (kg/month)	Influent SS (mg/l)	Effluent SS (mg/l)	**SS removed** (kg/month)
Plant 1	0.88	27.28	1273.38	21.10	34162	594.35	21.75	15621
Plant 2	84.13	2608.03	1460.32	27.42	3737051	765.40	10.00	1970106
Plant 3	41.88	1298.28	870.54	33.55	1086647	304.29	11.36	380305
Plant 4	41.52	1287.12	378.90	56.89	414466	93.50	7.09	111220
Plant 5	13.57	420.67	602.10	44.62	234515	152.90	15.81	57670
Plant 6	13.87	429.97	224.77	24.86	85955	58.69	10.23	20836
Plant 7	28.12	871.72	771.82	33.80	643347	236.95	12.43	195719
Plant 8	143.40	4445.40	628.00	36.64	2628832	200.00	15.73	819154
Plant 9	215.89	6692.59	590.94	36.88	3708096	224.00	10.55	1428533

Mar-10	**Ave Flow (ML/d)**	**Monthly Flow (ML)**	Influent N (mg/l)	Effluent N (mg/l)	**N removed** (kg/month)	Influent PO4 (mg/l)	Effluent PO4 (mg/l)	**PO4 removed** (kg/month)
Plant 1	0.88	27.28	26.62	3.84	621	7.90	0.18	211
Plant 2	84.13	2608.03	31.31	1.11	78763	8.08	0.70	19247
Plant 3	41.88	1298.28	13.78	0.30	17501	3.64	0.60	3947
Plant 4	41.52	1287.12	10.51	2.07	10863	1.36	0.38	1261
Plant 5	13.57	420.67	17.12	0.79	6870	4.35	0.50	1620
Plant 6	13.87	429.97	14.58	0.69	5972	3.15	1.73	611
Plant 7	28.12	871.72	23.57	1.50	19239	5.65	1.01	4045
Plant 8	143.40	4445.40	22.60	6.14	73171	5.30	2.05	14448
Plant 9	215.89	6692.59	16.62	2.36	95436	4.29	1.79	16731

APPENDIX B1 (continued)

Apr-10	Ave Flow (ML/d)	Monthly Flow (ML)	Influent COD (mg/l)	Effluent COD (mg/l)	COD removed (kg/month)	Influent SS (mg/l)	Effluent SS (mg/l)	SS removed (kg/month)
Plant 1	0.76	22.80	958.79	40.50	20937	549.74	23.50	11998
Plant 2	82.84	2485.20	1578.00	39.55	3823368	770.05	10.55	1887509
Plant 3	46.24	1387.20	889.21	46.72	1168702	7281.80	12.37	10084153
Plant 4	45.12	1353.60	423.76	42.59	515952	81.66	11.86	94481
Plant 5	12.10	363.00	504.60	54.71	163310	142.20	20.00	44359
Plant 6	19.63	588.90	219.36	18.26	118428	77.09	14.63	36783
Plant 7	10.75	322.50	774.95	33.58	239092	240.89	13.63	73291
Plant 8	152.78	4583.40	689.20	49.74	2930901	240.07	13.95	1036398
Plant 9	231.10	6933.00	487.00	33.40	3144809	179.27	14.10	1145124

Apr-10	Ave Flow (ML/d)	Monthly Flow (ML)	Influent N (mg/l)	Effluent N (mg/l)	N removed (kg/month)	Influent PO4 (mg/l)	Effluent PO4 (mg/l)	PO4 removed (kg/month)
Plant 1	0.76	22.80	25.43	3.67	496	5.83	0.52	121
Plant 2	82.84	2485.20	32.40	0.71	78756	7.50	0.46	17496
Plant 3	46.24	1387.20	13.40	7.75	7838	4.01	0.22	5257
Plant 4	45.12	1353.60	10.99	1.85	12372	1.53	0.58	1286
Plant 5	12.10	363.00	15.37	2.66	4614	2.90	0.41	904
Plant 6	19.63	588.90	16.20	1.38	8727	2.82	0.30	1484
Plant 7	10.75	322.50	22.68	1.50	6831	6.67	0.56	1970
Plant 8	152.78	4583.40	24.49	9.14	70355	7.28	1.65	25805
Plant 9	231.10	6933.00	14.41	1.28	91030	2.99	0.55	16917

APPENDIX B1 (continued)

May-10	**Ave Flow (ML/d)**	**Monthly Flow (ML)**	Influent COD (mg/l)	Effluent COD (mg/l)	**COD removed** (kg/month)	Influent SS (mg/l)	Effluent SS (mg/l)	**SS removed** (kg/month)
Plant 1	0.68	21.08	1357.19	33.52	27903	534.71	24.86	10748
Plant 2	88.16	2732.96	1194.85	31.10	3180482	465.10	10.00	1243770
Plant 3	63.02	1953.62	802.43	58.20	1453943	267.48	12.48	498173
Plant 4	43.25	1340.75	447.07	48.71	534101	126.33	7.26	159643
Plant 5	10.21	316.51	645.24	58.71	185643	198.62	19.38	56731
Plant 6	17.20	533.20	211.75	19.14	102700	86.08	11.90	39553
Plant 7	31.33	971.23	824.21	32.00	769418	281.00	14.85	258493
Plant 8	153.00	4743.00	935.00	54.86	4174504	373.00	10.00	1721709
Plant 9	228.65	7088.15	534.35	32.39	3557968	160.10	12.00	1049755

May-10	**Ave Flow (ML/d)**	**Monthly Flow (ML)**	Influent N (mg/l)	Effluent N (mg/l)	**N removed** (kg/month)	Influent PO4 (mg/l)	Effluent PO4 (mg/l)	**PO4 removed** (kg/month)
Plant 1	0.68	21.08	25.34	0.81	517	6.43	0.18	132
Plant 2	88.16	2732.96	36.11	2.48	91909	7.70	0.41	19923
Plant 3	63.02	1953.62	14.55	1.23	26022	4.02	0.15	7561
Plant 4	43.25	1340.75	14.87	2.16	17041	3.10	0.51	3473
Plant 5	10.21	316.51	15.73	3.12	3991	3.40	0.45	934
Plant 6	17.20	533.20	15.13	0.46	7822	2.52	0.37	1146
Plant 7	31.33	971.23	36.34	1.87	33478	6.08	0.87	5058
Plant 8	153.00	4743.00	28.07	9.07	90117	5.07	1.38	17502
Plant 9	228.65	7088.15	15.59	0.66	105826	3.99	0.61	23958

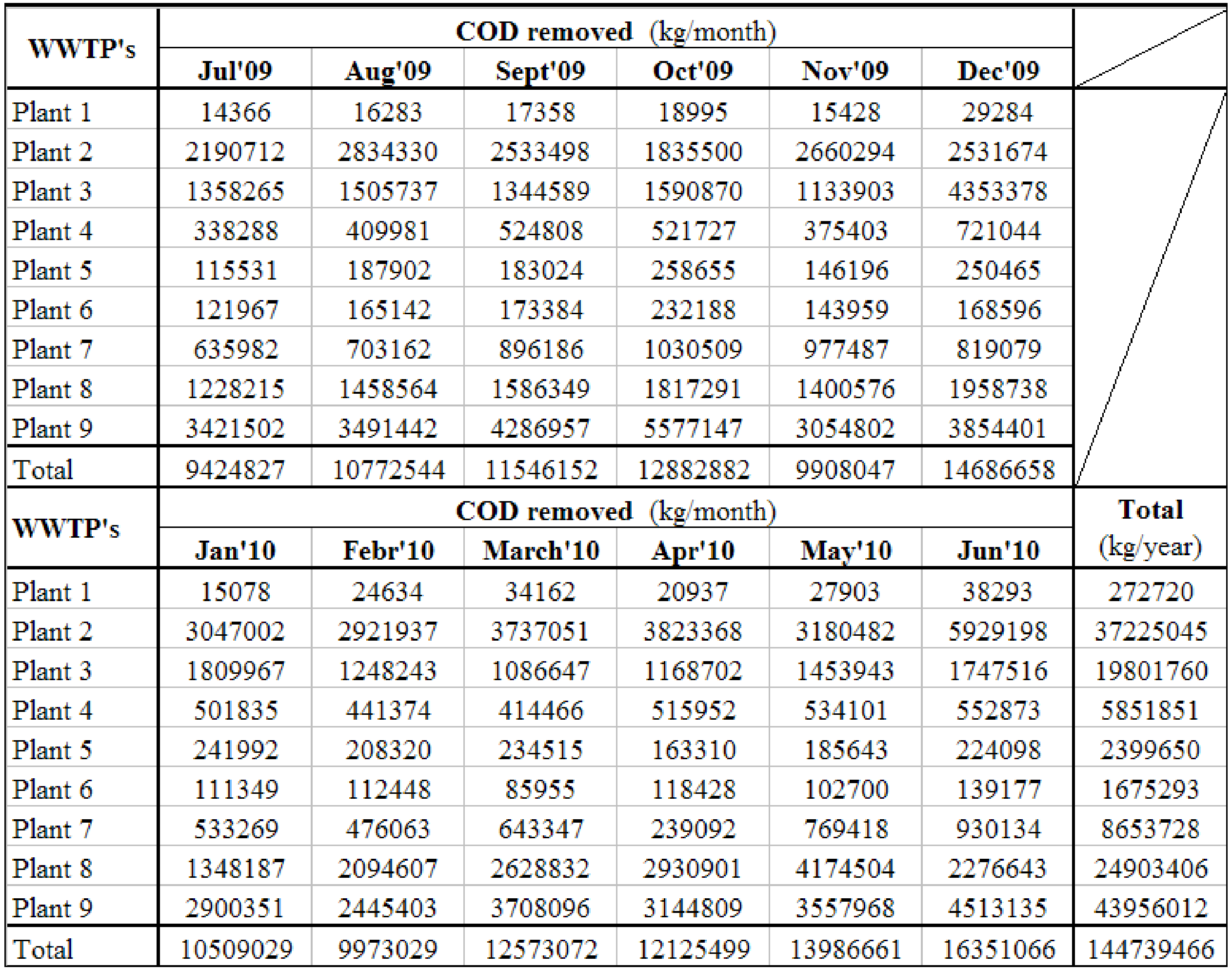
APPENDIX B1 (continued)

Jun-10	**Ave Flow (ML/d)**	**Monthly Flow (ML)**	Influent COD (mg/l)	Effluent COD (mg/l)	**COD removed** (kg/month)	Influent SS (mg/l)	Effluent SS (mg/l)	**SS removed** (kg/month)
Plant 1	0.73	21.90	1788.05	39.50	38293	1016.30	21.95	21776
Plant 2	77.99	2339.70	2566.52	32.35	5929198	1165.59	11.00	2701394
Plant 3	52.29	1568.70	1207.25	93.26	1747516	433.35	25.00	640579
Plant 4	33.46	1003.80	636.96	86.18	552873	156.64	26.61	130524
Plant 5	9.72	291.60	819.30	50.79	224098	245.60	18.89	66109
Plant 6	15.52	465.60	319.92	21.00	139177	121.25	11.30	51193
Plant 7	32.33	969.90	1000.00	41.00	930134	301.84	18.00	275296
Plant 8	116.50	3495.00	718.00	66.60	2276643	230.00	18.30	739892
Plant 9	186.87	5606.10	845.21	40.17	4513135	322.21	12.31	1737330

Jun-10	**Ave Flow (ML/d)**	**Monthly Flow (ML)**	Influent N (mg/l)	Effluent N (mg/l)	**N removed** (kg/month)	Influent PO4 (mg/l)	Effluent PO4 (mg/l)	**PO4 removed** (kg/month)
Plant 1	0.73	21.90	28.04	2.70	555	8.93	0.20	191
Plant 2	77.99	2339.70	37.91	1.73	84650	9.67	0.70	20987
Plant 3	52.29	1568.70	19.46	5.87	21319	7.11	1.60	8644
Plant 4	33.46	1003.80	16.47	3.73	12788	2.80	0.46	2349
Plant 5	9.72	291.60	19.43	1.65	5185	3.74	0.49	948
Plant 6	15.52	465.60	18.96	1.02	8353	3.11	0.56	1187
Plant 7	32.33	969.90	35.33	3.09	31270	7.03	0.68	6159
Plant 8	116.50	3495.00	23.20	9.80	46833	4.80	2.10	9437
Plant 9	186.87	5606.10	18.54	0.84	99228	3.54	0.43	17435

APPENDIX B2

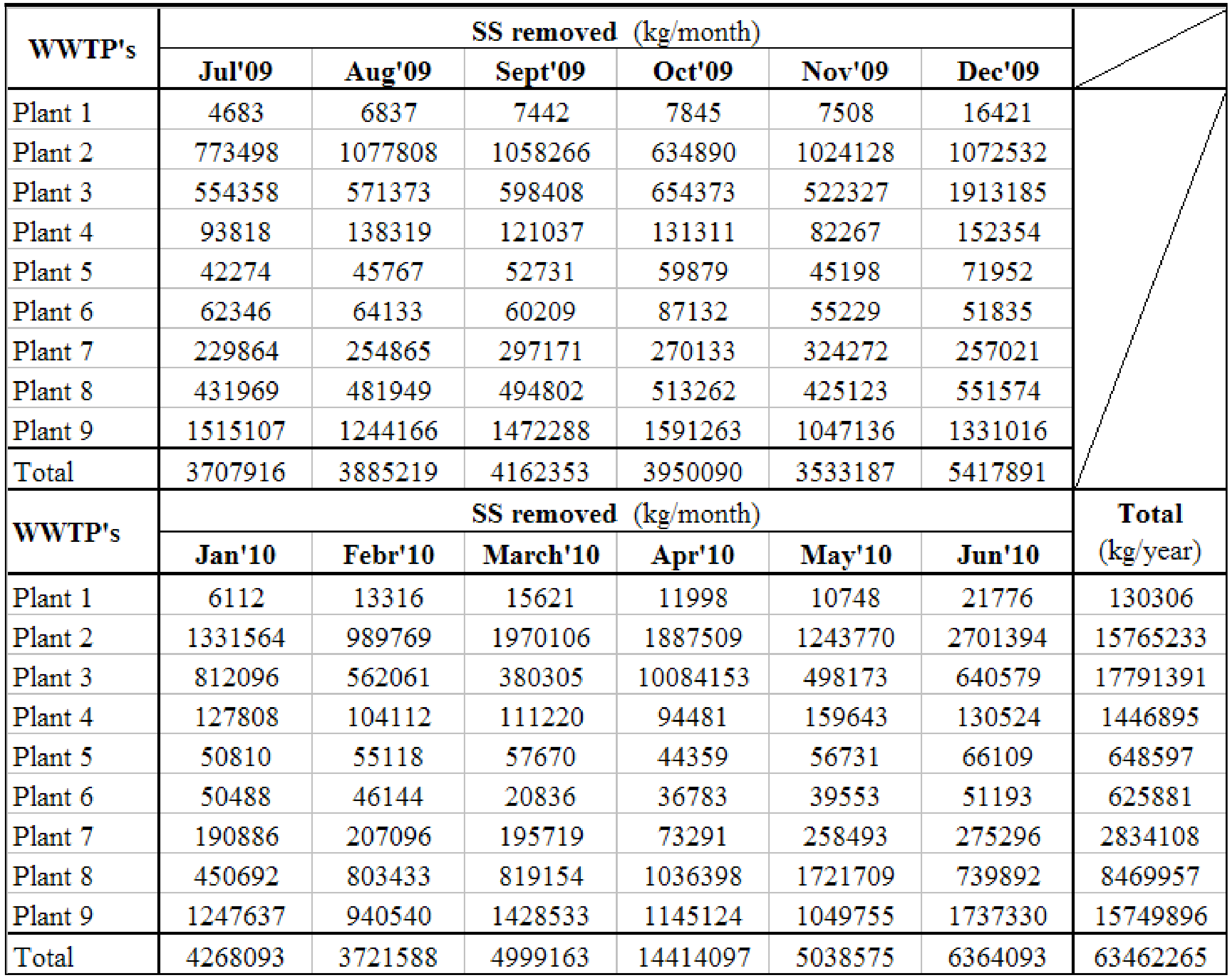
SUMMARY OF MONTHLY CONTAMINANT COD REMOVAL



WWTP's	COD removed (kg/month)						
	Jul'09	Aug'09	Sept'09	Oct'09	Nov'09	Dec'09	
Plant 1	14366	16283	17358	18995	15428	29284	
Plant 2	2190712	2834330	2533498	1835500	2660294	2531674	
Plant 3	1358265	1505737	1344589	1590870	1133903	4353378	
Plant 4	338288	409981	524808	521727	375403	721044	
Plant 5	115531	187902	183024	258655	146196	250465	
Plant 6	121967	165142	173384	232188	143959	168596	
Plant 7	635982	703162	896186	1030509	977487	819079	
Plant 8	1228215	1458564	1586349	1817291	1400576	1958738	
Plant 9	3421502	3491442	4286957	5577147	3054802	3854401	
Total	9424827	10772544	11546152	12882882	9908047	14686658	
WWTP's	COD removed (kg/month)						Total (kg/year)
	Jan'10	Febr'10	March'10	Apr'10	May'10	Jun'10	
Plant 1	15078	24634	34162	20937	27903	38293	272720
Plant 2	3047002	2921937	3737051	3823368	3180482	5929198	37225045
Plant 3	1809967	1248243	1086647	1168702	1453943	1747516	19801760
Plant 4	501835	441374	414466	515952	534101	552873	5851851
Plant 5	241992	208320	234515	163310	185643	224098	2399650
Plant 6	111349	112448	85955	118428	102700	139177	1675293
Plant 7	533269	476063	643347	239092	769418	930134	8653728
Plant 8	1348187	2094607	2628832	2930901	4174504	2276643	24903406
Plant 9	2900351	2445403	3708096	3144809	3557968	4513135	43956012
Total	10509029	9973029	12573072	12125499	13986661	16351066	144739466

APPENDIX B3

SUMMARY OF MONTHLY CONTAMINANT SS REMOVAL



WWTP's	**SS removed** (kg/month)						
	Jul'09	**Aug'09**	**Sept'09**	**Oct'09**	**Nov'09**	**Dec'09**	
Plant 1	4683	6837	7442	7845	7508	16421	
Plant 2	773498	1077808	1058266	634890	1024128	1072532	
Plant 3	554358	571373	598408	654373	522327	1913185	
Plant 4	93818	138319	121037	131311	82267	152354	
Plant 5	42274	45767	52731	59879	45198	71952	
Plant 6	62346	64133	60209	87132	55229	51835	
Plant 7	229864	254865	297171	270133	324272	257021	
Plant 8	431969	481949	494802	513262	425123	551574	
Plant 9	1515107	1244166	1472288	1591263	1047136	1331016	
Total	3707916	3885219	4162353	3950090	3533187	5417891	

WWTP's	**SS removed** (kg/month)						**Total** (kg/year)
	Jan'10	**Febr'10**	**March'10**	**Apr'10**	**May'10**	**Jun'10**	
Plant 1	6112	13316	15621	11998	10748	21776	130306
Plant 2	1331564	989769	1970106	1887509	1243770	2701394	15765233
Plant 3	812096	562061	380305	10084153	498173	640579	17791391
Plant 4	127808	104112	111220	94481	159643	130524	1446895
Plant 5	50810	55118	57670	44359	56731	66109	648597
Plant 6	50488	46144	20836	36783	39553	51193	625881
Plant 7	190886	207096	195719	73291	258493	275296	2834108
Plant 8	450692	803433	819154	1036398	1721709	739892	8469957
Plant 9	1247637	940540	1428533	1145124	1049755	1737330	15749896
Total	4268093	3721588	4999163	14414097	5038575	6364093	63462265

APPENDIX B4

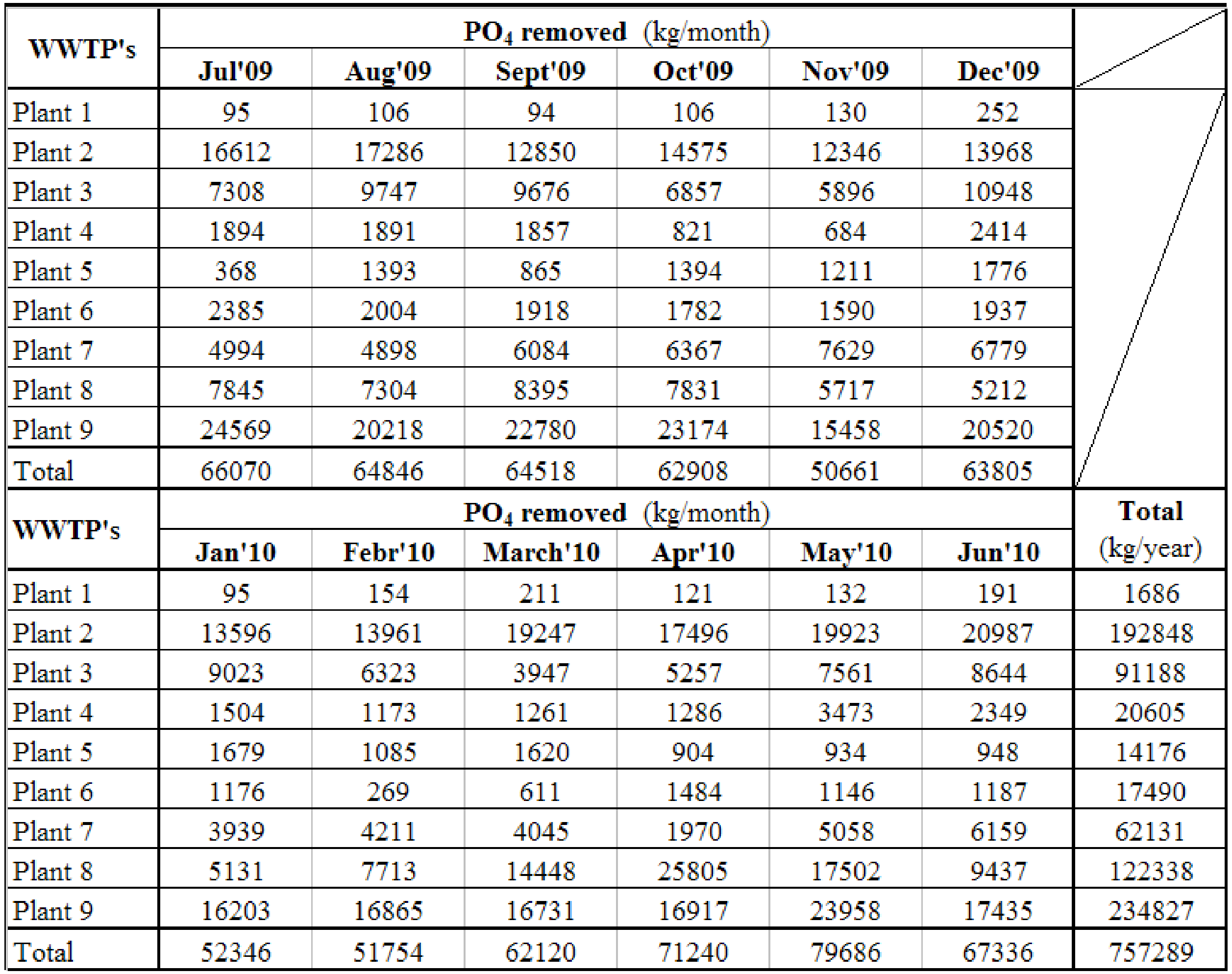
SUMMARY OF MONTHLY CONTAMINANT N REMOVAL

WWTP's	N removed (kg/month)						
	Jul'09	Aug'09	Sept'09	Oct'09	Nov'09	Dec'09	
Plant 1	387	314	355	223	94	313	
Plant 2	77609	69905	56571	73124	75834	75327	
Plant 3	10160	21006	23263	33502	22093	23196	
Plant 4	8660	6767	7281	4338	5484	10559	
Plant 5	4989	5884	6640	5906	4492	5465	
Plant 6	4702	7175	8149	9505	8692	7801	
Plant 7	21297	21170	26633	32198	34857	33140	
Plant 8	37040	38470	33340	42368	31156	41694	
Plant 9	76893	66485	71252	78276	29918	53795	
Total	241737	237176	233485	279439	212621	251289	

WWTP's	N removed (kg/month)						Total (kg/year)
	Jan'10	Febr'10	March'10	Apr'10	May'10	Jun'10	
Plant 1	554	506	621	496	517	555	4934
Plant 2	99168	72550	78763	78756	91909	84650	934165
Plant 3	17781	25293	17501	7838	26022	21319	248974
Plant 4	11277	10851	10863	12372	17041	12788	118282
Plant 5	5339	5382	6870	4614	3991	5185	64756
Plant 6	8576	4614	5972	8727	7822	8353	90089
Plant 7	17877	17702	19239	6831	33478	31270	295690
Plant 8	31125	45780	73171	70355	90117	46833	581448
Plant 9	81015	68757	95436	91030	105826	99228	917912
Total	272712	251433	308436	281019	376724	310180	3256251

APPENDIX B5

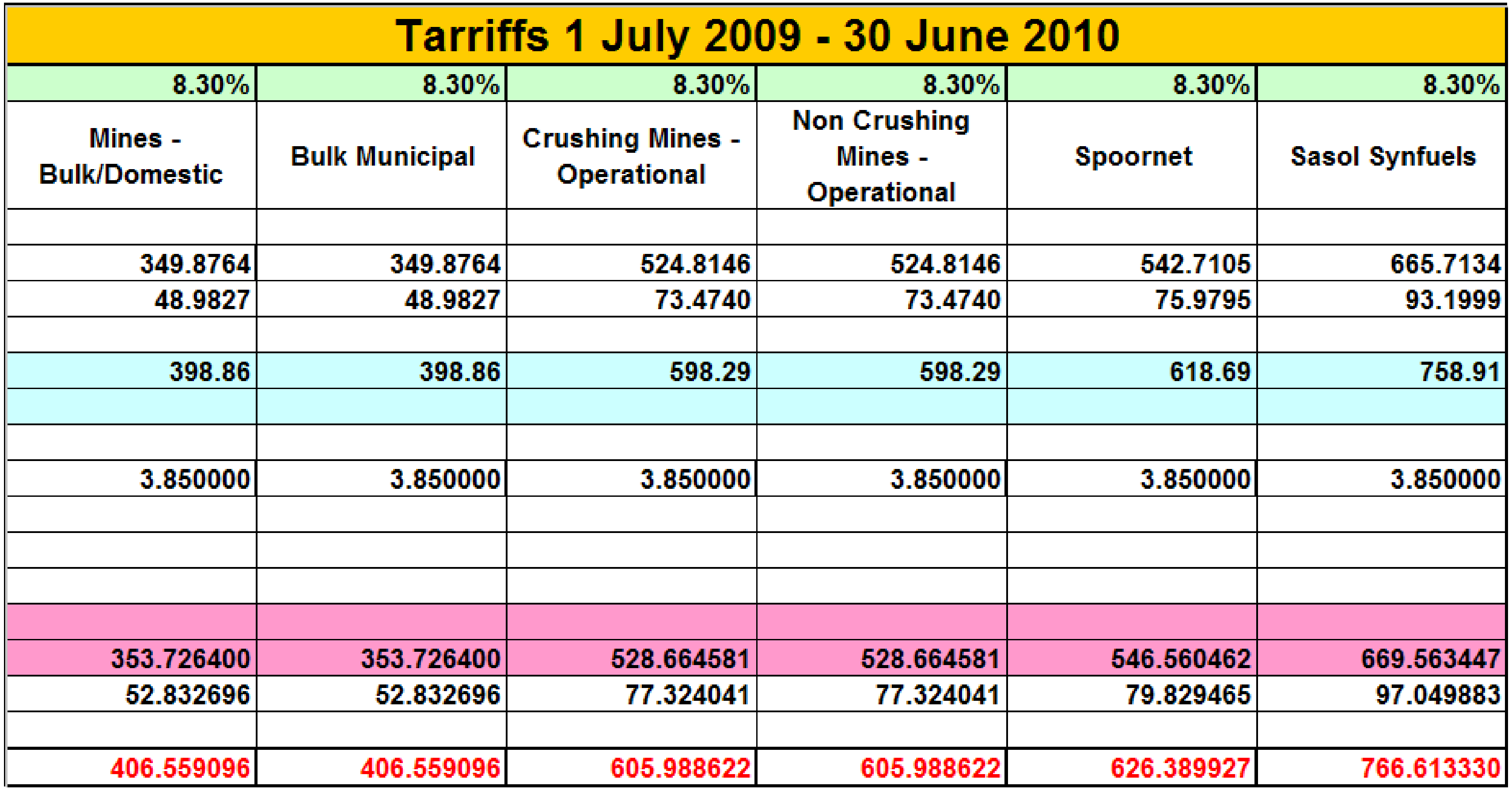
SUMMARY OF MONTHLY CONTAMINANT P REMOVAL



WWTP's	PO_4 removed (kg/month)						
	Jul'09	Aug'09	Sept'09	Oct'09	Nov'09	Dec'09	
Plant 1	95	106	94	106	130	252	
Plant 2	16612	17286	12850	14575	12346	13968	
Plant 3	7308	9747	9676	6857	5896	10948	
Plant 4	1894	1891	1857	821	684	2414	
Plant 5	368	1393	865	1394	1211	1776	
Plant 6	2385	2004	1918	1782	1590	1937	
Plant 7	4994	4898	6084	6367	7629	6779	
Plant 8	7845	7304	8395	7831	5717	5212	
Plant 9	24569	20218	22780	23174	15458	20520	
Total	66070	64846	64518	62908	50661	63805	
WWTP's	PO_4 removed (kg/month)						Total (kg/year)
	Jan'10	Febr'10	March'10	Apr'10	May'10	Jun'10	
Plant 1	95	154	211	121	132	191	1686
Plant 2	13596	13961	19247	17496	19923	20987	192848
Plant 3	9023	6323	3947	5257	7561	8644	91188
Plant 4	1504	1173	1261	1286	3473	2349	20605
Plant 5	1679	1085	1620	904	934	948	14176
Plant 6	1176	269	611	1484	1146	1187	17490
Plant 7	3939	4211	4045	1970	5058	6159	62131
Plant 8	5131	7713	14448	25805	17502	9437	122338
Plant 9	16203	16865	16731	16917	23958	17435	234827
Total	52346	51754	62120	71240	79686	67336	757289

APPENDIX B6

RAND WATER BULK WATER TARIFFS (1 JULY 2009 – 30 JUNE 2010)



Tarriffs 1 July 2009 - 30 June 2010					
8.30%	8.30%	8.30%	8.30%	8.30%	8.30%
Mines - Bulk/Domestic	Bulk Municipal	Crushing Mines - Operational	Non Crushing Mines - Operational	Spoornet	Sasol Synfuels
349.8764	349.8764	524.8146	524.8146	542.7105	665.7134
48.9827	48.9827	73.4740	73.4740	75.9795	93.1999
398.86	398.86	598.29	598.29	618.69	758.91
3.850000	3.850000	3.850000	3.850000	3.850000	3.850000
353.726400	353.726400	528.664581	528.664581	546.560462	669.563447
52.832696	52.832696	77.324041	77.324041	79.829465	97.049883
406.559096	406.559096	605.988622	605.988622	626.389927	766.613330

APPENDIX B7

ECONOMIC ANALYSIS CALCULATIONS FOR VARIOUS TREATED EFFLUENT REUSE LEVELS

WWTP's	**Economic viability analysis wrt level of direct reuse**						FWT$_{2010}$ (ZAR)
	100% direct reuse		80%		60%		
	Req FW rate	% FWT$_{2010}$	Req FW rate	% FWT$_{2010}$	Req FW rate	% FWT$_{2010}$	4.06559
Plant 1	2.90	71.31	3.50	86.03	4.41	108.42	
Plant 2	0.67	16.38	0.80	19.60	0.99	24.39	
Plant 3	0.72	17.78	0.86	21.25	1.07	26.39	
Plant 4	0.49	11.93	0.59	14.44	0.74	18.29	
Plant 5	0.70	17.14	0.84	20.68	1.06	26.07	
Plant 6	0.65	16.06	0.79	19.31	0.98	24.23	
Plant 7	0.50	12.22	0.60	14.66	0.74	18.32	
Plant 8	0.29	7.25	0.35	8.71	0.44	10.92	
Plant 9	0.42	10.42	0.51	12.54	0.64	15.76	

WWTP's	**Economic viability analysis wrt level of direct reuse**						FWT$_{2010}$ (ZAR)
	40% direct reuse		20%		Zero %		
	Req FW rate	% FWT$_{2010}$	Req FW rate	% FWT$_{2010}$	Req FW rate	% FWT$_{2010}$	4.06559
Plant 1	5.96	146.55	9.19	226.07	20.09	494.23	
Plant 2	1.31	32.28	1.94	47.71	3.72	91.40	
Plant 3	1.42	34.83	2.08	51.18	3.92	96.50	
Plant 4	1.01	24.95	1.59	39.22	3.72	91.58	
Plant 5	1.43	35.24	2.21	54.36	4.83	118.90	
Plant 6	1.32	32.49	2.01	49.32	4.16	102.33	
Plant 7	0.99	24.42	1.49	36.58	2.97	72.94	
Plant 8	0.59	14.62	0.90	22.13	1.85	45.47	
Plant 9	0.86	21.19	1.31	32.32	2.77	68.10	

APPENDIX C1

STAGED TREATMENT CAPACITY VERSUS FLOW BALANCE

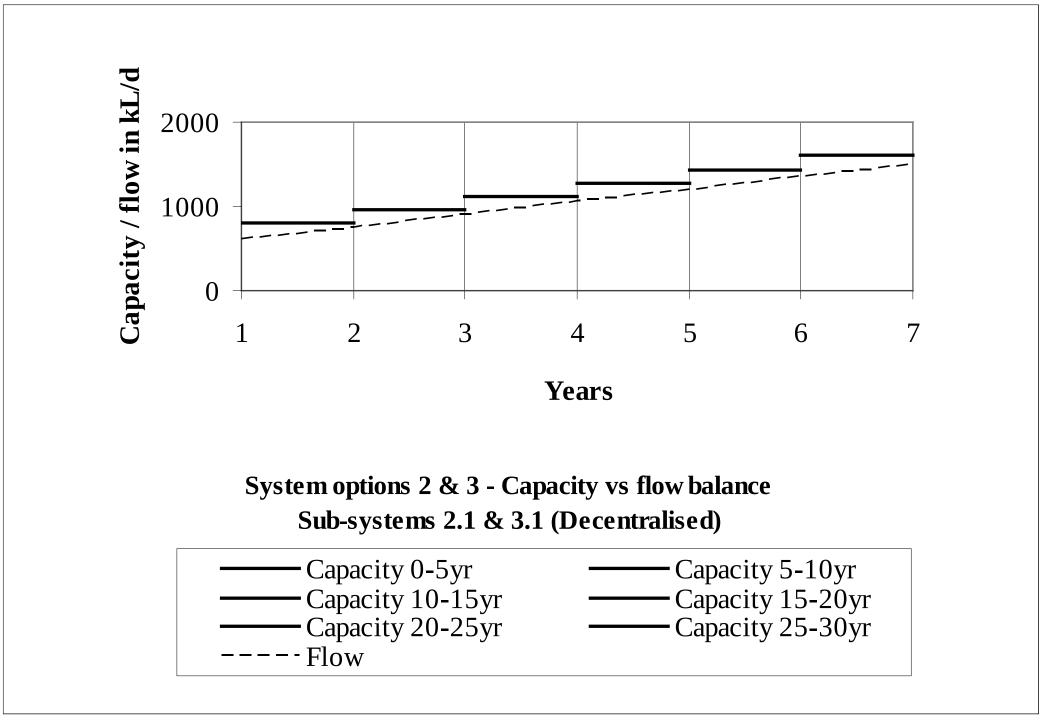


Figure C1.1 Decentralised sub-systems 2.1 & 3.1

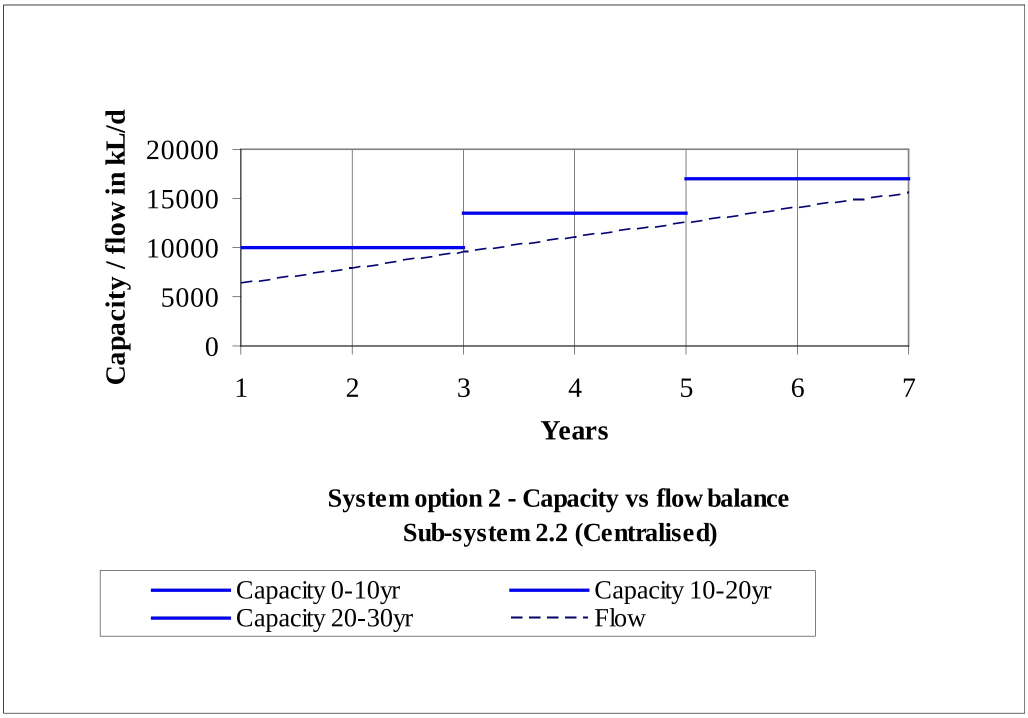


Figure C1.2 Centralised sub-system 2.2

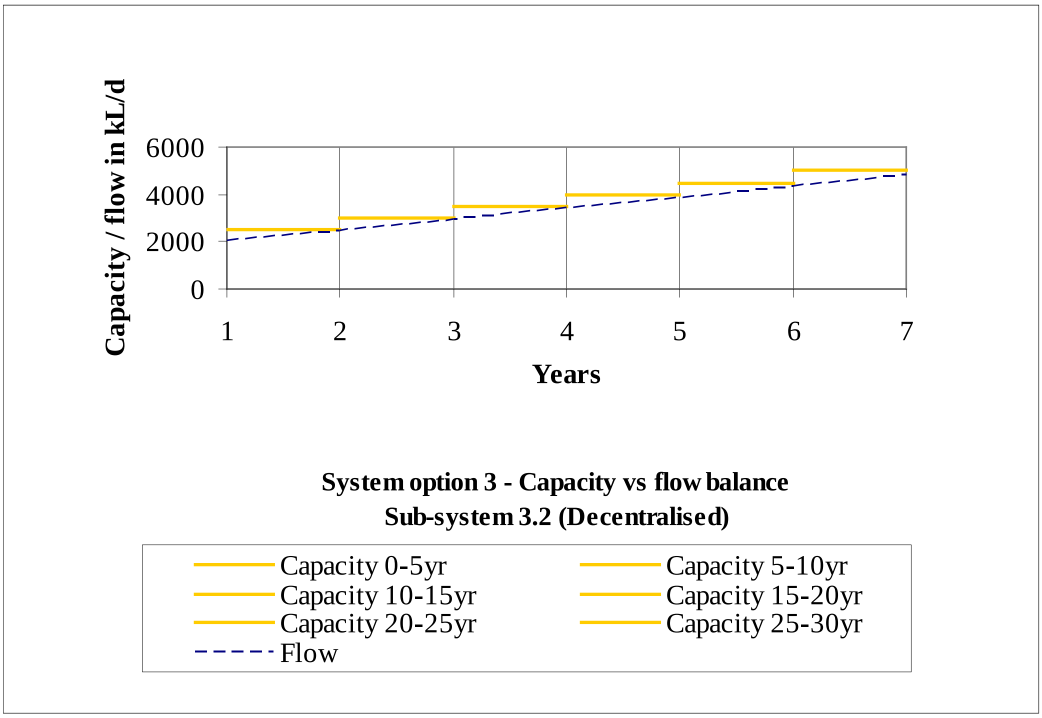


Figure C1.3 Decentralised sub-system 3.2

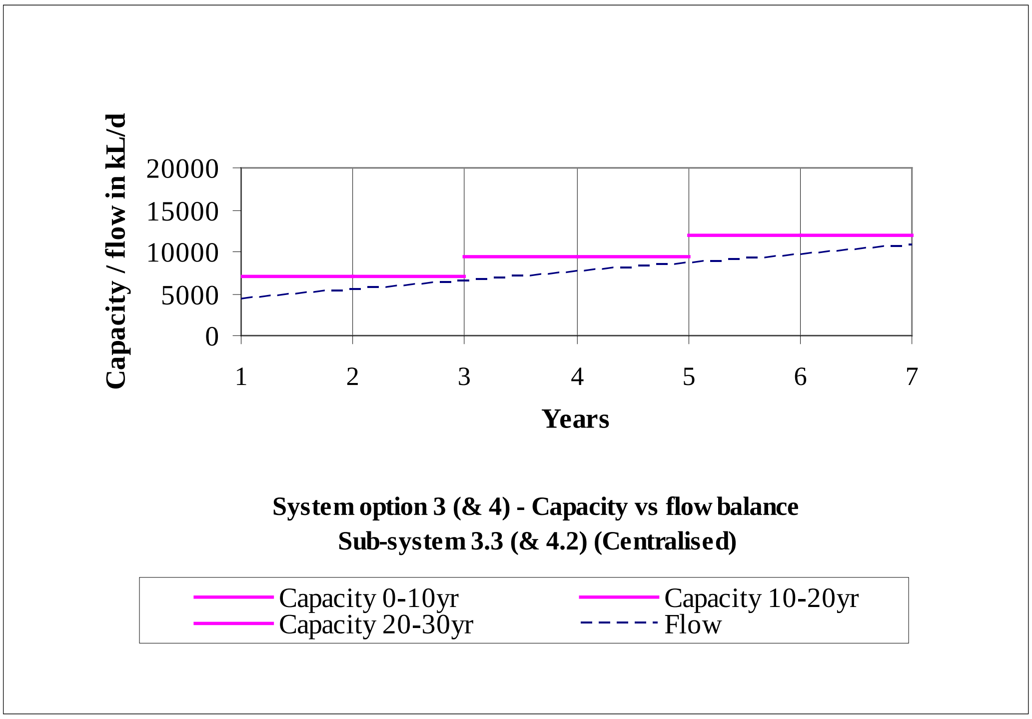


Figure C1.4 Centralised sub-system 3.3

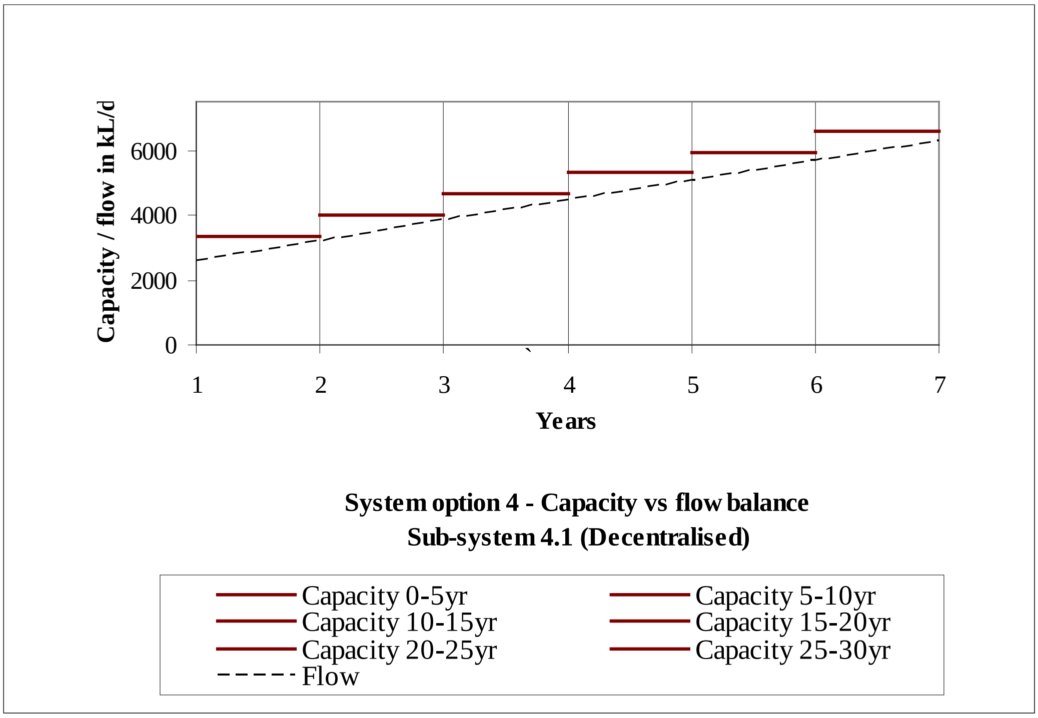


Figure C1.5 Decentralised sub-system 4.1

APPENDIX C2

TREATMENT TRAIN ALGORITHMS

(after Ekama 1981, Joksimovic 2006)

Unit processes	**Joksimovic algorithms**					*** WRC method**
	Useful life (years)	**Capital cost** (Euro) unless shown otherwise	**O&M cost** (Euro)	**Energy cost** (Euro)	**Land footprint** (ha)	**Sludge Production** (kg)
Bar screen	15	11035 (Qp) $^{0.5138}$	1229 × (Qp) $^{0.4835}$	-	0.0045 (Qave)	-
Coarse screen **E&M**	30 15	17670 (Qp) $^{0.5138}$ 20% Capital cost	10% Capital cost -	0.01 kWh / kL	0.0045 (Qave)	-
Grit chamber **E&M**	30 15	20320 (Qp) $^{0.4426}$ 33.3% Capital cost	10% Capital cost	0.01 kWh / kL	$-4\times10^{-12}\left(Q_p\right)^{2+3\times10^{7\times\left(Q_p\right)+0.0076}}$	
Primary sedimentation (wo coagulation) **E&M**	30 15	13667 (Q ave) $^{0.5146}$ 33.3% Capital cost	2% Capital cost -	0.35 kWh /PE.yr -	3.33 x 10^{-6} (Qave)	COD removed (30%) kg/d; Xt = 3.1 kgSS / kg COD
Activated sludge (N & P removal) **E&M**	30 15	2725 (Pop) $^{-0.2795}$ (Euro/PE) 6% Capital cost	10% Capital cost -	[35 - **50** - 70] kWh.PE / yr -	[0.08 - 0.09 - 0.10] 10^{-6} / PE -	Rs = 15 days; F_{up} = 0.04; MLSS = 3.1 kg/m3
Membrane Biological Reactor (MBR) **E&M**	30 15	6929 (Q ave) $^{0.75}$ 40% Capital cost	0.336 × 1000 (Q ave) $^{-0.28}$ (Euro/kL) -	[0.4 - **0.6** - 0.7] (KWh / kL) -	0.06 x 10^{-4} (Qave) -	0.3 kg / kg BOD
Disinfect (Cl gas)	15	5307 (Qp) $^{0.6392}$	1767 × (Qp) $^{0.6524}$	-	0.0015 (constant)	-

Note:

Flow dimensions: Q ave in kL/d ; Q p in kL/hr & Population Equivalent (PE) = 200 l/d

- **WRC method:** Ekama *et al.*, 1981 *Theory, design and operation of nutrient removal activated sludge processes* WRC South Africa

APPENDIX C3

COLLECTOR NETWORK COST CURVES

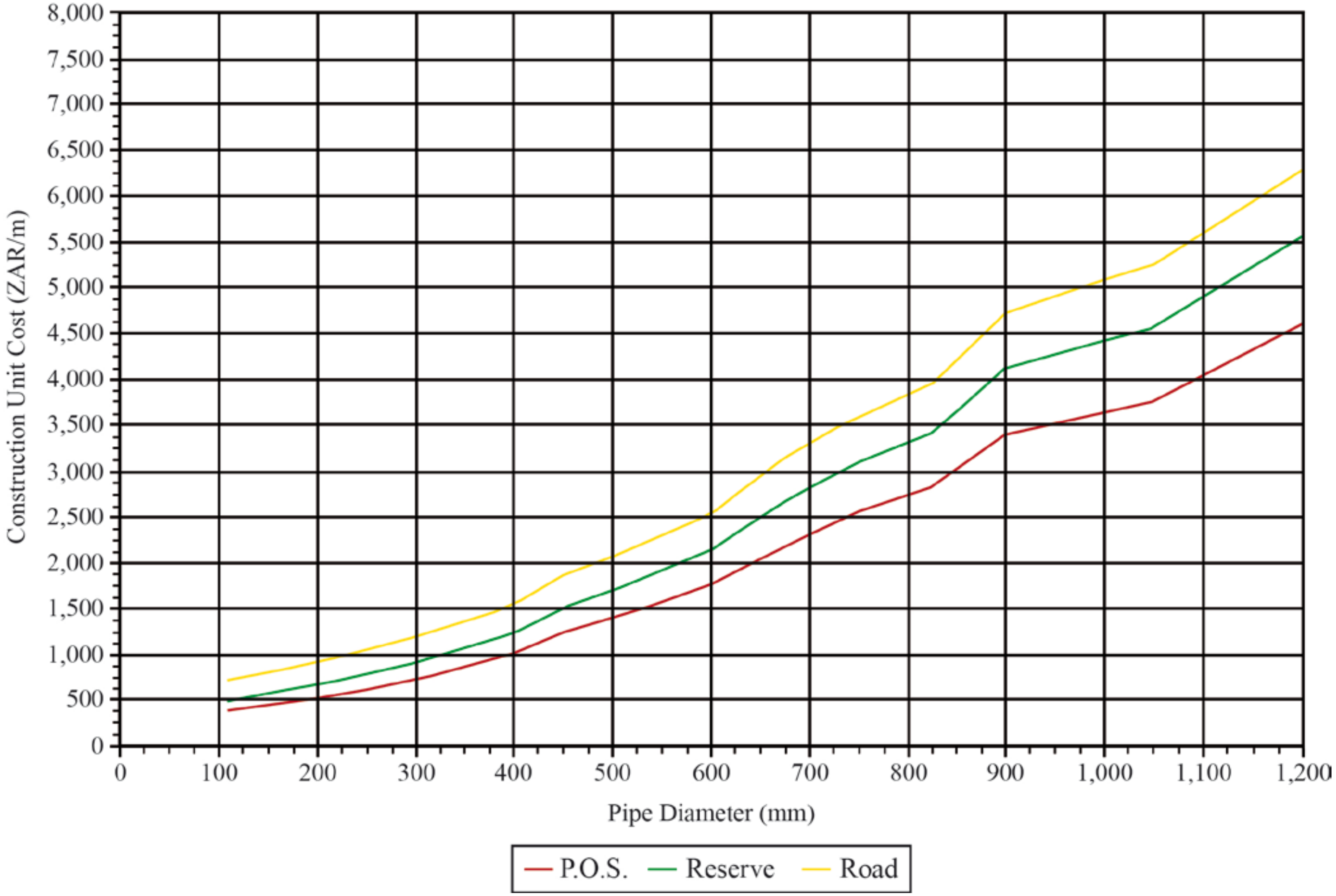


Figure C3.1 Gravity pipe construction unit cost (2009/2010)

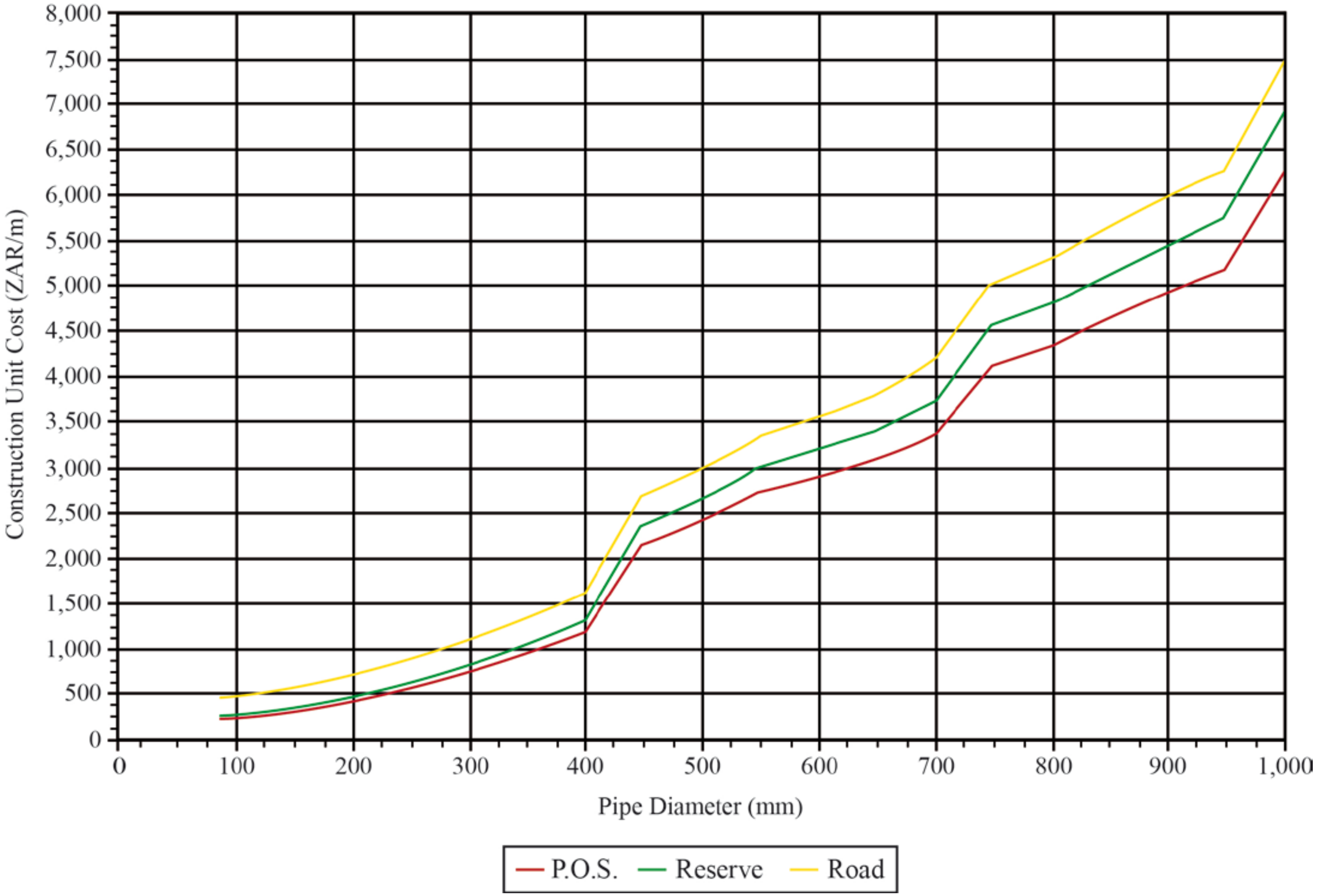


Figure C3.2 Rising main construction unit cost (2009/2010)

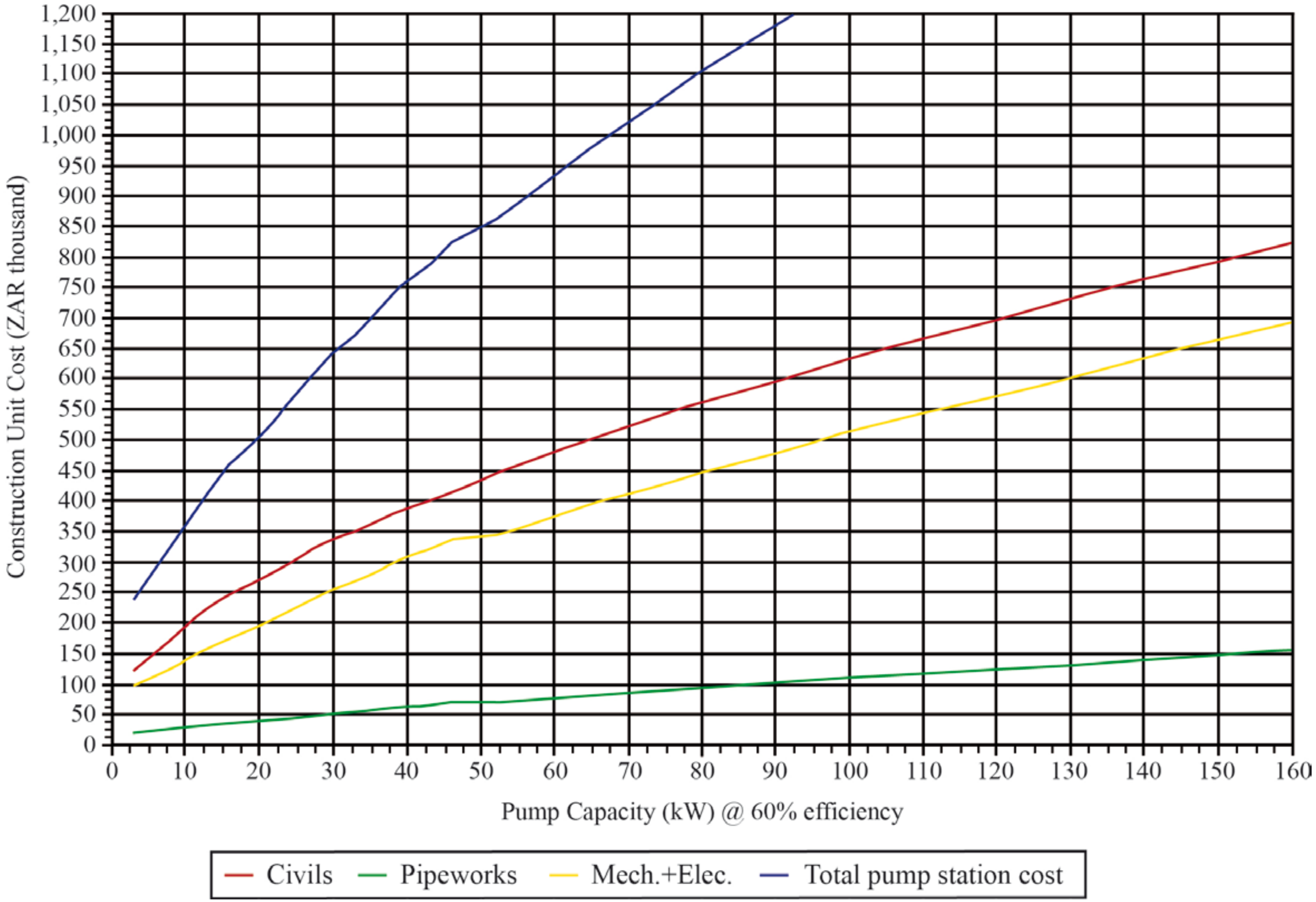
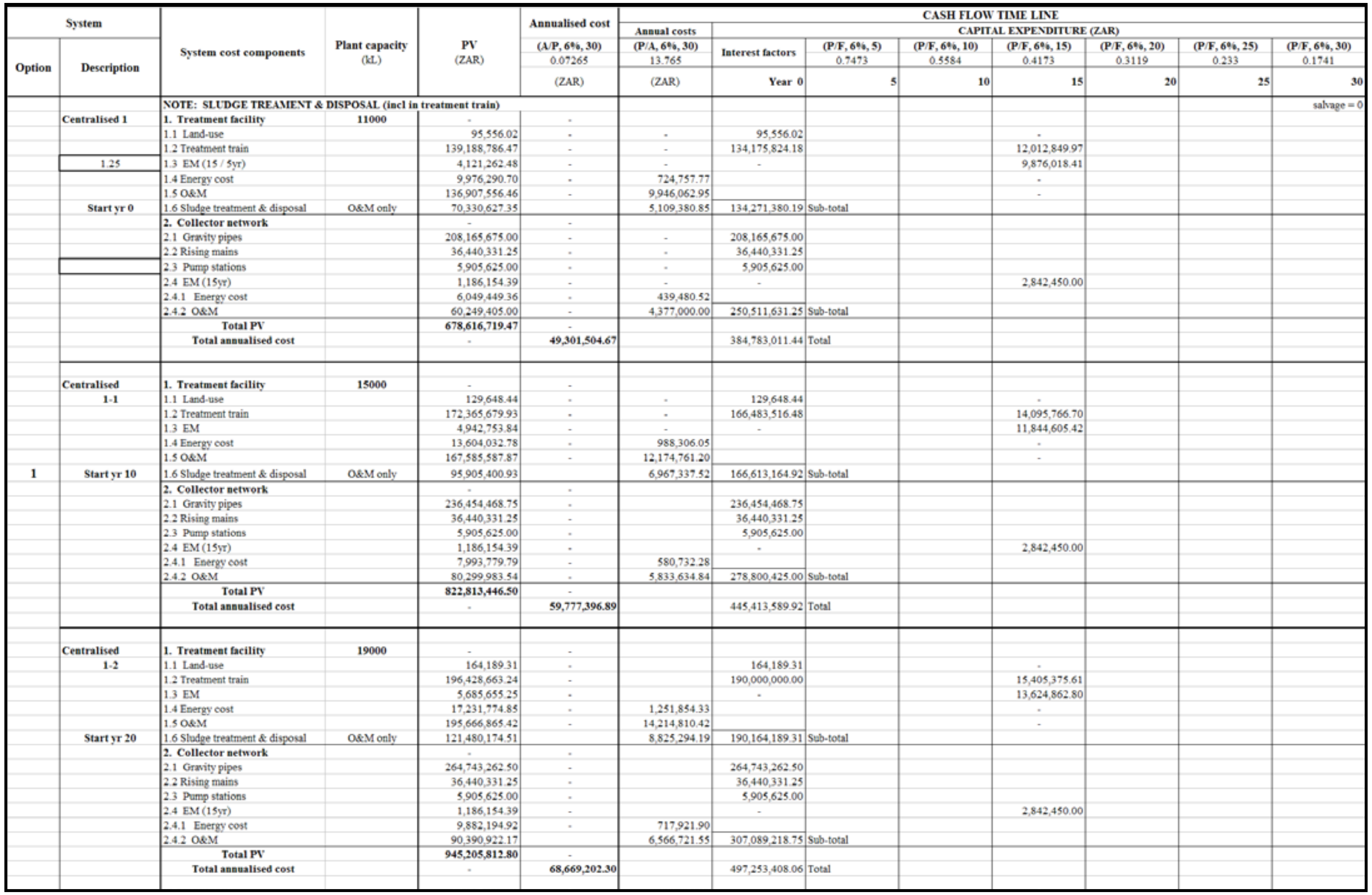


Figure C3.3 Sewer pump station construction cost (2009/2010)

APPENDIX C4

DETAILED CASH FLOW OF SUB-SYSTEMS

Table C4.1 System option 1 - Centralised

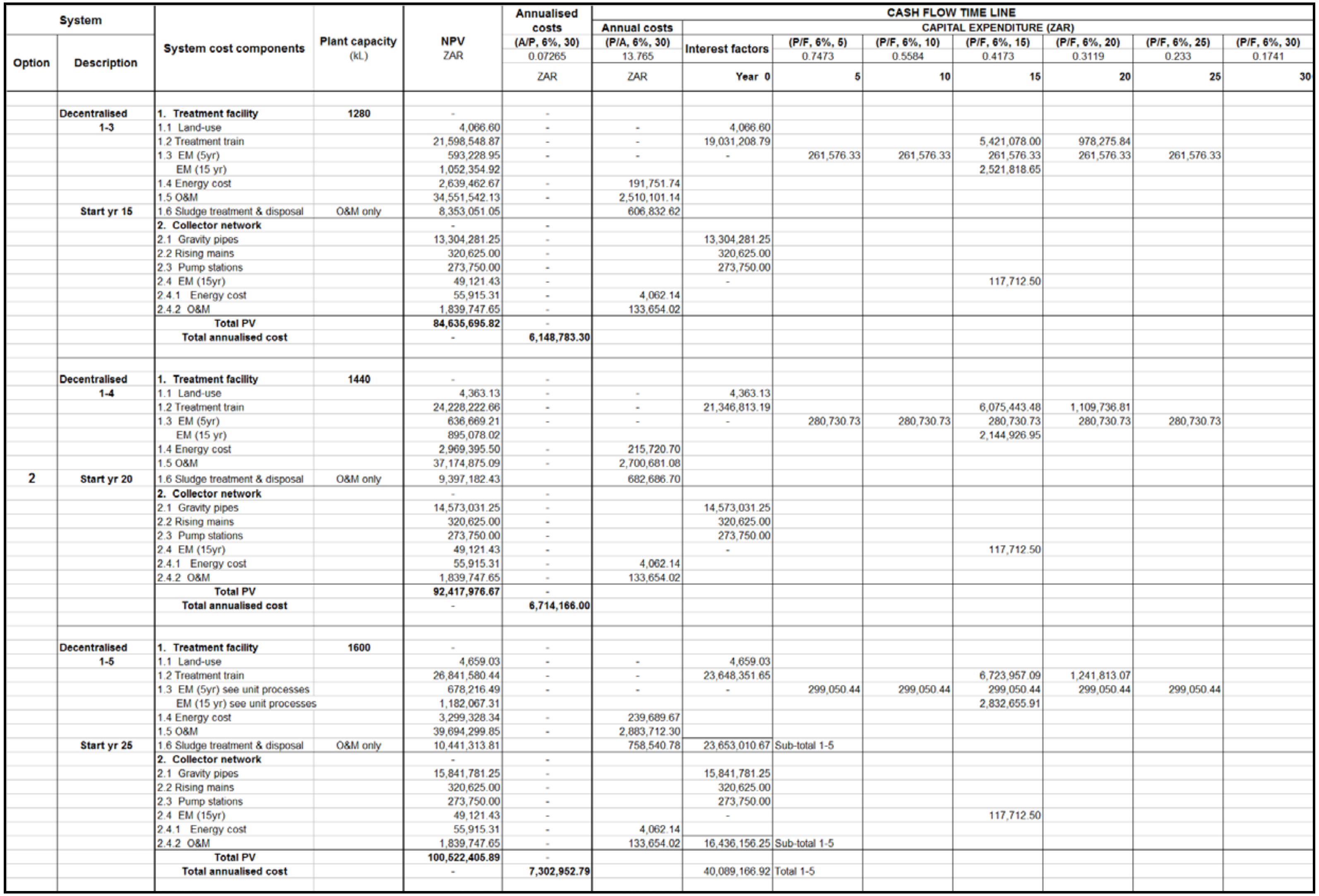


System		System cost components	Plant capacity (kL)	PV (ZAR)	Annualised cost	CASH FLOW TIME LINE							
						Annual costs	CAPITAL EXPENDITURE (ZAR)						
Option	Description				(A/P, 6%, 30)	(P/A, 6%, 30)	Interest factors	(P/F, 6%, 5)	(P/F, 6%, 10)	(P/F, 6%, 15)	(P/F, 6%, 20)	(P/F, 6%, 25)	(P/F, 6%, 30)
					0.07265	13.765		0.7473	0.5584	0.4173	0.3119	0.233	0.1741
					(ZAR)	(ZAR)	Year 0	5	10	15	20	25	30
		NOTE: SLUDGE TREAMENT & DISPOSAL (incl in treatment train)											salvage = 0
	Centralised 1	**1. Treatment facility**	**11000**	-	-								
		1.1 Land-use		95,556.02	-	-	95,556.02			-			
		1.2 Treatment train		139,188,786.47	-	-	134,175,824.18			12,012,849.97			
	1.25	1.3 EM (15 / 5yr)		4,121,262.48	-	-	-			9,876,018.41			
		1.4 Energy cost		9,976,290.70	-	724,757.77				-			
		1.5 O&M		136,907,556.46	-	9,946,062.95				-			
	Start yr 0	1.6 Sludge treatment & disposal	O&M only	70,330,627.35		5,109,380.85	134,271,380.19	Sub-total					
		2. Collector network		-	-								
		2.1 Gravity pipes		208,165,675.00	-	-	208,165,675.00						
		2.2 Rising mains		36,440,331.25	-	-	36,440,331.25						
		2.3 Pump stations		5,905,625.00	-	-	5,905,625.00						
		2.4 EM (15yr)		1,186,154.39	-	-	-			2,842,450.00			
		2.4.1 Energy cost		6,049,449.36	-	439,480.52							
		2.4.2 O&M		60,249,405.00	-	4,377,000.00	250,511,631.25	Sub-total					
		Total PV		**678,616,719.47**	-								
		Total annualised cost		-	**49,301,504.67**		384,783,011.44	Total					
	Centralised	**1. Treatment facility**	**15000**	-	-								
	1-1	1.1 Land-use		129,648.44	-	-	129,648.44			-			
		1.2 Treatment train		172,365,679.93	-	-	166,483,516.48			14,095,766.70			
		1.3 EM		4,942,753.84	-	-	-			11,844,605.42			
		1.4 Energy cost		13,604,032.78	-	988,306.05				-			
		1.5 O&M		167,585,587.87	-	12,174,761.20				-			
1	**Start yr 10**	1.6 Sludge treatment & disposal	O&M only	95,905,400.93		6,967,337.52	166,613,164.92	Sub-total					
		2. Collector network		-	-								
		2.1 Gravity pipes		236,454,468.75	-		236,454,468.75						
		2.2 Rising mains		36,440,331.25	-		36,440,331.25						
		2.3 Pump stations		5,905,625.00	-		5,905,625.00						
		2.4 EM (15yr)		1,186,154.39	-		-			2,842,450.00			
		2.4.1 Energy cost		7,993,779.79	-	580,732.28							
		2.4.2 O&M		80,299,983.54	-	5,833,634.84	278,800,425.00	Sub-total					
		Total PV		**822,813,446.50**	-								
		Total annualised cost		-	**59,777,396.89**		445,413,589.92	Total					
	Centralised	**1. Treatment facility**	**19000**	-	-								
	1-2	1.1 Land-use		164,189.31	-		164,189.31			-			
		1.2 Treatment train		196,428,663.24	-		190,000,000.00			15,405,375.61			
		1.3 EM		5,685,655.25	-		-			13,624,862.80			
		1.4 Energy cost		17,231,774.85	-	1,251,854.33				-			
		1.5 O&M		195,666,865.42	-	14,214,810.42				-			
	Start yr 20	1.6 Sludge treatment & disposal	O&M only	121,480,174.51		8,825,294.19	190,164,189.31	Sub-total					
		2. Collector network		-	-								
		2.1 Gravity pipes		264,743,262.50	-		264,743,262.50						
		2.2 Rising mains		36,440,331.25	-		36,440,331.25						
		2.3 Pump stations		5,905,625.00	-		5,905,625.00						
		2.4 EM (15yr)		1,186,154.39	-		-			2,842,450.00			
		2.4.1 Energy cost		9,882,194.92	-	717,921.90							
		2.4.2 O&M		90,390,922.17		6,566,721.55	307,089,218.75	Sub-total					
		Total PV		**945,205,812.80**	-								
		Total annualised cost		-	**68,669,202.30**		497,253,408.06	Total					

Table C4.2 System option 2 - Decentralised 2.1 (= 3.1)

System		System cost components	Plant capacity (kL)	PV ZAR	Annualised costs	CASH FLOW TIME LINE							
						Annual costs	CAPITAL EXPENDITURE (ZAR)						
					(A/P, 6%, 30)	(P/A, 6%, 30)	Interest factors	(P/F, 6%, 5)	(P/F, 6%, 10)	(P/F, 6%, 15)	(P/F, 6%, 20)	(P/F, 6%, 25)	(P/F, 6%, 30)
					0.07265	13.765		0.7473	0.5584	0.4173	0.3119	0.233	0.1741
Option	Description				ZAR	ZAR	Year 0	5	10	15	20	25	30
		NOTE: SLUDGE TREATMENT & DISPOSAL (incl in treatment train)											salvage = 0
	Decentralised 1	**1. Treatment facility**	**800**	-	-								
		1.1 Land-use		3,345.04	-	-	3,345.04						
		1.2 Treatment train		13,612,072.38	-	-	12,000,000.00			3,422,349.52	589,695.19		
	1.25	1.3 EM (5yr)		447,456.01	-	-	-	197,299.71	197,299.71	197,299.71	197,299.71	197,299.71	
		EM (15 yr)		825,488.19						1,978,164.86			
		1.4 Energy cost		1,649,664.17	-	119,844.84							
		1.5 O&M		25,833,234.56	-	1,876,733.35							
	Start yr 0	1.6 Sludge treatment & disposal	O&M only	5,220,656.91		379,270.39							
		2. Collector network		-	-								
		2.1 Gravity pipes		9,498,031.25	-	-	9,498,031.25						
		2.2 Rising mains		320,625.00	-	-	320,625.00						
		2.3 Pump stations		273,750.00	-	-	273,750.00						
		2.3.1 EM (15yr)		49,121.43	-	-	-			117,712.50			
		2.3.2 Energy cost		55,915.31	-	4,062.14							
		2.4 O&M		1,839,747.65	-	133,654.02							
		Total PV		**59,629,107.89**	-								
		Total annualised cost		-	**4,332,054.69**								
	Decentralised 1-1	**1. Treatment facility**	**960**	-	-								
		1.1 Land-use		3,385.15	-	-	3,385.15						
		1.2 Treatment train		16,290,402.37	-	-	14,357,802.20			4,094,560.35	717,986.97		
		1.3 EM (5yr) see unit processes		499,182.20	-	-	-	220,107.68	220,107.68	220,107.68	220,107.68	220,107.68	
		EM (15 yr) see unit processes		906,750.00						2,172,897.19			
		1.4 Energy cost		1,979,597.00	-	143,813.80							
		1.5 O&M		28,911,466.76	-	2,100,360.83							
2	**Start yr 5**	1.6 Sludge treatment & disposal	O&M only	6,264,788.29		455,124.47							
		2. Collector network			-								
		2.1 Gravity pipes		10,766,781.25	-		10,766,781.25						
		2.2 Rising mains		320,625.00	-		320,625.00						
		2.3 Pump stations		273,750.00	-		273,750.00						
		2.4 EM (15yr)		49,121.43	-		-			117,712.50			
		2.4.1 Energy cost		55,915.31	-	4,062.14							
	Midvaal	2.4.2 O&M		1,839,747.65	-	133,654.02							
		Total PV		**68,161,512.40**	-								
		Total annualised cost		-	**4,951,933.88**								
	Decentralised 1-2	**1. Treatment facility**	**1120**	-	-								
		1.1 Land-use		3,769.39	-		3,769.39						
		1.2 Treatment train		18,952,590.98	-		16,701,538.46			4,760,798.96	847,614.96		
		1.3 EM (5yr)		547,554.27	-		-	241,436.69	241,436.69	241,436.69	241,436.69	241,436.69	
		EM (15 yr)		981,949.22						2,353,101.42			
		1.4 Energy cost		2,309,529.83	-	167,782.77							
		1.5 O&M		31,805,548.14	-	2,310,610.11							
	Start yr 10	1.6 Sludge treatment & disposal	O&M only	7,308,919.67		530,978.54							
		2. Collector network		-	-								
		2.1 Gravity pipes		12,035,531.25	-		12,035,531.25						
		2.2 Rising mains		320,625.00	-		320,625.00						
		2.3 Pump stations		273,750.00	-		273,750.00						
		2.4 EM (15yr)		49,121.43	-		-			117,712.50			
		2.4.1 Energy cost		55,915.31	-	4,062.14							
		2.4.2 O&M		1,839,747.65		133,654.02							
		Total PV		**76,484,552.12**	-								
		Total annualised cost		-	**5,556,602.71**								

Table C4.2 (continued)

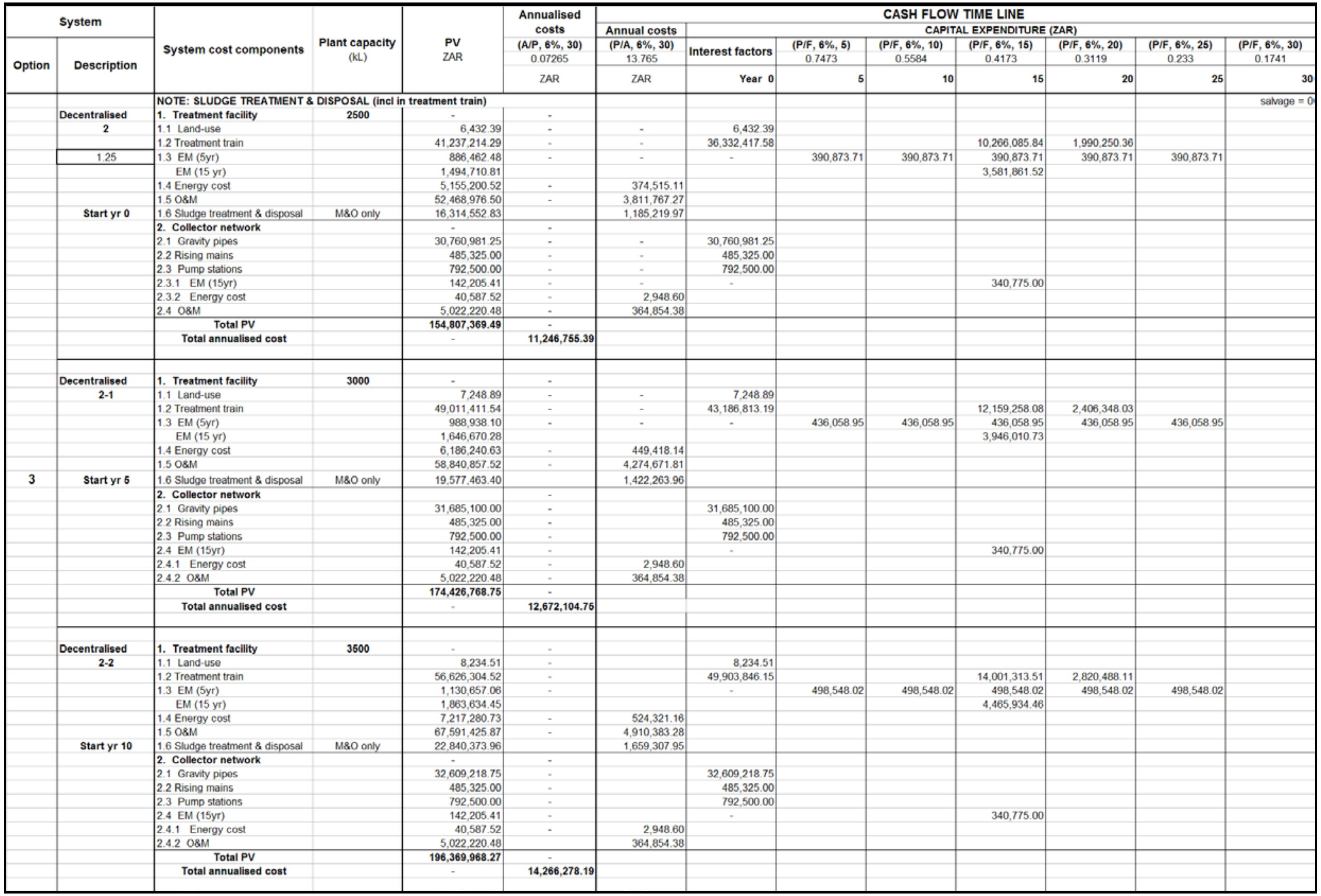


System		System cost components	Plant capacity (kL)	NPV ZAR	Annualised costs	CASH FLOW TIME LINE							
						Annual costs	CAPITAL EXPENDITURE (ZAR)						
Option	Description				(A/P, 6%, 30) 0.07265	(P/A, 6%, 30) 13.765	Interest factors	(P/F, 6%, 5) 0.7473	(P/F, 6%, 10) 0.5584	(P/F, 6%, 15) 0.4173	(P/F, 6%, 20) 0.3119	(P/F, 6%, 25) 0.233	(P/F, 6%, 30) 0.1741
					ZAR	ZAR	Year 0	5	10	15	20	25	30
	Decentralised	**1. Treatment facility**	**1280**	-	-								
	1-3	1.1 Land-use		4,066.60	-	-	4,066.60						
		1.2 Treatment train		21,598,548.87	-	-	19,031,208.79			5,421,078.00	978,275.84		
		1.3 EM (5yr)		593,228.95	-	-	-	261,576.33	261,576.33	261,576.33	261,576.33	261,576.33	
		EM (15 yr)		1,052,354.92						2,521,818.65			
		1.4 Energy cost		2,639,462.67	-	191,751.74							
		1.5 O&M		34,551,542.13	-	2,510,101.14							
	Start yr 15	1.6 Sludge treatment & disposal	O&M only	8,353,051.05		606,832.62							
		2. Collector network		-	-								
		2.1 Gravity pipes		13,304,281.25	-		13,304,281.25						
		2.2 Rising mains		320,625.00	-		320,625.00						
		2.3 Pump stations		273,750.00	-		273,750.00						
		2.4 EM (15yr)		49,121.43	-		-			117,712.50			
		2.4.1 Energy cost		55,915.31	-	4,062.14							
		2.4.2 O&M		1,839,747.65	-	133,654.02							
		Total PV		**84,635,695.82**	-								
		Total annualised cost		-	**6,148,783.30**								
	Decentralised	**1. Treatment facility**	**1440**	-	-								
	1-4	1.1 Land-use		4,363.13	-	-	4,363.13						
		1.2 Treatment train		24,228,222.66	-	-	21,346,813.19			6,075,443.48	1,109,736.81		
		1.3 EM (5yr)		636,669.21	-	-	-	280,730.73	280,730.73	280,730.73	280,730.73	280,730.73	
		EM (15 yr)		895,078.02						2,144,926.95			
		1.4 Energy cost		2,969,395.50	-	215,720.70							
		1.5 O&M		37,174,875.09	-	2,700,681.08							
2	**Start yr 20**	1.6 Sludge treatment & disposal	O&M only	9,397,182.43		682,686.70							
		2. Collector network		-	-								
		2.1 Gravity pipes		14,573,031.25	-		14,573,031.25						
		2.2 Rising mains		320,625.00	-		320,625.00						
		2.3 Pump stations		273,750.00	-		273,750.00						
		2.4 EM (15yr)		49,121.43	-		-			117,712.50			
		2.4.1 Energy cost		55,915.31	-	4,062.14							
		2.4.2 O&M		1,839,747.65	-	133,654.02							
		Total PV		**92,417,976.67**	-								
		Total annualised cost		-	**6,714,166.00**								
	Decentralised	**1. Treatment facility**	**1600**	-	-								
	1-5	1.1 Land-use		4,659.03	-	-	4,659.03						
		1.2 Treatment train		26,841,580.44	-	-	23,648,351.65			6,723,957.09	1,241,813.07		
		1.3 EM (5yr) see unit processes		678,216.49	-	-	-	299,050.44	299,050.44	299,050.44	299,050.44	299,050.44	
		EM (15 yr) see unit processes		1,182,067.31						2,832,655.91			
		1.4 Energy cost		3,299,328.34	-	239,689.67							
		1.5 O&M		39,694,299.85	-	2,883,712.30							
	Start yr 25	1.6 Sludge treatment & disposal	O&M only	10,441,313.81		758,540.78	23,653,010.67	Sub-total 1-5					
		2. Collector network		-	-								
		2.1 Gravity pipes		15,841,781.25	-		15,841,781.25						
		2.2 Rising mains		320,625.00	-		320,625.00						
		2.3 Pump stations		273,750.00	-		273,750.00						
		2.4 EM (15yr)		49,121.43	-		-			117,712.50			
		2.4.1 Energy cost		55,915.31	-	4,062.14							
		2.4.2 O&M		1,839,747.65	-	133,654.02	16,436,156.25	Sub-total 1-5					
		Total PV		**100,522,405.89**	-								
		Total annualised cost		-	**7,302,952.79**		40,089,166.92	Total 1-5					

Table C4.3 System option 2 - Centralised 2.2

System		System cost components	Plant capacity (kL)	PV ZAR	Annualised costs	CASH FLOW TIME LINE							
						Annual costs	CAPITAL EXPENDITURE (ZAR)						
Option	Description				(A/P, 6%, 30)	(P/A, 6%, 30)	Interest factors	(P/F, 6%, 5)	(P/F, 6%, 10)	(P/F, 6%, 15)	(P/F, 6%, 20)	(P/F, 6%, 25)	(P/F, 6%, 30)
					0.07265	13.765		0.7473	0.5584	0.4173	0.3119	0.233	0.1741
					ZAR	ZAR	Year 0	5	10	15	20	25	30
		NOTE: SLUDGE TREAMENT & DISPOSAL (incl in treatment train)											salvage = 0
	Centralised 2	**1. Treatment facility**	**10000**	-	-								
		1.1 Land-use		87,430.31	-	-	87,430.31			-			
		1.2 Treatment train		108,888,008.28	-	-	104,901,960.78			9,551,994.95			
	1.25	1.3 EM (15 / 5yr)		3,899,087.29	-	-	-			9,343,607.20			
		1.4 Energy cost		9,069,355.19	-	658,870.70				-			
		1.5 O&M		160,863,680.71	-	11,686,427.95				-			
	Start yr 0	1.6 Sludge treatment & disposal	O&M only	63,936,933.95		4,644,891.68	104,989,391.10	Sub-total 2-2					
		2. Collector network		-	-								
		2.1 Gravity pipes		194,705,143.75	-	-	194,705,143.75						
		2.2 Rising mains		31,443,500.00	-	-	31,443,500.00						
		2.3 Pump stations		5,188,125.00	-	-	5,188,125.00						
		2.4 EM (15yr)		1,057,406.90	-	-				2,533,925.00			
		2.4.1 Energy cost		5,262,695.50	-	382,324.41							
		2.4.2 O&M		53,854,208.28	-	3,912,401.62	231,336,768.75	Sub-total 2-2					
		Total PV		**638,255,575.14**	-								
		Total annualised cost		-	**46,369,267.53**		336,326,159.85	Total 2-2					
	Centralised	**1. Treatment facility**	**13500**	-	-								
	2-1	1.1 Land-use		116,279.50	-	-	116,279.50			-			
		1.2 Treatment train		160,994,769.36	-	-	155,398,351.65			13,411,017.77			
		1.3 EM		4,645,644.67	-	-	-			11,132,625.62			
		1.4 Energy cost		12,243,629.50	-	889,475.45				-			
		1.5 O&M		156,440,353.23	-	11,365,081.96				-			
2	**Start yr 10**	1.6 Sludge treatment & disposal	O&M only	86,314,860.84		6,270,603.77	155,514,631.15	Sub-total 2-2					
		2. Collector network		-	-								
		2.1 Gravity pipes		218,716,009.38	-		218,716,009.38						
		2.2 Rising mains		31,531,300.00	-		31,531,300.00						
		2.3 Pump stations		5,188,125.00	-		5,188,125.00						
		2.4 EM (15yr)		1,057,406.90	-		-			2,533,925.00			
		2.4.1 Energy cost		6,963,987.20	-	505,919.88							
		2.4.2 O&M		71,328,734.80	-	5,181,891.38	255,435,434.38	Sub-total 2-2					
		Total PV		**755,541,100.38**	-								
		Total annualised cost		-	**54,890,060.94**		410,950,065.53	Total 2-2					
	Centralised	**1. Treatment facility**	**17000**	-	-								
	2-2	1.1 Land-use		146,797.51	-		146,797.51			-			
		1.2 Treatment train		185,533,922.27	-		179,340,659.34			14,841,272.29			
		1.3 EM		5,322,272.81	-		-			12,754,068.55			
		1.4 Energy cost		15,417,903.82	-	1,120,080.19				-			
		1.5 O&M		181,895,384.19	-	13,214,339.57				-			
	Start yr 20	1.6 Sludge treatment & disposal	O&M only	108,692,787.72		7,896,315.85	179,487,456.85	Sub-total 2-2					
		2. Collector network		-	-								
		2.1 Gravity pipes		242,726,875.00	-		242,726,875.00						
		2.2 Rising mains		31,531,300.00	-		31,531,300.00						
		2.3 Pump stations		5,188,125.00	-		5,188,125.00						
		2.4 EM (15yr)		1,057,406.90	-		-			2,533,925.00			
		2.4.1 Energy cost		8,665,276.33	-	629,515.17							
		2.4.2 O&M		80,419,746.59		5,842,335.39	279,446,300.00	Sub-total 2-2					
		Total PV		**866,597,798.14**	-								
		Total annualised cost		-	**62,958,330.03**		458,933,756.85	Total 2-2					

Table C4.4 System option 3 - Decentralised 3.2

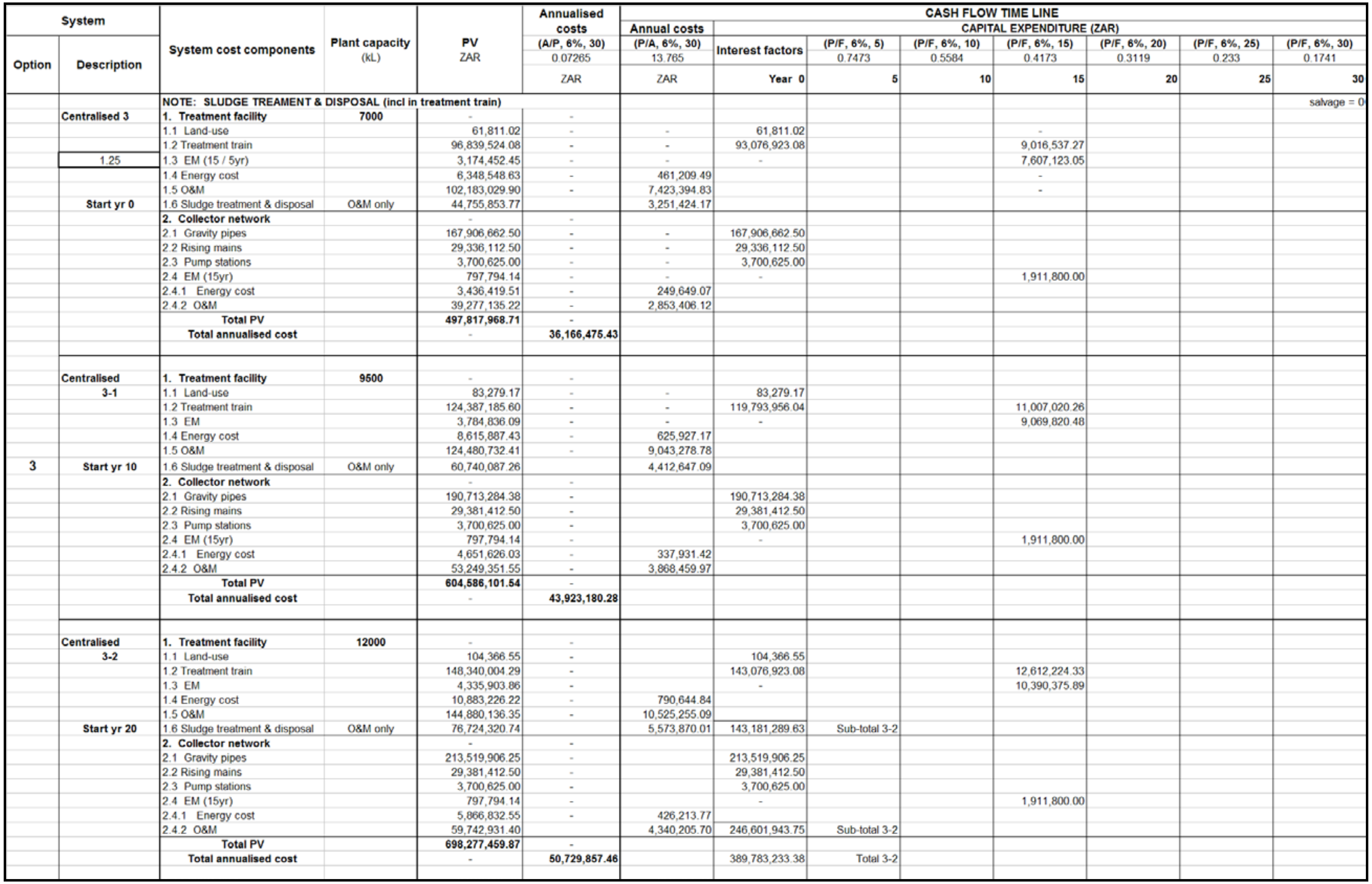


System		System cost components	Plant capacity (kL)	PV ZAR	Annualised costs	CASH FLOW TIME LINE							
Option	Description				(A/P, 6%, 30) 0.07265	Annual costs	CAPITAL EXPENDITURE (ZAR)						
						(P/A, 6%, 30) 13.765	Interest factors	(P/F, 6%, 5) 0.7473	(P/F, 6%, 10) 0.5584	(P/F, 6%, 15) 0.4173	(P/F, 6%, 20) 0.3119	(P/F, 6%, 25) 0.233	(P/F, 6%, 30) 0.1741
					ZAR	ZAR	Year 0	5	10	15	20	25	30
		NOTE: SLUDGE TREATMENT & DISPOSAL (incl in treatment train)											salvage = 0
	Decentralised	**1. Treatment facility**	**2500**	-	-								
	2	1.1 Land-use		6,432.39	-	-	6,432.39						
		1.2 Treatment train		41,237,214.29	-	-	36,332,417.58			10,266,085.84	1,990,250.36		
	1.25	1.3 EM (5yr)		886,462.48	-	-	-	390,873.71	390,873.71	390,873.71	390,873.71	390,873.71	
		EM (15 yr)		1,494,710.81						3,581,861.52			
		1.4 Energy cost		5,155,200.52	-	374,515.11							
		1.5 O&M		52,468,976.50	-	3,811,767.27							
	Start yr 0	1.6 Sludge treatment & disposal	M&O only	16,314,552.83		1,185,219.97							
		2. Collector network		-	-								
		2.1 Gravity pipes		30,760,981.25	-	-	30,760,981.25						
		2.2 Rising mains		485,325.00	-	-	485,325.00						
		2.3 Pump stations		792,500.00	-	-	792,500.00						
		2.3.1 EM (15yr)		142,205.41	-	-	-			340,775.00			
		2.3.2 Energy cost		40,587.52	-	2,948.60							
		2.4 O&M		5,022,220.48	-	364,854.38							
		Total PV		**154,807,369.49**	-								
		Total annualised cost		-	**11,246,755.39**								
	Decentralised	**1. Treatment facility**	**3000**	-	-								
	2-1	1.1 Land-use		7,248.89	-	-	7,248.89						
		1.2 Treatment train		49,011,411.54	-	-	43,186,813.19			12,159,258.08	2,406,348.03		
		1.3 EM (5yr)		988,938.10	-	-	-	436,058.95	436,058.95	436,058.95	436,058.95	436,058.95	
		EM (15 yr)		1,646,670.28						3,946,010.73			
		1.4 Energy cost		6,186,240.63	-	449,418.14							
		1.5 O&M		58,840,857.52	-	4,274,671.81							
3	**Start yr 5**	1.6 Sludge treatment & disposal	M&O only	19,577,463.40		1,422,263.96							
		2. Collector network			-								
		2.1 Gravity pipes		31,685,100.00	-		31,685,100.00						
		2.2 Rising mains		485,325.00	-		485,325.00						
		2.3 Pump stations		792,500.00	-		792,500.00						
		2.4 EM (15yr)		142,205.41	-		-			340,775.00			
		2.4.1 Energy cost		40,587.52	-	2,948.60							
		2.4.2 O&M		5,022,220.48	-	364,854.38							
		Total PV		**174,426,768.75**	-								
		Total annualised cost		-	**12,672,104.75**								
	Decentralised	**1. Treatment facility**	**3500**	-	-								
	2-2	1.1 Land-use		8,234.51	-		8,234.51						
		1.2 Treatment train		56,626,304.52	-		49,903,846.15			14,001,313.51	2,820,488.11		
		1.3 EM (5yr)		1,130,657.06	-		-	498,548.02	498,548.02	498,548.02	498,548.02	498,548.02	
		EM (15 yr)		1,863,634.45						4,465,934.46			
		1.4 Energy cost		7,217,280.73	-	524,321.16							
		1.5 O&M		67,591,425.87	-	4,910,383.28							
	Start yr 10	1.6 Sludge treatment & disposal	M&O only	22,840,373.96		1,659,307.95							
		2. Collector network		-	-								
		2.1 Gravity pipes		32,609,218.75	-		32,609,218.75						
		2.2 Rising mains		485,325.00	-		485,325.00						
		2.3 Pump stations		792,500.00	-		792,500.00						
		2.4 EM (15yr)		142,205.41	-		-			340,775.00			
		2.4.1 Energy cost		40,587.52	-	2,948.60							
		2.4.2 O&M		5,022,220.48		364,854.38							
		Total PV		**196,369,968.27**	-								
		Total annualised cost		-	**14,266,278.19**								

Table C4.4 (continued)

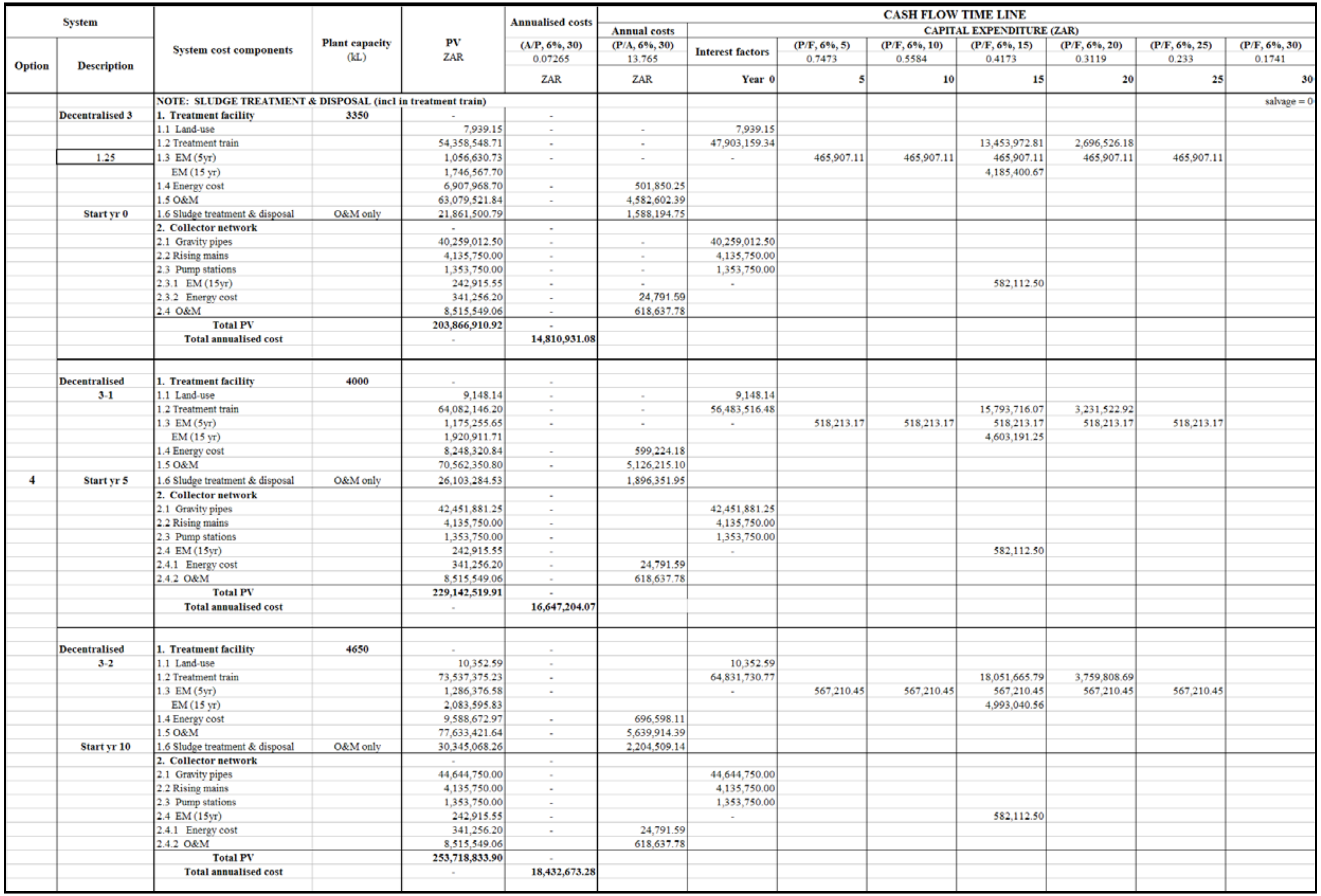
System		System cost components	Plant capacity (kL)	PV	Annualised costs	CASH FLOW TIME LINE							
						Annual costs	CAPITAL EXPENDITURE (ZAR)						
Option	Description			ZAR	(A/P, 6%, 30) 0.07265	(P/A, 6%, 30) 13.765	Interest factors	(P/F, 6%, 5) 0.7473	(P/F, 6%, 10) 0.5584	(P/F, 6%, 15) 0.4173	(P/F, 6%, 20) 0.3119	(P/F, 6%, 25) 0.233	(P/F, 6%, 30) 0.1741
					ZAR	ZAR	Year 0	5	10	15	20	25	30
	Decentralised	**1. Treatment facility**	**4000**	-	-								
	2-3	1.1 Land-use		9,148.14	-	-	9,148.14						
		1.2 Treatment train		64,082,146.20	-	-	56,483,516.48			15,793,716.07	3,231,522.92		
		1.3 EM (5yr)		1,175,255.65	-	-	-	518,213.17	518,213.17	518,213.17	518,213.17	518,213.17	
		EM (15 yr)		1,920,911.71						4,603,191.25			
		1.4 Energy cost		8,248,320.84	-	599,224.18							
		1.5 O&M		70,562,350.80	-	5,126,215.10							
	Start yr 15	1.6 Sludge treatment & disposal	M&O only	26,103,284.53		1,896,351.95							
		2. Collector network		-	-								
		2.1 Gravity pipes		33,533,337.50	-		33,533,337.50						
		2.2 Rising mains		485,325.00	-		485,325.00						
		2.3 Pump stations		792,500.00	-		792,500.00						
		2.4 EM (15yr)		142,205.41	-		-			340,775.00			
		2.4.1 Energy cost		40,587.52	-	2,948.60							
		2.4.2 O&M		5,022,220.48	-	364,854.38							
		Total PV		**212,117,593.77**	-								
		Total annualised cost		-	**15,410,343.19**								
	Decentralised	**1. Treatment facility**	**4500**	-	-								
	2-4	1.1 Land-use	Req	10,076.34	-	-	10,076.34						
		1.2 Treatment train		71,379,190.62	-	-	62,925,824.18			17,537,729.45	3,638,576.27		
		1.3 EM (5yr)		1,261,315.88	-	-	-	556,160.27	556,160.27	556,160.27	556,160.27	556,160.27	
		EM (15 yr)		2,046,949.81						4,905,223.61			
		1.4 Energy cost	Req	9,279,360.94	-	674,127.20							
		1.5 O&M		76,033,609.27	-	5,523,691.19							
3	**Start yr 20**	1.6 Sludge treatment & disposal	M&O only	29,366,195.09		2,133,395.94							
		2. Collector network		-	-								
		2.1 Gravity pipes		34,457,456.25	-		34,457,456.25						
		2.2 Rising mains		485,325.00	-		485,325.00						
		2.3 Pump stations		792,500.00	-		792,500.00						
		2.4 EM (15yr)		142,205.41	-		-			340,775.00			
		2.4.1 Energy cost		40,587.52	-	2,948.60							
		2.4.2 O&M		5,022,220.48	-	364,854.38							
		Total PV		**230,316,992.61**	-								
		Total annualised cost		-	**16,732,529.51**								
	Decentralised	**1. Treatment facility**	**5000**	-	-								
	2-5	1.1 Land-use		11,002.09	-	-	11,002.09						
		1.2 Treatment train		78,517,681.16	-	-	69,230,769.23			19,234,453.85	4,040,956.51		
		1.3 EM (5yr)		1,343,625.87	-	-	-	592,453.75	592,453.75	592,453.75	592,453.75	592,453.75	
		EM (15 yr)		2,167,230.70						5,193,459.62			
		1.4 Energy cost		10,310,401.05	-	749,030.23							
		1.5 O&M		81,299,035.82	-	5,906,214.01							
	Start yr 25	1.6 Sludge treatment & disposal	M&O only	32,629,105.66		2,370,439.93	69,241,771.32	Sub-total 2-5					
		2. Collector network		-	-								
		2.1 Gravity pipes		35,381,575.00	-		35,381,575.00						
		2.2 Rising mains		485,325.00	-		485,325.00						
		2.3 Pump stations		792,500.00	-		792,500.00						
		2.4 EM (15yr)		142,205.41	-		-			340,775.00			
		2.4.1 Energy cost		40,587.52	-	2,948.60							
		2.4.2 O&M		5,022,220.48	-	364,854.38	36,659,400.00	Sub-total 2-5					
		Total PV		**248,142,495.75**	-								
		Total annualised cost		-	**18,027,552.32**		105,901,171.32	Total 2-5					

Table C4.5 System option 3 - Centralised 3.3 (= 4.2)



System					Annualised costs	CASH FLOW TIME LINE							
						Annual costs	CAPITAL EXPENDITURE (ZAR)						
Option	Description	System cost components	Plant capacity (kL)	PV	(A/P, 6%, 30)	(P/A, 6%, 30)	Interest factors	(P/F, 6%, 5)	(P/F, 6%, 10)	(P/F, 6%, 15)	(P/F, 6%, 20)	(P/F, 6%, 25)	(P/F, 6%, 30)
				ZAR	0.07265	13.765		0.7473	0.5584	0.4173	0.3119	0.233	0.1741
					ZAR	ZAR	Year 0	5	10	15	20	25	30
		NOTE: SLUDGE TREAMENT & DISPOSAL (incl in treatment train)											salvage = 0
	Centralised 3	1. Treatment facility	7000	-	-								
		1.1 Land-use		61,811.02	-	-	61,811.02			-			
		1.2 Treatment train		96,839,524.08	-	-	93,076,923.08			9,016,537.27			
	1.25	1.3 EM (15 / 5yr)		3,174,452.45	-	-	-			7,607,123.05			
		1.4 Energy cost		6,348,548.63	-	461,209.49				-			
		1.5 O&M		102,183,029.90	-	7,423,394.83				-			
	Start yr 0	1.6 Sludge treatment & disposal	O&M only	44,755,853.77		3,251,424.17							
		2. Collector network		-	-								
		2.1 Gravity pipes		167,906,662.50	-	-	167,906,662.50						
		2.2 Rising mains		29,336,112.50	-	-	29,336,112.50						
		2.3 Pump stations		3,700,625.00	-	-	3,700,625.00						
		2.4 EM (15yr)		797,794.14	-	-	-			1,911,800.00			
		2.4.1 Energy cost		3,436,419.51	-	249,649.07							
		2.4.2 O&M		39,277,135.22	-	2,853,406.12							
		Total PV		**497,817,968.71**	-								
		Total annualised cost		-	**36,166,475.43**								
	Centralised 3-1	1. Treatment facility	9500	-	-								
		1.1 Land-use		83,279.17	-	-	83,279.17						
		1.2 Treatment train		124,387,185.60	-	-	119,793,956.04			11,007,020.26			
		1.3 EM		3,784,836.09	-	-	-			9,069,820.48			
		1.4 Energy cost		8,615,887.43	-	625,927.17							
		1.5 O&M		124,480,732.41	-	9,043,278.78							
3	Start yr 10	1.6 Sludge treatment & disposal	O&M only	60,740,087.26		4,412,647.09							
		2. Collector network		-	-								
		2.1 Gravity pipes		190,713,284.38	-		190,713,284.38						
		2.2 Rising mains		29,381,412.50	-		29,381,412.50						
		2.3 Pump stations		3,700,625.00	-		3,700,625.00						
		2.4 EM (15yr)		797,794.14	-		-			1,911,800.00			
		2.4.1 Energy cost		4,651,626.03	-	337,931.42							
		2.4.2 O&M		53,249,351.55	-	3,868,459.97							
		Total PV		**604,586,101.54**	-								
		Total annualised cost		-	**43,923,180.28**								
	Centralised 3-2	1. Treatment facility	12000	-	-								
		1.1 Land-use		104,366.55	-		104,366.55						
		1.2 Treatment train		148,340,004.29	-		143,076,923.08			12,612,224.33			
		1.3 EM		4,335,903.86	-		-			10,390,375.89			
		1.4 Energy cost		10,883,226.22	-	790,644.84							
		1.5 O&M		144,880,136.35	-	10,525,255.09							
	Start yr 20	1.6 Sludge treatment & disposal	O&M only	76,724,320.74		5,573,870.01	143,181,289.63	Sub-total 3-2					
		2. Collector network		-	-								
		2.1 Gravity pipes		213,519,906.25	-		213,519,906.25						
		2.2 Rising mains		29,381,412.50	-		29,381,412.50						
		2.3 Pump stations		3,700,625.00	-		3,700,625.00						
		2.4 EM (15yr)		797,794.14	-		-			1,911,800.00			
		2.4.1 Energy cost		5,866,832.55	-	426,213.77							
		2.4.2 O&M		59,742,931.40		4,340,205.70	246,601,943.75	Sub-total 3-2					
		Total PV		**698,277,459.87**	-								
		Total annualised cost		-	**50,729,857.46**		389,783,233.38	Total 3-2					

Table C4.6 System option 4 - Decentralised 4.1



System		System cost components	Plant capacity (kL)	PV ZAR	Annualised costs	CASH FLOW TIME LINE							
						Annual costs	CAPITAL EXPENDITURE (ZAR)						
Option	Description				(A/P, 6%, 30) 0.07265	(P/A, 6%, 30) 13.765	Interest factors	(P/F, 6%, 5) 0.7473	(P/F, 6%, 10) 0.5584	(P/F, 6%, 15) 0.4173	(P/F, 6%, 20) 0.3119	(P/F, 6%, 25) 0.233	(P/F, 6%, 30) 0.1741
					ZAR	ZAR	Year 0	5	10	15	20	25	30
		NOTE: SLUDGE TREATMENT & DISPOSAL (incl in treatment train)											salvage = 0
	Decentralised 3	**1. Treatment facility**	**3350**	-	-								
		1.1 Land-use		7,939.15	-	-	7,939.15						
		1.2 Treatment train		54,358,548.71	-	-	47,903,159.34			13,453,972.81	2,696,526.18		
	1.25	1.3 EM (5yr)		1,056,630.73	-	-	-	465,907.11	465,907.11	465,907.11	465,907.11	465,907.11	
		EM (15 yr)		1,746,567.70						4,185,400.67			
		1.4 Energy cost		6,907,968.70	-	501,850.25							
		1.5 O&M		63,079,521.84	-	4,582,602.39							
	Start yr 0	1.6 Sludge treatment & disposal	O&M only	21,861,500.79		1,588,194.75							
		2. Collector network		-	-								
		2.1 Gravity pipes		40,259,012.50	-	-	40,259,012.50						
		2.2 Rising mains		4,135,750.00	-	-	4,135,750.00						
		2.3 Pump stations		1,353,750.00	-	-	1,353,750.00						
		2.3.1 EM (15yr)		242,915.55	-	-	-			582,112.50			
		2.3.2 Energy cost		341,256.20	-	24,791.59							
		2.4 O&M		8,515,549.06	-	618,637.78							
		Total PV		**203,866,910.92**	-								
		Total annualised cost		-	**14,810,931.08**								
	Decentralised	**1. Treatment facility**	**4000**	-	-								
	3-1	1.1 Land-use		9,148.14	-	-	9,148.14						
		1.2 Treatment train		64,082,146.20	-	-	56,483,516.48			15,793,716.07	3,231,522.92		
		1.3 EM (5yr)		1,175,255.65	-	-	-	518,213.17	518,213.17	518,213.17	518,213.17	518,213.17	
		EM (15 yr)		1,920,911.71						4,603,191.25			
		1.4 Energy cost		8,248,320.84	-	599,224.18							
		1.5 O&M		70,562,350.80	-	5,126,215.10							
4	**Start yr 5**	1.6 Sludge treatment & disposal	O&M only	26,103,284.53		1,896,351.95							
		2. Collector network			-								
		2.1 Gravity pipes		42,451,881.25	-		42,451,881.25						
		2.2 Rising mains		4,135,750.00	-		4,135,750.00						
		2.3 Pump stations		1,353,750.00	-		1,353,750.00						
		2.4 EM (15yr)		242,915.55	-		-			582,112.50			
		2.4.1 Energy cost		341,256.20	-	24,791.59							
		2.4.2 O&M		8,515,549.06	-	618,637.78							
		Total PV		**229,142,519.91**	-								
		Total annualised cost		-	**16,647,204.07**								
	Decentralised	**1. Treatment facility**	**4650**	-	-								
	3-2	1.1 Land-use		10,352.59	-		10,352.59						
		1.2 Treatment train		73,537,375.23	-		64,831,730.77			18,051,665.79	3,759,808.69		
		1.3 EM (5yr)		1,286,376.58	-		-	567,210.45	567,210.45	567,210.45	567,210.45	567,210.45	
		EM (15 yr)		2,083,595.83						4,993,040.56			
		1.4 Energy cost		9,588,672.97	-	696,598.11							
		1.5 O&M		77,633,421.64	-	5,639,914.39							
	Start yr 10	1.6 Sludge treatment & disposal	O&M only	30,345,068.26		2,204,509.14							
		2. Collector network		-	-								
		2.1 Gravity pipes		44,644,750.00	-		44,644,750.00						
		2.2 Rising mains		4,135,750.00	-		4,135,750.00						
		2.3 Pump stations		1,353,750.00	-		1,353,750.00						
		2.4 EM (15yr)		242,915.55	-		-			582,112.50			
		2.4.1 Energy cost		341,256.20	-	24,791.59							
		2.4.2 O&M		8,515,549.06		618,637.78							
		Total PV		**253,718,833.90**	-								
		Total annualised cost		-	**18,432,673.28**								

Table C4.6 (continued)

System		System cost components	Plant capacity (kL)	PV ZAR	Annualised costs	CASH FLOW TIME LINE							
						Annual costs	CAPITAL EXPENDITURE (ZAR)						
Option	Description				(A/P, 6%, 30) 0.07265	(P/A, 6%, 30) 13.765	Interest factors	(P/F, 6%, 5) 0.7473	(P/F, 6%, 10) 0.5584	(P/F, 6%, 15) 0.4173	(P/F, 6%, 20) 0.3119	(P/F, 6%, 25) 0.233	(P/F, 6%, 30) 0.1741
					ZAR	ZAR	Year 0	5	10	15	20	25	30
	Decentralised	**1. Treatment facility**	**5300**	-	-								
	3-3	1.1 Land-use		11,553.00	-	-	11,553.00						
		1.2 Treatment train		82,724,765.39	-	-	72,947,802.20			20,230,196.72	4,279,904.14		
		1.3 EM (5yr)		1,391,431.64	-	-	-	613,533.07	613,533.07	613,533.07	613,533.07	613,533.07	
		EM (15 yr)		2,236,995.23						5,360,640.38			
		1.4 Energy cost		10,929,025.11	-	793,972.04							
		1.5 O&M		84,371,537.62	-	6,129,425.18							
	Start yr 15	1.6 Sludge treatment & disposal	O&M only	34,586,852.00		2,512,666.33							
		2. Collector network		-	-								
		2.1 Gravity pipes		46,837,618.75	-		46,837,618.75						
		2.2 Rising mains		4,135,750.00	-		4,135,750.00						
		2.3 Pump stations		1,353,750.00	-		1,353,750.00						
		2.4 EM (15yr)		242,915.55	-		-			582,112.50			
		2.4.1 Energy cost		341,256.20	-	24,791.59							
		2.4.2 O&M		8,515,549.06	-	618,637.78							
		Total PV		**277,678,999.55**	-								
		Total annualised cost		-	**20,173,379.32**								
	Decentralised	**1. Treatment facility**	**5950**	-	-								
	3-4	1.1 Land-use		12,715.27	-	-	12,715.27						
		1.2 Treatment train		91,644,803.62	-	-	80,831,730.77			22,331,322.34	4,790,676.62		
		1.3 EM (5yr)		1,491,442.56	-	-	-	657,631.54	657,631.54	657,631.54	657,631.54	657,631.54	
		EM (15 yr)		2,382,770.98						5,709,971.20			
		1.4 Energy cost		12,269,377.25	-	891,345.97							
		1.5 O&M		90,832,657.44	-	6,598,812.75							
4	**Start yr 20**	1.6 Sludge treatment & disposal	O&M only	38,828,635.73		2,820,823.52							
		2. Collector network		-	-								
		2.1 Gravity pipes		49,030,487.50	-		49,030,487.50						
		2.2 Rising mains		4,135,750.00	-		4,135,750.00						
		2.3 Pump stations		1,353,750.00	-		1,353,750.00						
		2.4 EM (15yr)		242,915.55	-		-			582,112.50			
		2.4.1 Energy cost		341,256.20	-	24,791.59							
		2.4.2 O&M		8,515,549.06	-	618,637.78							
		Total PV		**301,082,111.15**	-								
		Total annualised cost		-	**21,873,615.38**								
	Decentralised	**1. Treatment facility**	**6600**	-	-								
	3-5	1.1 Land-use		13,874.19	-	-	13,874.19						
		1.2 Treatment train		100,297,933.20	-	-	88,483,516.48			24,356,774.19	5,291,230.67		
		1.3 EM (5yr)		1,587,167.33	-	-	-	699,840.09	699,840.09	699,840.09	699,840.09	699,840.09	
		EM (15 yr)		2,522,138.70						6,043,946.09			
		1.4 Energy cost		13,609,729.38	-	988,719.90							
		1.5 O&M		97,058,277.37	-	7,051,091.71							
	Start yr 25	1.6 Sludge treatment & disposal	O&M only	43,070,419.47		3,128,980.71	88,497,390.68	Sub-total 3-5					
		2. Collector network		-	-								
		2.1 Gravity pipes		51,223,356.25	-		51,223,356.25						
		2.2 Rising mains		4,135,750.00	-		4,135,750.00						
		2.3 Pump stations		1,353,750.00	-		1,353,750.00						
		2.4 EM (15yr)		242,915.55	-		-			582,112.50			
		2.4.1 Energy cost		341,256.20	-	24,791.59							
		2.4.2 O&M		8,515,549.06	-	618,637.78	56,712,856.25	Sub-total 3-5					
		Total PV		**323,972,116.70**	-								
		Total annualised cost		-	**23,536,574.28**		145,210,246.93	Total 3-5					

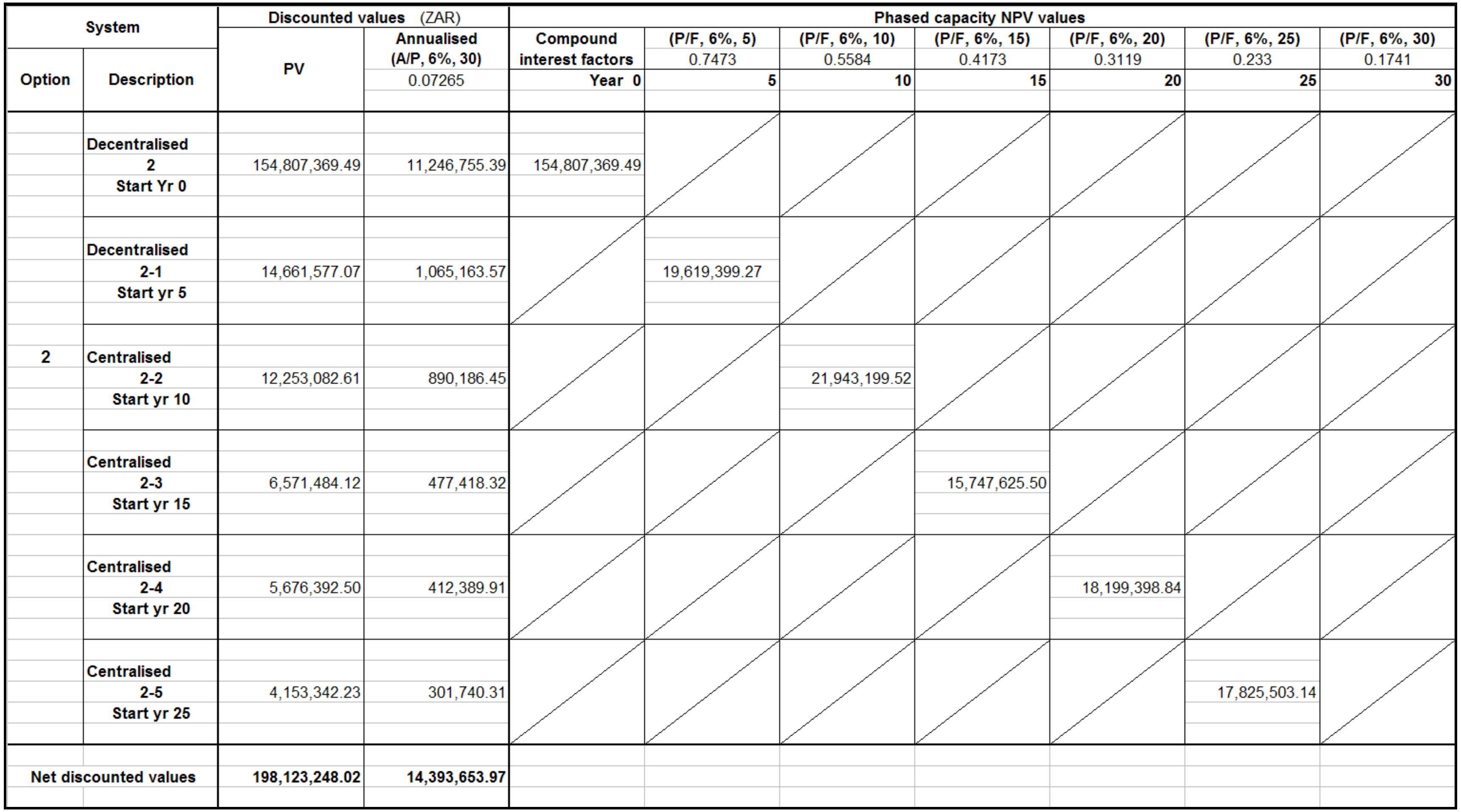
APPENDIX C5

DISCOUNTED STAGED CAPACITY COSTS OF SUB-SYSTEMS

Table C5.1 System option 1 – Fully centralised

System		Discounted values (ZAR)		Phased capacity PV values (treatment + collection)						
Option	Description	PV	Annualised (A/P, 6%, 30) 0.07265	Functional factors Year 0	(P/F, 6%, 5) 0.7473 5	(P/F, 6%, 10) 0.5584 10	(P/F, 6%, 15) 0.4173 15	(P/F, 6%, 20) 0.3119 20	(P/F, 6%, 25) 0.233 25	(P/F, 6%, 30) 0.1741 30
1	**Centralised** **1** **Start Yr 0**	678,616,719.47	49,301,504.67							
	Centralised **1-1** **Start yr 10**	80,519,452.37	5,849,738.21			144,196,727.03				
	Centralised **1-2** **Start yr 20**	38,174,179.05	2,773,354.11					122,392,366.30		
Net discounted values		**797,310,350.90**	**57,924,596.99**							

Table C5.2 System option 2 - Decentralised 2.1 (= 3.1)



System		Discounted values (ZAR)		Phased capacity NPV values						
Option	Description	PV	Annualised (A/P, 6%, 30) 0.07265	Compound interest factors Year 0	(P/F, 6%, 5) 0.7473 5	(P/F, 6%, 10) 0.5584 10	(P/F, 6%, 15) 0.4173 15	(P/F, 6%, 20) 0.3119 20	(P/F, 6%, 25) 0.233 25	(P/F, 6%, 30) 0.1741 30
	Decentralised 2 Start Yr 0	154,807,369.49	11,246,755.39	154,807,369.49						
	Decentralised 2-1 Start yr 5	14,661,577.07	1,065,163.57		19,619,399.27					
2	**Centralised 2-2 Start yr 10**	12,253,082.61	890,186.45			21,943,199.52				
	Centralised 2-3 Start yr 15	6,571,484.12	477,418.32				15,747,625.50			
	Centralised 2-4 Start yr 20	5,676,392.50	412,389.91					18,199,398.84		
	Centralised 2-5 Start yr 25	4,153,342.23	301,740.31						17,825,503.14	
Net discounted values		**198,123,248.02**	**14,393,653.97**							

Table C5.3 System option 2 - Centralised 2.2

System		Discounted values (ZAR)		Phased capacity PV values						
Option	Description	PV	Annualised (A/P, 6%, 30)	Functional factors	(P/F, 6%, 5)	(P/F, 6%, 10)	(P/F, 6%, 15)	(P/F, 6%, 20)	(P/F, 6%, 25)	(P/F, 6%, 30)
			0.07265		0.7473	0.5584	0.4173	0.3119	0.233	0.1741
				Year 0	5	10	15	20	25	30
2	Centralised 2 Start Yr 0	638,255,575.14	46,369,267.53							
	Centralised 2-1 Start yr 10	65,492,237.29	4,758,011.04			117,285,525.24				
	Centralised 2-2 Start yr 20	34,638,584.03	2,516,493.13					111,056,697.75		
Net discounted values		**738,386,396.47**	**53,643,771.70**							

Table C5.4 System option 3 - Decentralised 3.2

System		Discounted values (ZAR)		Phased capacity PV values						
			Annualised	Compound	(P/F, 6%, 5)	(P/F, 6%, 10)	(P/F, 6%, 15)	(P/F, 6%, 20)	(P/F, 6%, 25)	(P/F, 6%, 30)
			(A/P, 6%, 30)	interest factors	0.7473	0.5584	0.4173	0.3119	0.233	0.1741
Option	**Description**	**PV**	0.07265	**Year 0**	**5**	**10**	**15**	**20**	**25**	**30**
3	**Decentralised 2 Start Yr 0**	154,807,369.49	11,246,755.39	154,807,369.49						
	Decentralised 2-1 Start yr 5	14,661,577.07	1,065,163.57		19,619,399.27					
	Decentralised 2-2 Start yr 10	12,253,082.61	890,186.45			21,943,199.52				
	Decentralised 2-3 Start yr 15	6,571,484.12	477,418.32				15,747,625.50			
	Decentralised 2-4 Start yr 20	5,676,392.50	412,389.91					18,199,398.84		
	Decentralised 2-5 Start yr 25	4,153,342.23	301,740.31						17,825,503.14	
Net discounted values		**198,123,248.02**	**14,393,653.97**							

Table C5.5 System option 3 - Centralised 3.3 (= 4.2)

System		**Discounted values** (ZAR)		**Phased capacity PV values**						
Option	**Description**	**PV**	**Annualised (A/P, 6%, 30)**	**Functional factors**	**(P/F, 6%, 5)**	**(P/F, 6%, 10)**	**(P/F, 6%, 15)**	**(P/F, 6%, 20)**	**(P/F, 6%, 25)**	**(P/F, 6%, 30)**
			0.07265		0.7473	0.5584	0.4173	0.3119	0.233	0.1741
				Year 0	**5**	**10**	**15**	**20**	**25**	**30**
3	**Centralised 3 Start Yr 0**	497,817,968.71	36,166,475.43							
	Centralised 3-1 Start yr 10	59,619,325.37	4,331,343.99			106,768,132.83				
	Centralised 3-2 Start yr 20	29,222,334.66	2,123,002.61					93,691,358.32		
Net discounted values		**586,659,628.75**	**42,620,822.03**							

Table C5.6 System option 4 - Decentralised 4.1

System		Discounted values (ZAR)		Phased capacity PV values (Treatment+collection)						
Option	Description	PV	Annualised (A/P, 6%, 30) 0.07265	Functional factors Year 0	(P/F, 6%, 5) 0.7473 5	(P/F, 6%, 10) 0.5584 10	(P/F, 6%, 15) 0.4173 15	(P/F, 6%, 20) 0.3119 20	(P/F, 6%, 25) 0.233 25	(P/F, 6%, 30) 0.1741 30
4	**Decentralised 3 Start Yr 0**	203,866,910.92	14,810,931.08	203,866,910.92						
	Decentralised 3-1 Start yr 5	18,888,462.60	1,372,246.81		25,275,608.99					
	Decentralised 3-2 Start yr 10	13,723,413.73	997,006.01			24,576,313.99				
	Decentralised 3-3 Start yr 15	9,998,577.12	726,396.63				23,960,165.64			
	Decentralised 3-4 Start yr 20	7,299,430.51	530,303.63					23,403,111.61		
	Decentralised 3-5 Start yr 25	5,333,371.29	387,469.42						22,890,005.54	
Net discounted values		**259,110,166.18**	**18,824,353.57**							

APPENDIX C6

OUTPUT DISTANCE FUNCTION VALUES, POLLUTANT SHADOW PRICES AND COMBINED REMOVAL BENEFITS

Table C6.1 Staged full capacity - system level scenario

System options	Description	System level pollutant shadow prices (ZAR/kg) (desireable output (effluent) value = 1 ZAR/m^3)					Distance function values	Annual flow (kL)	System level pollutant removal benefit in ZAR/m^3 (desireable output (effluent) value = 1 ZAR/m^3)				
		SS	**BOD**	**COD**	**N**	**P**			**SS**	**BOD**	**COD**	**N**	**P**
1	Centralised 1	-1.12450	-0.13744	-1.22740	-1.52470	-4.85840	0.9360	3163333	0.2059	0.0336	0.6298	0.0722	0.0469
	1-1	-1.11570	-0.13182	-1.22580	-1.46060	-5.57060	1.0000	4380000	0.2042	0.0322	0.6290	0.0692	0.0537
	1-2	-1.11510	-0.12831	-1.22520	-1.45150	-5.74810	0.9971	5596667	0.2041	0.0314	0.6287	0.0688	0.0554
	Decentralised 1	-0.02545	-0.00131	-0.96194	-0.24389	-59.88600	1.0000	246375	0.0052	0.0004	0.5437	0.0052	0.4336
	1-1	-0.02635	-0.00109	-0.95898	-0.35784	-59.78500	0.9438	301125	0.0053	0.0003	0.5421	0.0076	0.4328
	1-2	-0.02779	-0.00096	-0.95716	-0.43828	-59.66800	1.0000	355875	0.0056	0.0003	0.5410	0.0093	0.4320
2	1-3	-0.02926	-0.00086	-0.95598	-0.49734	-59.55900	1.0000	410625	0.0059	0.0002	0.5404	0.0106	0.4312
	1-4	-0.04369	0.00000	-0.95796	-0.57042	-58.82200	0.9707	465375	0.0089	0.0000	0.5415	0.0121	0.4259
	1-5	-0.03493	-0.00049	-0.95531	-0.58228	-59.22700	0.9732	520125	0.0071	0.0001	0.5400	0.0124	0.4288
	Centralised 2	-1.16610	-0.14088	-1.24750	-1.24000	-4.27720	0.9956	2889583	0.2135	0.0344	0.6401	0.0587	0.0413
	2-1	-1.12650	-0.13486	-1.23320	-1.34550	-5.44630	0.7608	3996750	0.2062	0.0330	0.6328	0.0637	0.0525
	2-2	-1.12350	-0.13131	-1.23180	-1.34370	-5.67900	1.0000	5103917	0.2057	0.0321	0.6321	0.0637	0.0548
	Decentralised 1						**= SAME AS OPTION 2**						
	Decentralised 2	-0.12448	-0.00916	-0.95834	-1.27960	-54.19200	1.0000	815167	0.0252	0.0026	0.5417	0.0271	0.3924
	2-1	-0.10137	-0.00752	-0.95186	-1.26020	-55.48100	1.0000	985500	0.0206	0.0021	0.5380	0.0267	0.4017
3	2-2	-0.08258	-0.00722	-0.94787	-1.16300	-56.62300	1.0000	1155833	0.0167	0.0021	0.5358	0.0247	0.4100
	2-3	-0.07800	-0.00591	-0.94531	-1.23100	-56.81100	1.0000	1326167	0.0158	0.0017	0.5343	0.0261	0.4113
	2-4	-0.07254	-0.00536	-0.94358	-1.23370	-57.11800	1.0000	1496500	0.0147	0.0015	0.5334	0.0262	0.4135
	2-5	-0.06891	-0.00494	-0.94238	-1.23710	-57.32200	1.0000	1666833	0.0140	0.0014	0.5327	0.0262	0.4150
	Centralised 3	-1.17120	-0.15270	-1.24060	-1.59350	-2.51900	0.9833	1989250	0.2144	0.0373	0.6366	0.0755	0.0243
	3-1	-1.15520	-0.14702	-1.23710	-1.53520	-3.44660	0.9866	2755750	0.2115	0.0359	0.6348	0.0727	0.0332
	3-2	-1.15060	-0.14359	-1.23530	-1.53360	-3.72920	1.0000	3522250	0.2106	0.0351	0.6339	0.0727	0.0360
	Decentralised 3	-0.15756	-0.00909	-0.95902	-1.56100	-52.42300	0.9916	1061542	0.0320	0.0026	0.5421	0.0331	0.3795
	3-1	-0.13818	-0.00797	-0.95351	-1.54360	-53.50500	1.0000	1286625	0.0280	0.0023	0.5390	0.0327	0.3874
	3-2	-0.12686	-0.00721	-0.95014	-1.53770	-54.14000	0.9926	1511708	0.0257	0.0021	0.5371	0.0326	0.3920
4	3-3	-0.11989	-0.00664	-0.94798	-1.53700	-54.53500	0.9876	1736792	0.0243	0.0019	0.5358	0.0326	0.3948
	3-4	-0.11545	-0.00619	-0.94654	-1.53860	-54.78900	0.9897	1961875	0.0234	0.0018	0.5350	0.0326	0.3967
	3-5	-0.11257	-0.00584	-0.94556	-1.54100	-54.95500	1.0000	2186958	0.0228	0.0017	0.5345	0.0327	0.3979
	Centralised 3						**= SAME AS OPTION 3**						

Table C6.2 Staged full capacity - treatment level scenario

System options	Description	Treatment level pollutant shadow prices (ZAR/kg) (desireable output (effluent) value = 1 ZAR/m^3)					Distance function values	Annual flow (kL)	Treatment level pollutant removal benefit in ZAR/m^3 (desireable output (effluent) value = 1 ZAR/m^3)				
		SS	BOD	COD	N	P			SS	BOD	COD	N	P
1	Centralised 1	-0.09527	-1.76760	-0.32527	-4.32180	-18.39700	0.9075	3163333	0.0174	0.4320	0.1669	0.2047	0.1775
	1-1	-0.11588	-1.78970	-0.34054	-3.89700	-18.72200	1.0000	4380000	0.0212	0.4374	0.1747	0.1846	0.1806
	1-2	-0.12773	-1.80460	-0.35003	-3.65030	-18.82600	0.9720	5596667	0.0234	0.4410	0.1796	0.1729	0.1816
2	Decentralised 1	-0.13670	-1.58460	-0.24532	-11.11400	-19.92900	1.0000	246375	0.0277	0.4519	0.1387	0.2358	0.1443
	1-1	-0.14634	-1.58700	-0.25072	-10.59200	-20.67500	1.0000	301125	0.0297	0.4526	0.1417	0.2247	0.1497
	1-2	-0.15272	-1.58860	-0.25431	-10.24700	-21.16400	1.0000	355875	0.0310	0.4530	0.1437	0.2174	0.1532
	1-3	-0.15715	-1.58980	-0.25681	-10.00800	-21.50100	1.0000	410625	0.0319	0.4534	0.1452	0.2123	0.1557
	1-4	-0.16143	-1.59080	-0.25974	-9.80170	-21.71700	0.9753	465375	0.0327	0.4537	0.1468	0.2080	0.1572
	1-5	-0.16288	-1.59130	-0.26021	-9.70480	-21.90300	0.9746	520125	0.0330	0.4538	0.1471	0.2059	0.1586
	Centralised 2	-0.10192	-1.82180	-0.34237	-4.13750	-16.89100	0.9783	2889583	0.0187	0.4453	0.1757	0.1960	0.1629
	2-1	-0.11073	-1.80120	-0.34118	-3.98720	-18.04800	1.0000	3996750	0.0203	0.4402	0.1751	0.1889	0.1741
	2-2	-0.12138	-1.81280	-0.34923	-3.76780	-18.20200	1.0000	5103917	0.0222	0.4431	0.1792	0.1785	0.1756
3	Decentralised 1						= SAME AS OPTION 2						
	Decentralised 2	-0.21011	-1.60760	-0.28686	-7.10650	-25.48300	1.0000	815167	0.0426	0.4584	0.1621	0.1508	0.1845
	2-1	-0.21862	-1.61130	-0.29186	-6.63940	-26.07900	1.0000	985500	0.0443	0.4595	0.1650	0.1409	0.1888
	2-2	-0.22334	-1.61500	-0.29478	-6.36640	-26.37300	1.0000	1155833	0.0453	0.4606	0.1666	0.1351	0.1909
	2-3	-0.22822	-1.61630	-0.29771	-6.11070	-26.70500	0.9744	1326167	0.0463	0.4609	0.1683	0.1296	0.1933
	2-4	-0.23122	-1.61800	-0.29959	-5.94760	-26.88800	1.0000	1496500	0.0469	0.4614	0.1693	0.1262	0.1947
	2-5	-0.23345	-1.61930	-0.30102	-5.82670	-27.01700	1.0000	1666833	0.0473	0.4618	0.1702	0.1236	0.1956
	Centralised 3	-0.05092	-1.73000	-0.29540	-5.22520	-17.33900	0.9997	1989250	0.0093	0.4228	0.1516	0.2475	0.1672
	3-1	-0.06900	-1.74470	-0.30748	-4.85820	-17.78500	0.9916	2755750	0.0126	0.4264	0.1578	0.2302	0.1716
	3-2	-0.07878	-1.75410	-0.31447	-4.65840	-17.97300	0.9832	3522250	0.0144	0.4287	0.1614	0.2207	0.1734
4	Decentralised 3	-0.22779	-1.61550	-0.29730	-6.13430	-26.71200	0.9441	1061542	0.0462	0.4607	0.1680	0.5667	0.1934
	3-1	-0.23602	-1.61980	-0.30230	-5.68160	-27.25100	0.9743	1286625	0.0479	0.4619	0.1709	0.5782	0.1973
	3-2	-0.24168	-1.62300	-0.30583	-5.37170	-27.60000	0.9928	1511708	0.0490	0.4628	0.1729	0.1140	0.1998
	3-3	-0.24575	-1.62550	-0.30844	-5.14970	-27.83400	1.0000	1736792	0.0498	0.4636	0.1743	0.1093	0.2015
	3-4	-0.24876	-1.62750	-0.31041	-4.98640	-27.99700	1.0000	1961875	0.0505	0.4641	0.1755	0.1058	0.2027
	3-5	-0.25102	-1.62910	-0.31193	-4.86400	-28.11000	0.9968	2186958	0.0509	0.4646	0.1763	0.1032	0.2035
	Centralised 3						= SAME AS OPTION 3						

APPENDIX C7

SYSTEM LEVEL SCENARIOS – ECONOMIC BREAKEVEN CALCULATIONS FOR VARIOUS REUSE LEVELS

Table C7.1 Reuse tariff compared to the 2010 Fresh water tariff (FWT$_{2010}$)

System options	Description	System level economic break-even viability analysis - annualised cost & benefits						FWT$_{2010}$ (ZAR)
		100% direct reuse		80%		60%		
		Req FW rate	% FWT$_{2010}$	Req FW rate	% FWT$_{2010}$	Req FW rate	% FWT$_{2010}$	4.06559
1	Centralised 1	6.77	166.58	7.55	185.58	8.52	209.49	
	System option 1	6.77	**166.58**	7.55	**185.58**	8.52	**209.49**	
2	Centralised 2	6.87	169.07	7.66	188.36	8.64	212.62	
	Decentralised 1	7.60	186.86	8.46	208.15	9.55	234.92	
	System option 2	6.94	**170.63**	7.73	**190.09**	8.72	**214.58**	
3	Centralised 3	7.92	194.83	8.83	217.07	9.96	245.03	
	Decentralised 1	7.60	186.86	8.46	208.15	9.55	234.92	
	Decentralised 2	5.92	145.72	6.60	162.30	7.45	183.14	
	System option 3	7.33	**180.20**	8.17	**200.91**	9.21	**226.60**	
4	Centralised 3	7.92	194.83	8.83	217.07	9.96	245.03	
	Decentralised 3	5.92	145.62	6.59	162.19	7.44	183.01	
	System option 4	7.18	**176.55**	8.00	**196.68**	9.02	**221.98**	

System options	Description	System level economic break-even viability analysis - annualised cost & benefits						FWT$_{2010}$ (ZAR)
		40% direct reuse		20%		Zero %		
		Req FW rate	% FWT$_{2010}$	Req FW rate	% FWT$_{2010}$	Req FW rate	% FWT$_{2010}$	4.06559
1	Centralised 1	9.78	240.46	11.47	282.18	13.88	341.41	
	System option 1	9.78	**240.46**	11.47	**282.18**	13.88	**341.41**	
2	Centralised 2	9.92	244.06	11.64	286.40	14.09	346.53	
	Decentralised 1	10.96	269.58	12.86	316.24	15.55	382.44	
	System option 2	10.01	**246.30**	11.75	**289.02**	14.22	**349.68**	
3	Centralised 3	11.44	281.26	13.42	330.07	16.24	399.38	
	Decentralised 1	10.96	269.58	12.86	316.24	15.55	382.44	
	Decentralised 2							
	System option 3	10.57	**260.03**	12.40	**305.09**	15.00	**369.03**	
4	Centralised 3	11.44	281.26	13.42	330.07	16.24	399.38	
	Decentralised 3	8.54	209.97	10.01	246.25	12.10	297.68	
	System option 4	10.36	**254.76**	12.15	**298.90**	14.70	**361.54**	

Table C7.2 Reuse tariff compared to a discounted escalated Fresh water tariff @ 6% pa ($FWT_{Annualised}$)

System options	Description	System level economic break-even viability analysis - annualised cost & benefits						$FWT_{Annualised}$ (ZAR)
		100% direct reuse		80%		60%		
		Req FW rate	% FWT_{2010}	Req FW rate	% FWT_{2010}	Req FW rate	% FWT_{2010}	**6.58788**
1	Centralised 1	6.77	102.80	7.55	114.53	8.52	129.28	
	System option 1	6.77	**102.80**	7.55	**114.53**	8.52	**129.28**	
2	Centralised 2	6.87	104.34	7.66	116.24	8.64	131.22	
	Decentralised 1	7.60	115.32	8.46	128.46	9.55	144.98	
	System option 2	6.94	**105.30**	7.73	**117.31**	8.72	**132.42**	
3	Centralised 3	7.92	120.24	8.83	133.96	9.96	151.22	
	Decentralised 1	7.60	115.32	8.46	128.46	9.55	144.98	
	Decentralised 2	5.92	89.93	6.60	100.16	7.45	113.02	
	System option 3	7.33	**111.20**	8.17	**123.99**	9.21	**139.84**	
4	Centralised 3	7.92	120.24	8.83	133.96	9.96	151.22	
	Decentralised 3	5.92	89.86	6.59	100.09	7.44	112.94	
	System option 4	7.18	**108.96**	8.00	**121.38**	9.02	**136.99**	

System options	Description	System level economic break-even viability analysis - annualised cost & benefits						$FWT_{Annualised}$ (ZAR)
		40% direct reuse		20%		Zero %		
		Req FW rate	% FWT_{2010}	Req FW rate	% FWT_{2010}	Req FW rate	% FWT_{2010}	**6.58788**
1	Centralised 1	9.78	148.40	11.47	174.14	13.88	210.70	
	System option 1	9.78	**148.40**	11.47	**174.14**	13.88	**210.70**	
2	Centralised 2	9.92	150.62	11.64	176.75	14.09	213.86	
	Decentralised 1	10.96	166.37	12.86	195.16	15.55	236.01	
	System option 2	10.01	**152.00**	11.75	**178.36**	14.22	**215.80**	
3	Centralised 3	11.44	173.58	13.42	203.70	16.24	246.47	
	Decentralised 1	10.96	166.37	12.86	195.16	15.55	236.01	
	Decentralised 2	8.54	129.67	10.02	152.07	12.11	183.83	
	System option 3	10.57	**160.47**	12.40	**188.28**	15.00	**227.74**	
4	Centralised 3	11.44	173.58	13.42	203.70	16.24	246.47	
	Decentralised 3	8.54	129.58	10.01	151.97	12.10	183.71	
	System option 4	10.36	**157.22**	12.15	**184.46**	14.70	**223.12**	

Table C7.3 Reuse tariff compared to a discounted escalated Fresh water tariff @ 8% pa ($\mathrm{FWT}_{\mathrm{Annualised}}$)

System options	Description	System level economic break-even point viability analysis wrt direct reuse level						$\mathrm{FWT}_{\mathrm{Annualised}}$ (ZAR)
		100% direct reuse		80%		60%		
		Req FW rate	% FWT_{2010}	Req FW rate	% FWT_{2010}	Req FW rate	% FWT_{2010}	7.05461
1	Centralised 1	6.65	94.28	7.39	104.82	8.33	118.02	
	System option 1	6.65	**94.28**	7.39	**104.82**	8.33	**118.02**	
2	Centralised 2	6.75	95.69	7.51	106.40	8.45	119.79	
	Decentralised 1	7.38	104.68	8.20	116.23	9.22	130.65	
	System option 2	6.81	**96.49**	7.57	**107.27**	8.52	**120.76**	
3	Centralised 3	7.78	110.27	8.65	122.60	9.74	138.04	
	Decentralised 1	7.38	104.68	8.20	116.23	9.22	130.65	
	Decentralised 2	5.76	81.72	6.40	90.74	7.20	102.00	
	System option 3	7.17	**101.63**	8.00	**113.41**	8.97	**127.15**	
4	Centralised 3	7.78	110.27	8.65	122.60	9.74	138.04	
	Decentralised 3	5.76	81.64	6.39	90.65	7.19	101.89	
	System option 4	7.02	**99.57**	7.81	**110.65**	8.78	**124.51**	

System options	Description	System level economic break-even point viability analysis wrt direct reuse level						$\mathrm{FWT}_{\mathrm{Annualised}}$ (ZAR)
		40% direct reuse		20%		Zero %		
		Req FW rate	% FWT_{2010}	Req FW rate	% FWT_{2010}	Req FW rate	% FWT_{2010}	7.054611768
1	Centralised 1	9.53	135.02	11.13	157.75	13.38	189.67	
	System option 1	9.53	**135.02**	11.13	**157.75**	13.38	**189.67**	
2	Centralised 2	9.67	137.05	11.30	160.12	13.58	192.53	
	Decentralised 1	10.52	149.16	12.26	173.78	14.68	208.13	
	System option 2	9.74	**138.13**	11.38	**161.34**	13.68	**193.92**	
3	Centralised 3	11.14	157.93	13.02	184.51	15.65	221.86	
	Decentralised 1	10.52	149.16	12.26	173.78	14.68	208.13	
	Decentralised 2	8.21	116.45	9.57	135.67	11.46	162.48	
	System option 3	10.25	**145.28**	11.96	**169.55**	14.36	**203.56**	
4	Centralised 3	11.14	157.93	13.02	184.51	15.65	221.86	
	Decentralised 3	8.21	116.32	9.56	135.51	11.45	162.28	
	System option 4	10.04	**142.33**	11.72	**166.11**	14.07	**199.43**	

Table C7.4 Reuse tariff compared to a discounted escalated Fresh water tariff @ 10% pa ($FWT_{Annualised}$)

System options	**Description**	**System level economic break-even point viability analysis wrt direct reuse level**						$FWT_{Annualised}$ (ZAR)
		100% direct reuse		80%		60%		
		Req FW rate	% FWT_{2010}	Req FW rate	% FWT_{2010}	Req FW rate	% FWT_{2010}	**7.39124**
1	Centralised 1	6.77	91.63	7.55	102.08	8.52	115.23	
	System option 1	6.77	**91.63**	7.55	**102.08**	8.52	**115.23**	
2	Centralised 2	6.87	93.00	7.66	103.61	8.64	116.95	
	Decentralised 1	7.60	102.79	8.46	114.50	9.55	129.22	
	System option 2	6.94	**93.85**	7.73	**104.56**	8.72	**118.03**	
3	Centralised 3	7.92	107.17	8.83	119.40	9.96	134.78	
	Decentralised 1	7.60	102.79	8.46	114.50	9.55	129.22	
	Decentralised 2	5.92	80.16	6.60	89.28	7.45	100.74	
	System option 3	7.33	**99.12**	8.17	**110.51**	9.21	**124.64**	
4	Centralised 3	7.92	107.17	8.83	119.40	9.96	134.78	
	Decentralised 3	5.92	80.10	6.59	89.21	7.44	100.67	
	System option 4	7.18	**97.11**	8.00	**108.18**	9.02	**122.10**	

System options	**Description**	**System level economic break-even point viability analysis wrt direct reuse level**						$FWT_{Annualised}$ (ZAR)
		40% direct reuse		20%		Zero %		
		Req FW rate	% FWT_{2010}	Req FW rate	% FWT_{2010}	Req FW rate	% FWT_{2010}	**7.39124262**
1	Centralised 1	9.78	132.27	11.47	155.21	13.88	187.80	
	System option 1	9.78	**132.27**	11.47	**155.21**	13.88	**187.80**	
2	Centralised 2	9.92	134.25	11.64	157.54	14.09	190.61	
	Decentralised 1	10.96	148.28	12.86	173.95	15.55	210.36	
	System option 2	10.01	**135.48**	11.75	**158.98**	14.22	**192.34**	
3	Centralised 3	11.44	154.71	13.42	181.56	16.24	219.68	
	Decentralised 1	10.96	148.28	12.86	173.95	15.55	210.36	
	Decentralised 2	8.54	115.58	10.02	135.54	12.11	163.85	
	System option 3	10.57	**143.03**	12.40	**167.82**	15.00	**202.99**	
4	Centralised 3	11.44	154.71	13.42	181.56	16.24	219.68	
	Decentralised 3	8.54	115.50	10.01	135.45	12.10	163.74	
	System option 4	10.36	**140.13**	12.15	**164.41**	14.70	**198.87**	

APPENDIX C8

TREATMENT LEVEL SCENARIOS – ECONOMIC BREAKEVEN CALCULATIONS FOR VARIOUS REUSE LEVELS

Table C8.1 Reuse tariff compared to the 2010 Fresh water tariff (FWT$_{2010}$)

System options	Description	Treatment level economic break-even viability analysis - annualised cost & benefits						FWT$_{2010}$ (ZAR)
		100% direct reuse		80%		60%		
		Req FW rate	% FWT$_{2010}$	Req FW rate	% FWT$_{2010}$	Req FW rate	% FWT$_{2010}$	**4.06559**
1	Centralised 1	3.71	91.19	4.13	101.54	4.66	114.53	
	System option 1	3.71	**91.19**	4.13	**101.54**	4.66	**114.53**	
2	Centralised 2	3.81	93.82	4.25	104.47	4.79	117.84	
	Decentralised 1	6.12	150.55	6.81	167.60	7.68	189.02	
	System option 2	4.02	**98.79**	4.47	**110.00**	5.04	**124.08**	
3	Centralised 3	4.18	102.91	4.66	114.58	5.25	129.25	
	Decentralised 1	6.12	150.55	6.81	167.60	7.68	189.02	
	Decentralised 2	4.74	116.49	5.27	129.71	5.95	146.31	
	System option 3	4.51	**110.93**	5.02	**123.53**	5.66	**139.32**	
4	Centralised 3	4.18	102.91	4.66	114.58	5.25	129.25	
	Decentralised 3	4.23	104.06	4.67	114.97	5.22	128.44	
	System option 4	4.20	**103.35**	4.66	**114.74**	5.24	**128.94**	

System options	Description	System level economic break-even viability analysis - annualised cost & benefits						FWT$_{2010}$ (ZAR)
		40% direct reuse		20%		Zero %		
		Req FW rate	% FWT$_{2010}$	Req FW rate	% FWT$_{2010}$	Req FW rate	% FWT$_{2010}$	**4.06559**
1	Centralised 1	5.34	131.35	6.26	153.94	7.56	185.93	
	System option 1	5.34	**131.35**	6.26	**153.94**	7.56	**185.93**	
2	Centralised 2	5.49	135.13	6.44	158.38	7.78	191.28	
	Decentralised 1	8.81	216.71	10.32	253.90	12.46	306.51	
	System option 2	5.78	**142.28**	6.78	**166.75**	8.19	**201.39**	
3	Centralised 3	6.03	148.22	7.06	173.72	8.53	209.82	
	Decentralised 1	8.81	216.71	10.32	253.90	12.46	306.51	
	Decentralised 2							
	System option 3	6.50	**159.77**	7.61	**187.25**	9.19	**226.15**	
4	Centralised 3	6.03	148.22	7.06	173.72	8.53	209.82	
	Decentralised 3	5.92	145.49	6.82	167.76	8.05	198.06	
	System option 4	5.98	**147.15**	6.97	**171.35**	8.34	**205.07**	

Table C8.2 Reuse tariff compared to a discounted escalated Fresh water tariff @ 6% pa ($FWT_{Annualised}$)

System options	Description	Treatment level economic break-even viability analysis - annualised cost & benefits						$FWT_{Annualised}$ (ZAR)
		100% direct reuse		80%		60%		
		Req FW rate	% FWT_{2010}	Req FW rate	% FWT_{2010}	Req FW rate	% FWT_{2010}	6.58788
1	Centralised 1	3.71	56.28	4.13	62.66	4.66	70.68	
	System option 1	3.71	**56.28**	4.13	**62.66**	4.66	**70.68**	
2	Centralised 2	3.81	57.90	4.25	64.47	4.79	72.72	
	Decentralised 1	6.12	92.91	6.81	103.43	7.68	116.65	
	System option 2	4.02	**60.97**	4.47	**67.88**	5.04	**76.57**	
3	Centralised 3	4.18	63.51	4.66	70.71	5.25	79.76	
	Decentralised 1	6.12	92.91	6.81	103.43	7.68	116.65	
	Decentralised 2	4.73	71.74	5.26	79.87	5.93	90.06	
	System option 3	4.51	**68.42**	5.02	**76.23**	5.66	**85.93**	
4	Centralised 3	4.18	63.51	4.66	70.71	5.25	79.76	
	Decentralised 3	4.23	64.22	4.67	70.95	5.22	79.27	
	System option 4	4.20	**63.78**	4.66	**70.81**	5.24	**79.57**	

System options	Description	System level economic break-even viability analysis - annualised cost & benefits						$FWT_{Annualised}$ (ZAR)
		40% direct reuse		20%		Zero %		
		Req FW rate	% FWT_{2010}	Req FW rate	% FWT_{2010}	Req FW rate	% FWT_{2010}	6.58788
1	Centralised 1	5.34	81.06	6.26	95.00	7.56	114.74	
	System option 1	5.34	**81.06**	6.26	**95.00**	7.56	**114.74**	
2	Centralised 2	5.49	83.40	6.44	97.74	7.78	118.05	
	Decentralised 1	8.81	133.74	10.32	156.69	12.46	189.16	
	System option 2	5.78	**87.81**	6.78	**102.91**	8.19	**124.28**	
3	Centralised 3	6.03	91.47	7.06	107.21	8.53	129.49	
	Decentralised 1	8.81	133.74	10.32	156.69	12.46	189.16	
	Decentralised 2							
	System option 3	6.49	**98.52**	7.61	**115.44**	9.18	**139.40**	
4	Centralised 3	6.03	91.47	7.06	107.21	8.53	129.49	
	Decentralised 3	5.92	89.79	6.82	103.53	8.05	122.23	
	System option 4	5.98	**90.81**	6.97	**105.74**	8.34	**126.56**	

Table C8.3 Reuse tariff compared to a discounted escalated Fresh water tariff @ 8% pa ($FWT_{Annualised}$)

System options	Description	Treatment level economic break-even viability analysis - annualised cost & benefits						$FWT_{Annualised}$ (ZAR)
		100% direct reuse		80%		60%		
		Req FW rate	% FWT_{2010}	Req FW rate	% FWT_{2010}	Req FW rate	% FWT_{2010}	7.05461
1	Centralised 1	3.71	52.55	4.13	58.52	4.66	66.01	
	System option 1	3.71	**52.55**	4.13	**58.52**	4.66	**66.01**	
2	Centralised 2	3.81	54.07	4.25	60.20	4.79	67.91	
	Decentralised 1	6.12	86.76	6.81	96.59	7.68	108.93	
	System option 2	4.02	**56.93**	4.47	**63.39**	5.04	**71.51**	
3	Centralised 3	4.18	59.31	4.66	66.04	5.25	74.49	
	Decentralised 1	6.12	86.76	6.81	96.59	7.68	108.93	
	Decentralised 2	4.73	67.00	5.26	74.58	5.93	84.10	
	System option 3	4.51	**63.89**	5.02	**71.19**	5.66	**80.24**	
4	Centralised 3	4.18	59.31	4.66	66.04	5.25	74.49	
	Decentralised 3	4.23	59.97	4.67	66.26	5.22	74.02	
	System option 4	4.20	**59.56**	4.66	**66.12**	5.24	**74.31**	

System options	Description	System level economic break-even viability analysis - annualised cost & benefits						$FWT_{Annualised}$ (ZAR)
		40% direct reuse		20%		Zero %		
		Req FW rate	% FWT_{2010}	Req FW rate	% FWT_{2010}	Req FW rate	% FWT_{2010}	7.05461
1	Centralised 1	5.34	75.70	6.26	88.72	7.56	107.15	
	System option 1	5.34	**75.70**	6.26	**88.72**	7.56	**107.15**	
2	Centralised 2	5.49	77.88	6.44	91.27	7.78	110.24	
	Decentralised 1	8.81	124.89	10.32	146.33	12.46	176.64	
	System option 2	5.78	**82.00**	6.78	**96.10**	8.19	**116.06**	
3	Centralised 3	6.03	85.42	7.06	100.12	8.53	120.92	
	Decentralised 1	8.81	124.89	10.32	146.33	12.46	176.64	
	Decentralised 2							
	System option 3	6.49	**92.00**	7.61	**107.81**	9.18	**130.18**	
4	Centralised 3	6.03	85.42	7.06	100.12	8.53	120.92	
	Decentralised 3	5.92	83.85	6.82	96.68	8.05	114.14	
	System option 4	5.98	**84.80**	6.97	**98.75**	8.34	**118.18**	

Table C8.4 Reuse tariff compared to a discounted escalated Fresh water tariff @ 10% pa ($FWT_{Annualised}$)

System options	Description	Treatment level economic break-even viability analysis - annualised cost & benefits						$FWT_{Annualised}$ (ZAR)
		100% direct reuse		80%		60%		
		Req FW rate	% FWT_{2010}	Req FW rate	% FWT_{2010}	Req FW rate	% FWT_{2010}	7.39124
1	Centralised 1	3.71	50.16	4.13	55.85	4.66	63.00	
	System option 1	3.71	**50.16**	4.13	**55.85**	4.66	**63.00**	
2	Centralised 2	3.81	51.61	4.25	57.46	4.79	64.82	
	Decentralised 1	6.12	82.81	6.81	92.19	7.68	103.97	
	System option 2	4.02	**54.34**	4.47	**60.51**	5.04	**68.25**	
3	Centralised 3	4.18	56.60	4.66	63.03	5.25	71.10	
	Decentralised 1	6.12	82.81	6.81	92.19	7.68	103.97	
	Decentralised 2	4.73	63.95	5.26	71.19	5.93	80.27	
	System option 3	4.51	**60.98**	5.02	**67.94**	5.66	**76.59**	
4	Centralised 3	4.18	56.60	4.66	63.03	5.25	71.10	
	Decentralised 3	4.23	57.24	4.67	63.24	5.22	70.65	
	System option 4	4.20	**56.85**	4.66	**63.11**	5.24	**70.92**	

System options	Description	System level economic break-even viability analysis - annualised cost & benefits						$FWT_{Annualised}$ (ZAR)
		40% direct reuse		20%		Zero %		
		Req FW rate	% FWT_{2010}	Req FW rate	% FWT_{2010}	Req FW rate	% FWT_{2010}	7.39124
1	Centralised 1	5.34	72.25	6.26	84.68	7.56	102.27	
	System option 1	5.34	**72.25**	6.26	**84.68**	7.56	**102.27**	
2	Centralised 2	5.49	74.33	6.44	87.12	7.78	105.22	
	Decentralised 1	8.81	119.20	10.32	139.66	12.46	168.60	
	System option 2	5.78	**78.26**	6.78	**91.72**	8.19	**110.78**	
3	Centralised 3	6.03	81.53	7.06	95.56	8.53	115.41	
	Decentralised 1	8.81	119.20	10.32	139.66	12.46	168.60	
	Decentralised 2							
	System option 3	6.49	**87.81**	7.61	**102.90**	9.18	**124.25**	
4	Centralised 3	6.03	81.53	7.06	95.56	8.53	115.41	
	Decentralised 3	5.92	80.03	6.82	92.27	8.05	108.95	
	System option 4	5.98	**80.94**	6.97	**94.25**	8.34	**112.80**	

APPENDIX C9

MCA SCORE ASSESSMENT SHEETS

Table C9.1 Technical category

Category	Main criteria	Sub criteria	Ranking	Normalised category weight coefficients (%)	Overall Individual weight coefficients (%)
Technical	**Performance**	COD removal			
		BOD removal			
		TSS removal			
		Nitrogen removal			
		Phosphorus removal			
		FC removal			
	Reliability				
	Ease of construction				
	Adaptability	Upgrade			
		Flow variation			
		Water quality variation			
	Sludge Production				
	Ease of O&M				
	Column sum				

Table C9.2 Social category

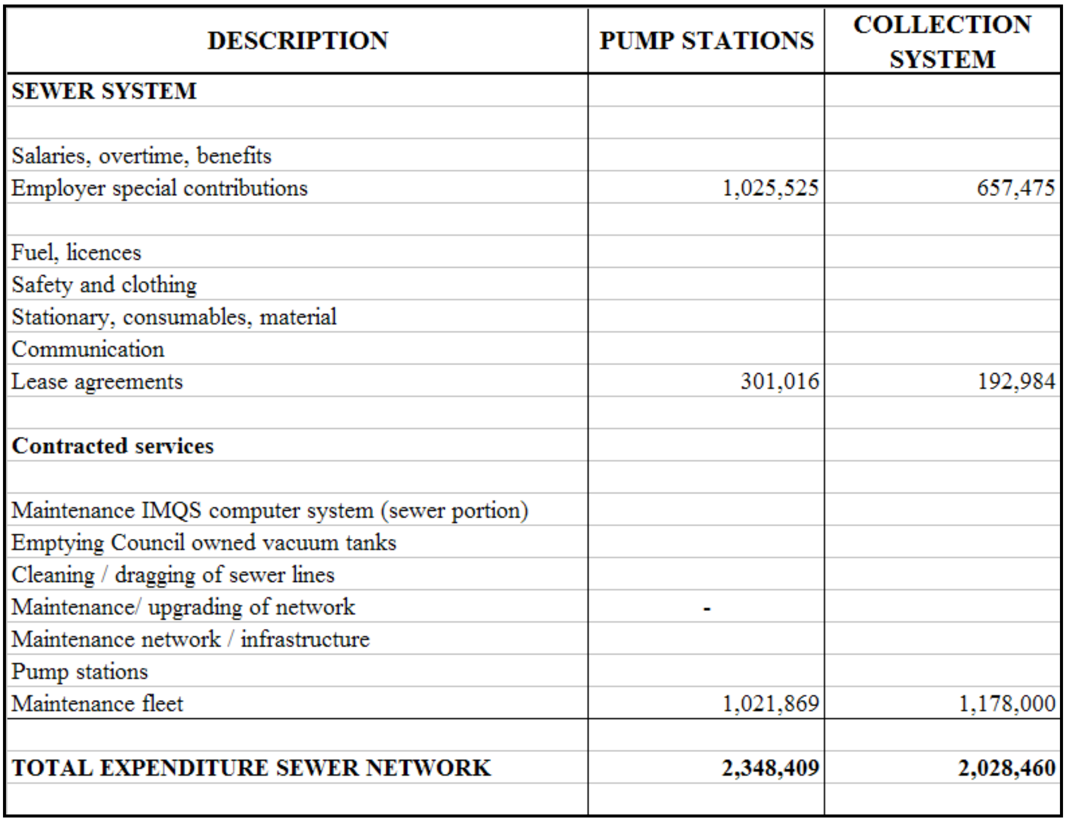
Category	Main criteria	Sub criteria	Ranking	Normalised category weight coefficients (%)	Overall Individual weight coefficients (%)
Social	**Acceptance**				
	Awareness				
	Job creation				
	Institutional requirements	Regulatory Skills requirements Managerial Complexity			
	Sludge Production				
	Ease of O&M				
	Column sum				

Table C9.3 Environmental category

Category	Main criteria	Sub criteria	Ranking	Normalised category weight coefficients (%)	Overall Individual weight coefficients (%)
Environmental	**Resource utilisation**	Power requirements Land footprint Chemical requirements Potential for reuse & reclamation Fresh water conservation			
	Environmental Impact	Groundwater pollution Surface water pollution Air emissions / odour generation			
	Environmental protection	Natural resource enhancement Natural resource reclamation Public health protection			
	Column sum				

APPENDIX C10

MIDVAAL LOCAL MUNICIPALITY SEWER SYSTEM BUDGET 2010/2011 (EXTRACT FOR COLLECTION NETWORK)



DESCRIPTION	PUMP STATIONS	COLLECTION SYSTEM
SEWER SYSTEM		
Salaries, overtime, benefits		
Employer special contributions	1,025,525	657,475
Fuel, licences		
Safety and clothing		
Stationary, consumables, material		
Communication		
Lease agreements	301,016	192,984
Contracted services		
Maintenance IMQS computer system (sewer portion)		
Emptying Council owned vacuum tanks		
Cleaning / dragging of sewer lines		
Maintenance/ upgrading of network	-	
Maintenance network / infrastructure		
Pump stations		
Maintenance fleet	1,021,869	1,178,000
TOTAL EXPENDITURE SEWER NETWORK	**2,348,409**	**2,028,460**