# A Decision Support System for Integrated Semi-Centralised Urban Wastewater Treatment Systems

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# DECLARATION

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# ABSTRACT

The importance of adequate water supply and sanitation infrastructure as cornerstones for the development of civilizations is undeniable. Although a strategy based on centralised infrastructure has proven to be successful in the past, in some circumstances such conventional systems are inappropriate for future needs. A Semi-centralised Urban Wastewater Treatment System (SUWWTS) may be considered a viable sustainable urban water management solution to promote water security. A SUWWTS merges regulations of traditional centralised systems with the concepts of close-loop and resource recovery of decentralised systems. However, research on the design and feasibility of implementing semi-centralised systems is in its infancy.

This Thesis is a first attempt to articulate the complexity, to systematize and to automatize the design of a SUWWTS. Here we show a novel method, referred to as framework, for the development of SUWWTS with allowance for the socio-economic and geographic context of any urban area. To demonstrate the proposed framework a Decision Support System (DSS) was developed; its output is a recommended design comprised of several wastewater treatment plants, their respective technology, and their associated sewerage and reclaimed water distribution networks. The results demonstrate the capabilities and the usefulness of the DSS; it applies the design engineers' subjective preferences, such as regional technological inclinations and implementation strategies.

The results from a feasibility study on the city of Rio de Janeiro validated and demonstrated how the DSS can be used to assist decision-makers. This Thesis discusses the framework, the DSS and the demonstration case. Overall, it will hopefully help both other researchers and practitioners by contributing to the discussion on how to promote urban water security, to decrease urban areas' dependency on ecosystem services whilst delivering better social welfare.

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# WORKING TERMINOLOGY

| | |
|---|---|
| **ArcGIS** | A platform for designing and managing solutions through the application of geographic knowledge developed by the company Esri. |
| **ArcMap** | The map display and editing workhorse for ArcGIS. |
| **Biomass** | Production of new bacteria. |
| **$CO_2e$** | The concentration of $CO_2$ that would cause the same level of radiative forcing as a given type and concentration of greenhouse gas. |
| **Datum** | A frame of reference for measuring locations on the surface of the earth. |
| **Dijkstra's algorithm** | Solution to the single-source shortest path problem in graph theory. |
| **Fitness Function** | Criterion used to estimate how close a candidate is to being a solution. |
| **Geographic Information Systems** | A geographic information system (GIS) integrates hardware, software, and data for capturing, managing, analysing, and displaying all forms of geographically referenced information. GIS allows us to view, understand, question, interpret, and visualize data in many ways that reveal relationships, patterns, and trends in the form of maps, globes, reports, and charts. |
| **Gini Index** | The Gini index measures the extent to which the distribution of income or consumption expenditure among individuals or households within an economy deviates from a perfectly equal distribution. A Gini index of 0 represents perfect equality, while an index of 1.0 implies perfect inequality. |
| **Governance** | The process of decision-making and the process by which decisions are implemented or not implemented. |
| **Graph** | A mathematical structure used to model pairwise relations between objects from a certain collection. |
| **Gravity Sewer** | The principle is that wastewater is conveyed by gravity, although pumping lift stations might be required to reduce pipe's depth. |
| **Headloss** | Pressure drop. |
| **Information Content** | The logarithm of the probability of fulfilling the specified Functional Requirements or goals. |
| **Kjendahl Nitrogen** | Ammonia, organic and reduced nitrogen. |
| **Map projection** | A mathematical transformation of the globe onto some other surface. |
| **Network** | A directed graph. |

| | |
|---|---|
| **Normative theory** | Theory that deals with how decisions should be made, it identifies the logic of decision making. That is, normative preference theories such as expected theory, with which decision behaviour should conform. |
| **Path** | A sequence of vertices of a graph from a destination point to a source. |
| **Prescriptive theory** | Develops and tests methods for aiding people in conforming to desired normative principles. |
| **Pressure Sewer** | Wastewater transmission under pressure by pumps. |
| **Raster** | A spatial data model that defines space as an array of equally sized cells arranged in rows and columns and composed of single or multiple bands. Each cell contains an attribute value and location coordinates. |
| **Route** | A path through a network. |
| **Semi-centralised sanitation and reuse** | Alternative approach that merges concepts from centralised system with the concepts of close-loop and resource recovery of the DESAR principle. |
| **Separate Sewerage system** | Sewerage system (underground pipes) that transmits exclusively municipal (non-industrial) wastewater to treatment or disposal. |
| **Sewerage system** | Arrangement of pipes that convey wastewater to a wastewater treatment plant. |
| **Shapefile** | A vector data storage format for storing the location, shape, and attributes of geographic features. A Shapefile is stored in a set of related files and contains one feature class. A Shapefile stores non topological geometry and attribute information for the spatial features in a data set. The geometry for a feature is stored as a shape comprising a set of vector coordinates. Shapes can be points, lines, or polygons (areas). |
| **Sludge** | Bacterial biomass and settleable solids. |
| **Sustainability** | The process that fosters a dialogue that evaluates current and future lifestyle alternatives collectively defined and informed by regional environmental, social and economic interdependencies. |
| **Universal Transverse Mercator** | A cylindrical projection used in world maps. That is, the globe is encircled by an imaginary cylinder touching at the equator, and the earth is projected onto the cylinder. |
| **Vertex** | Fundamental unit of which graphs are formed. |
| **Wastewater quality** | Composition defined by BOD, COD total, COD soluble, $NH_3$, Kjendahl N, P total, TSS, VSS, pH, T. |

# LIST OF ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| **A2/O** | Wastewater treatment a configuration of an Anaerobic and Anoxic Tank (A2) and Aeration (O) tank |
| **AACE** | American Association of Cost Engineers |
| **ANA** | National Water Agency (*Agência Nacional de Águas*) |
| **BMFT** | German Federal Ministry of Education and Research |
| **bn** | Billion |
| **BNR** | Biological Nutrient Removal |
| **BOD** | Biological Oxygen Demand (biodegradable organic matter) |
| **BRL R$** | Brazilian Real (currency) |
| **CHP** | Combined Heat and Power |
| **$CO_2e$** | Equivalent carbon dioxide |
| **COD** | Chemical Oxygen Demand |
| **DA** | Decision Analysis |
| **DEM** | Digital Elevation Model |
| **DESAR** | Decentralised Sanitation and Reuse |
| **DP** | Dynamic Programming |
| **DSS** | Decision Support System |
| **EMBRAPA** | *Ministério da Agricultura, Pecuária e Abastecimento* (Ministry of Agriculture, Livestock and Supply) |
| **GA** | Genetic Algorithms |
| **GDP** | Gross Domestic Product |
| **GHG** | Green House Gases |
| **GIS** | Geographic Information Systems |
| **GUI** | Graphical User Interface |
| **HCI** | Human-Computer Interaction |
| **HDI** | Human Development Index |
| **HRT** | Hydraulic Retention Time |
| **IBGE** | *Instituto Brasileiro de Geografia e Estatística* (Brazilian Geography and Statistics Institute) |
| **iMBR** | Immerse Membrane Bioreactor |
| **I/O** | Input/Output |

| | |
|---|---|
| **IWRM** | Integrated Water Resources Management |
| **Kjendahl N** | Kjendahl Nitrogen |
| **LCA** | Life-Cycle Assessment |
| **MCDA** | Multi-criteria Decision Analysis |
| **MBR** | Membrane Bioreactor |
| **MLSS** | Mixed Liquor Suspended Solids (biomass concentrations) |
| **M** | Million |
| **MM** | Millions (currency) |
| **MRP** | Metal Reinforced Polyethylene |
| **N** | Nitrogen |
| **$NH_3$** | Ammonia |
| **NIMBY** | Not In My Back Yard |
| **O&M** | Operation and Management |
| **PU** | Perceived Usefulness |
| **PVC** | Polyvinyl Chloride |
| **ROW** | Right-Of-Way |
| **BRL R$** | Brazilian Real (currency) |
| **SAW** | Simple Additive Weighting |
| **SBR** | Sequencing Batch Reactor |
| **SRT** | Solids Retention Time |
| **SRTM** | Shuttle Radar Topographic Mission |
| **SUWWTS** | Semi-centralised Urban Wastewater Treatment System |
| **T** | Temperature |
| **TSS** | Total Suspended Solids |
| **TN** | Total Nitrogen |
| **TP** | Total Phosphorous |
| **UML** | Unified Modelling Language |
| **USD$** | United States Dollar |
| **UTM** | Universal Transverse Mercator |
| **VSS** | Volatile Suspended Solids |
| **WGS** | World Geodetic System |
| **WWTP** | Wastewater Treatment Plant |

# LIST OF NOTATION

| Symbol | Definition | Units |
|---|---|---|
| A | Set of arcs | |
| *a* | Alternative or options. | |
| *a(x)* | Acceptability function or specification which defines the probability that different levels of the performance variable will be acceptable | |
| *C* | Pressure head | m |
| ***C*** | Least-cost cell | |
| $C_{min}$ | Minimum pipeline depth | m |
| $C_{EP}$ | Annual pump energy cost | \$ year$^{-1}$ |
| $C_{PP}$ | Annual pumping pipeline construction cost | \$ year$^{-1}$ |
| $C_{PC}$ | Annual pump construction cost | \$ year$^{-1}$ |
| $C_{PG}$ | Annual gravitational pipeline construction cost | \$ year$^{-1}$ |
| *D* | Pipeline diameter | cm |
| $D_g$ | Pipeline diameter for gravitational pipelines | cm |
| $D_P$ | Pipeline (steel) diameter for pumping line | cm |
| *E* | Annual energy requirement | kWh |
| *EC* | Energy cost | \$ kWh$^{-1}$ |
| $FRC_{PP}$ | Annual pipe cost return coefficient | |
| $FRC_{pu}$ | Annual pump cost return coefficient | |
| $FRC_{pg}$ | Annual pipe cost return coefficient | |
| G | Graph | |
| *g* | Gravity | m s$^{-2}$ |
| *Hl* | Least excavation cost depth | m |
| *HR* | Number of annual pumping operational hours | h year$^{-1}$ |
| *I* | Design information content | |
| *i* | Number of alternative | |
| *int* | Annual interest | % |
| *j* | Number of criteria | |
| *J* | Pipeline slope | m m$^{-1}$ |
| $J_S$ | Soil slope | m m$^{-1}$ |
| *k* | Number of design characteristics/attributes to be evaluated | |
| *L* | Length of pipeline | m or km |

| Symbol | Definition | Units |
|---|---|---|
| $L_W$ | Gravity pipe excavation width | m |
| N | Set of nodes | |
| $n$ | Mannings's headloss coefficient | |
| $n$ | Number of design specifications or criteria | |
| $npp$ | Life span of the pressure pipeline | years |
| $npu$ | Pump life span | years |
| $npg$ | Life span of the gravity pipeline | years |
| $O$ | Annual operating hours | hours |
| $P$ | Wetted perimeter | |
| $P$ | Pump power | W or kW |
| $p_i$ | Probability of accepting a design based upon the ith characteristic | |
| $p(x)$ | Probability density function of unit area which quantifies the design's performance for characteristic x. | |
| $Q$ | Volumetric flow through pipeline | $m^3\ h^{-1}$ |
| $R_h$ | Hydraulic radius | cm |
| $r_{ij}$ | Normalized preferred ratings of the ith alternative with respect to the jth criterion | |
| $S$ | Hydraulic slope | $m\ m^{-1}$ |
| $Vg$ | Velocity of flow | $m\ s^{-1}$ |
| $\mathbb{Z}$ | Non-negative integer | |
| $x$ | Performance variable | |
| $\Delta h$ | Head difference along the line | m |
| $\rho$ | Density, wastewater | $kg\ m^{-3}$ |
| $\varepsilon$ | Pump efficiency | |
| $\lambda$ | Criterion weights | |
| $\Phi$ | Utility or cost of the ith alternative | |
| $\forall$ | For all | |
| $\in$ | Is an element of | |
| {} | Is a set | |
| $\sum$ | Sum | |

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# PART I
# THE CONTEXT

# CHAPTER 1
# DEFINITION OF PROBLEM AND GOAL

This Thesis presents a novel general methodological framework (the sequence of methods) for the development of a Decision Support System (DSS), a computer-based tool, for the design of Semi-centralised Urban Wastewater Treatment Systems (SUWWTS). The methodology is motivated by a belief that a computer-based tool can be a suitable approach to assist urban wastewater managers in their decision-making process. The methodological framework can be applied to any socio-economic and geographic urban area context.

The contributions of this Thesis are: (1) A methodological framework which documents the arrangement of methods from engineering, operations research, and management. (2) An application of the methodological framework in a demonstration case, Rio de Janeiro city of, to analyse SUWWTS for this important city. A SUWWTS is an alternative urban water management option which merges regulations of traditional centralised systems with the concepts of close-loop and resource recovery of the decentralised systems. Given the importance of water security to support social and economic livelihoods and the need to minimise the pressure on vital ecosystems, the feasibility of implementing semi-centralised systems should be assessed. To do so, both the complexity of urban wastewater management and the decision-maker's requirements of semi-centralised systems must be understood.

How does socio-economic and geographical urban context relate to the layout of a SUWWTS? This Thesis first describes the methodological framework which defines the construction guidelines for the development of a DSS for the design of SUWWTS. To validate this methodological framework a DSS was built implementing such guidelines.

Secondly, this Thesis describes the architecture and detailed design of the DSS. The DSS is designed to systematise and structure the decision-making process, thus it integrates different engineering models and computer-based tools that can be used considering the socio-economic and geographic context of any urban area.

Thirdly, the thesis summarizes the process of conducting experiments in the DSS, which includes details of sensitivity and scenario analysis. The demonstration case is the city of Rio de Janeiro. Finally, the thesis suggests several improvements that could be made to the framework and the DSS based on insights gained from the initial experiments conducted.

## 1.1 BACKGROUND

A problem faced in many urban areas is the unsustainable conditions in their resource and service infrastructure. Economic growth and demographic changes influence the rapid urbanisation process, by 2050 two-thirds of the world's population, projected to be 9 billion people, will be living in cities [1]. The rapid urbanisation has significant implications in resource and demand for services infrastructure [2].

The importance of adequate water supply and sanitation infrastructure for the development of civilizations is unquestionable [3]. Sanitation and wastewater management are central to poverty reduction and improved human health.

The prevalence of outdated strategies epitomized by the standard sanitation system of centralised wastewater treatment system and single pass, or end-of-pipe, is embedded in current institutional organisations, socio-economic and legal structures. Although those strategies have proven successful, such conventional systems have been criticised over their ecological, economic performance and resilience [4,5,6,7]. Undeniably current urban conditions have changed from those when the standard sanitation system was introduced nearly 150 years ago [8]. Population growth is putting the conventional systems to its limits to meet *adequate* water supply and sanitation requirements.

For this research the term *adequate water supply* encapsulates three concepts [9]. The quantity of water must be sufficient to meet basic human needs, e.g. for drinking, sanitation, agriculture, and goods production, to name a few. The quality of the water must be safe to human health and varies according to its use, e.g. drinking, industrial and agriculture. The accessibility to water should be physically convenient (water facilities must be within or close to the dwelling, affordable), and universal (for all people, thus it should be accessible to vulnerable and marginalized people).

The provision of *adequate sanitation* is equally important. The means for disposing sewage is crucial to mitigate health risks: to control the carriers of communicable diseases (mosquitoes, flies, mice), and to prevent waterborne disease epidemics.

Thus, accepting the need for a wastewater management paradigm shift [10], the current trend is to incorporate a sustainable urban wastewater management system into the urban planning process. Among the means to achieve this goal is the exploration of alternative technical solutions that need to be designed, analysed, and assessed [11,12] and of long-term strategies, such as urban resource recovery from wastewater treatment, the proper pricing of reclaimed water and improved education.

Many technologies have been developed and there has been on-going work worldwide on refining and integrating them into higher performing, more sustainable wastewater treatment systems. The technological advancement of the XXI century has generated the technology to explore innovative solutions, e.g. decentralisation [13], stormwater harvesting [14] or Sustainable Urban Drainage Systems (SUDS) [15]. Yet the water and sanitation sector is influenced by social context. Thus, there are situations in which the success of water supply and sanitation appears to be mainly a political, institutional, and administrative issue, rather than a technical one [16,17,18,19].

### 1.1.1 Semi-centralised Sanitation & Reuse Concept

In a traditional centralised system, the sewerage system conveys the wastewater to the wastewater treatment plant (WWTP) outside the city (usually long distances). Another long-distance transfer pipeline may have to be provided if *water reclamation* and reuse is also to be introduced. Water reclamation emphasises cleaning contaminated water, thus shifting the concept from waste disposal, or "end-of-pipe", to *resource recovery* [6]. Resource recovery is the selective extraction of energy and materials such as nutrients (nitrogen and phosphorous), water and organic matter, from wastewater, sludge, or sludge ash, for their reuse or recycling [20].

The centralised system can entail high construction and operating costs [21,22]. An alternative to this limitation is Decentralized Sanitation and Reuse, DESAR, a closed-loop sanitation system which stresses onsite wastewater treatment and onsite reuse. Yet, the DESAR concept faces implementation challenges such as the need of available resource recovery technologies, institutional actions (as current ones are designed to manage traditional centralised sewerage systems) and behavioural actions (changes in users, suppliers, and service managers) [23,24].

The approach emphasised in this Thesis is the implementation of the SUWWTS concept which is an alternative that merges regulations of centralised systems with the concepts of close-loop and resource recovery of the DESAR principle [25,26,27,28]. A centralized management approach of the semi-centralised sanitation and reuse system would be necessary for its successful implementation to benefit from economies of scale [29]. Figure 1-1 illustrates a simplified conceptual model of the SUWWTS.

Design regulations are shown as filled circles. The infrastructure interdependency with the energy sector is displayed as purple circles. The meaning of "minimum" in the input arrow in the left of the figure expresses the ideal of the closed loop concept in urban areas: water

extracted from open surfaces or underground sources should be minimal to reduce pressure on ecosystem services.

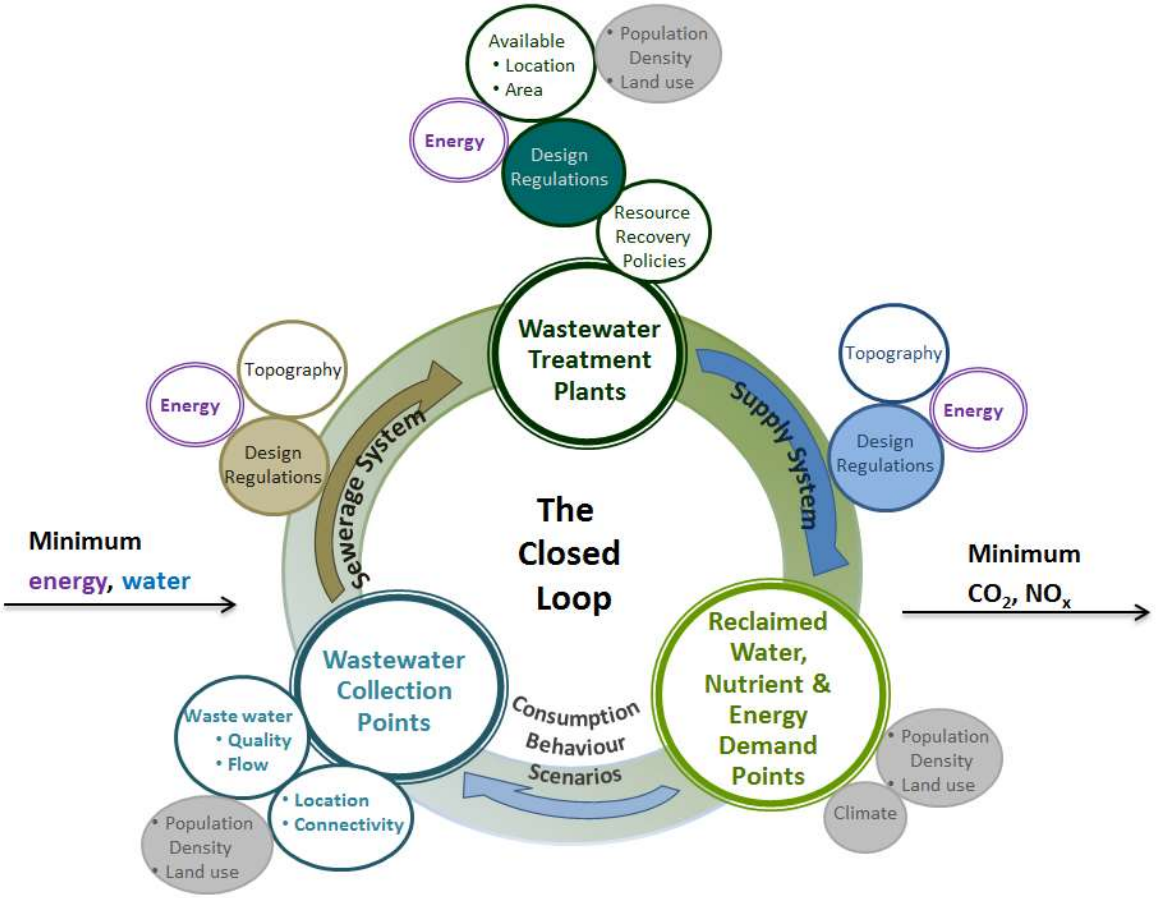



Figure 1-1 SUWWTS conceptual model.

Ideally an integrated semi-centralised water and sanitation service would also include the provision of resource recovery. *Although there is awareness on the need to recover resources from wastewater, the scope of this Thesis is limited to water and energy recovery.* This is because nutrient recovery technologies are less developed, especially phosphorous recovery processes [30,31,32], thus it was not possible to find reliable cost and design equations.

This closed-loop approach of managing resources efficiently can potentially maximise their value and minimise environmental impact for future generations. In this research project the receiving body explores the circularity or recycling of the water resource flow in contrast to the once through concept. There is an explicit advocacy of the closed loop ecological sanitation viewpoint.

The model's factors are socioeconomic change, e.g. population density, average annual population growth, average water consumption, land-use; available wastewater treatment technologies, the water-energy nexus and financial concerns. The driving forces are population growth and greenhouse gas emissions.

The proposed model incorporates a multi-sectorial approach, which is essential to generate feedback loops to enhance the decision quality. The key policy targets to be analysed are reclaimed resources from wastewater treatment, energy mix, electricity tariff (average), water demand management, and social factors (monthly income, socio-spatial planning).

### 1.1.2 Component Parts of a SUWWTS

A SUWWTS can be described as an urban region that contains several sewage collection points with a given wastewater composition. That is, carbon load (BOD), nutrients and flow based on the municipal (non-industrial) wastewater produced as a function of household income and population density. Figure 1-2 illustrates the major component parts of such a wastewater collection and treatment network. These are: the WWTPs, the pipe network (sewerage systems and reclaimed water supply pipes) and the reclaimed water tanks.

The collection points are connected by creating a network of sewer pipes, or sewerage system, illustrated as blue lines in Figure 1-2. Each pipe is characterised by (1) the path from a collection point to another and (2) a capacity that bounds the maximum flow over the pipe. The path is determined by the topography and soil of the urban region, and the capacity is determined by the maximum available commercial diameter for a particular pipe material recommended by construction codes. Ultimately the sewer network connects to a WWTP.

Each wastewater treatment plant is characterised by its technology, footprint, location, and operation requirements. These parameters are determined by the total flow of wastewater to be treated at the site and the plant technology selected according to the required reclaimed water quality. Each wastewater treatment plant is connected to the reclaimed water tank by a pipe.

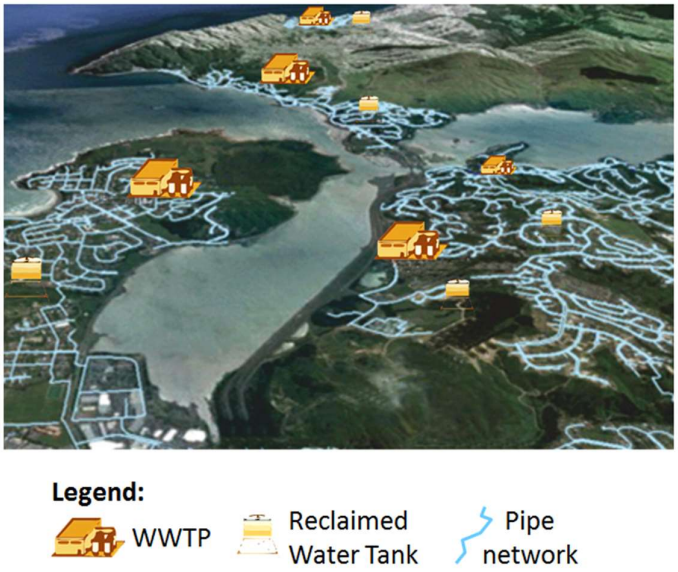



Figure 1-2 Illustration showing the component parts of the SUWWTS.

### 1.1.3 Discussion on the Implementation of SUWWTS

Although the SUWWTS might be a promising wastewater management alternative, its implementation must consider at least the following issues:

- Pre-existing contractual or infrastructure conditions. It must be assessed the feasibility of interconnections with current infrastructure since there could be geographic or political constraints (e.g. regions might have different regulations).
- Local factors that override network level decisions. There could be communities that may purposely choose another solution [33].

Given the difficulty to access data, interconnections with current infrastructure are not part of the scope of this research work. Thus, the identified niche of this research project is for:

- Urban or peri-urban areas that lack any wastewater management at all, or
- New planned cities built from scratch, e.g. Putrajaya, King Abdullah Economic City, Gujarat International Finance Tec-City [34].

## 1.2 RESEARCH MOTIVATION

It is the goal of this research to develop a general methodological framework for the development of a DSS, to aid in the decision-making process for the design of SUWWTS. The problem of decision-makers in urban wastewater management is to choose a SUWWTS that provides wastewater management services that are sustainable and robust to future uncertainty. Decision-makers are therefore faced with a difficult decision of choosing a layout design that, at least from a historical infrastructure decision's perspective, minimizes investment, but also has acceptable environmental, social, and economic benefits. Ultimately these decisions must balance goals and conflicting priorities of the different stakeholders involved.

Decision-makers need to make informed decisions, however an appropriate design aid such as a DSS does not exist at present. One of the reasons for this absence is the complexity of the wastewater management situation, as shown in Table 1-1.

Additionally, research in SUWWTS is in its infancy, as such, there are very few practical applications. This is particularly problematic given the risk-averse mentality prevalent among current decision-makers faced with the task of designing such systems. Further, assuming the existence of practical applications, the optimal design of a SUWWTS is extremely contextual because there are multiple performance criteria (definitions of the desired payoffs) and there is a great deal of uncertainty about the future conditions in which such a system must operate.

One approach to this dilemma is to apply a general methodological framework for the development of a DSS for the design of SUWWTS. However, such methodological framework is also lacking. As only 40% of the expected urban areas by 2030 are built [35], there is also substantial room for innovation in the design of cities of the future. Effective, innovative re-engineering strategies could enable cities to be considered more sustainable [36,37].

Table 1-1 Urban wastewater management state of affairs.

| Management challenges | Recommendations [38] |
|---|---|
| • Uncertainty in future conditions, e.g. population growth, water demand<br>• Complex engineering problem<br>• High number of stakeholders: decision-makers preferences<br>• Regional socio-economic context<br>• Regional technological preferences<br>• Impact of the wastewater treatment infrastructure and technologies that do not exist yet<br>• Feasibility of interconnections with current infrastructure<br>• Existing technologies are not good enough | • Communities should plan wastewater management against future scenarios, not current situations<br>• Solutions for wastewater management must be socially, culturally, economically, and environmentally appropriate<br>• Addressing sustainability necessitates assessing the economic, environmental, and social implications<br>• The successful and sustained management of wastewater will need an entirely new dimension of investment as soon as possible |

## 1.3 RESEARCH OBJECTIVES

In agreement with Robinson [39] it is accepted that

*"…the way forward involves the development of new forms of partnership, and new tools for creating political dialogue, that frame the problems as questions of political choice, given uncertainty and constraints; that renounce the goal of precise and unambiguous definition and knowledge; and that involve many more people in the conversation."*

It follows that a computer-based tool aspiring to such requirements can aid the decision-making process and higher-level design of SUWWTS. To accomplish the research goal, the objectives are:

- To create a framework to provide information to decision-makers in a useful way to stimulate work towards improving wastewater management proposals. To successfully develop the methodological framework, the management challenges in Table 1-1 must be overcome.
- To ensure that the methodological framework can be applied to any socio-economic and geographic urban area context. The methodological framework proposes construction guidelines of a DSS for SUWWTS.
- To implement the methodological framework and demonstrate the validity of the method in assisting decision-makers.

## 1.4 RESEARCH APPROACH

The following points outline the research approach to accomplish the research objectives.

1. **Define the objectives**. The objectives, stated in Section 1.3, are based on the premise that better decisions are the ones that incorporate the most relevant information available.
2. **Develop a methodological framework**. To assist decision-makers different methods are used to perform specific functions at different stages in the decision-making process (see Section 2.1). To perform those functions in an optimal way, methods must be combined in a specific arrangement. In this research this overall arrangement of methods is referred to as "methodological framework". The methods integrated are from engineering (e.g. probabilistic specification-based design model, sensitivity analysis), operations research (e.g. branch and bound) and management (e.g. scenario analysis).
3. **Construct a Decision Support System (DSS).** Figure 1-3 illustrates a simplified conceptual architecture of the DSS that is developed using the methodological framework's guidelines. Thus, at present the DSS is meant to be a design guide that will evolve over time. Figure 1-4 illustrates the inputs and outputs (I/O) of the DSS. The inputs are decision-makers' preferences, regional technological preferences, and socio-economic and geographic factors. The output is a SUWWTS layout, which consists of the number, location, type of technology and basic sizing of the wastewater treatment plants, and main sewer and reclaimed water supply networks.

   A couple of important elements that need to be considered in the development and use of the DSS are the impacts of political and existing infrastructure, yet at present these are not explicitly included in the DSS. It is acknowledged that sometimes single factors that are not related to optimisation and operation considerations often define decisions [40,41]. Additionally, the development of the DSS was subject to limited wastewater treatment plant design and cost equations availability.

4. **Apply the methodological framework in a demonstration case.** A series of experiments were performed to test the workings of the DSS in the city of Rio de Janeiro as an exercise to describe how to apply the framework's concept from the general goal to a specific case.

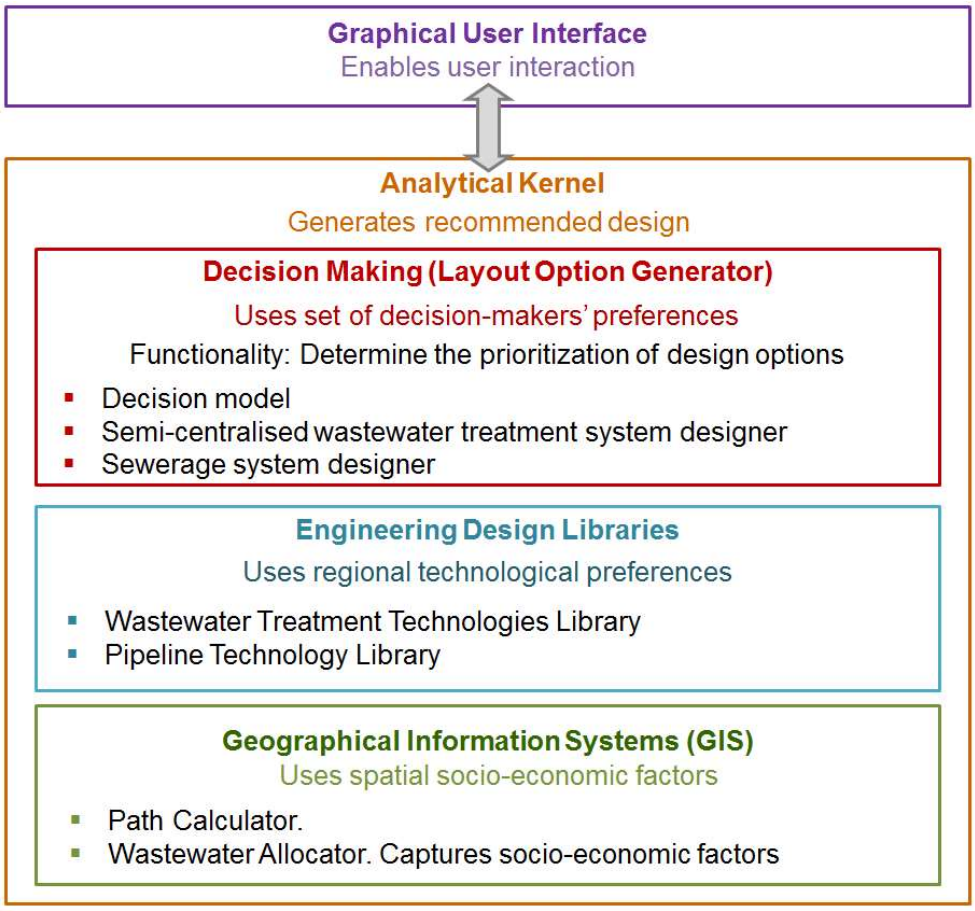



Figure 1-3 Simplified conceptual architecture of the prototype SUWWTS.

## < Inputs >

- ✓ General urban area characteristics' shapefiles:
  - Political divisions
  - Wastewater collection points location (text file can also be provided)
  - Exclusions zones
  - Wastewater treatment plants potential sites
  - Reclaimed water supply points
  - Environment (e.g. soil type, surface water)
  - Land use (e.g. infrastructure, future use)
- ✓ Raster:
  - Elevation
- ✓ Spatial data: projection and datum
- ✓ Socio-economic characteristics:
  - Household income per political division
  - Average household size
  - Population per political division
  - Residence types according to average monthly average income
  - Per capita water demand rate per average household income
  - Behavioural and social acceptance to reclaimed water use
- ✓ Wastewater quality
- ✓ Electricity supply mix
- ✓ Text file: Network, that is, feasible connectivity among wastewater collection points and WWTPs
- ✓ Desired set of WWTP technologies:
  - Cost equations (capital, operation, and management)
  - Land equations
  - Design equations
- ✓ Pipe technologies
  - Cost equations (capital, operation, and management)
  - Design equations
  - Regulations (e.g. recommended materials)
- ✓ Sustainability goals:
  - Reclaimed water use
  - Sustainability aspirations and their ideal values

## < Output: Recommended SUWWTS >

- ✓ Number of WWTPs
- ✓ Sewerage system: connectivity among wastewater collection points and WWTPs
- ✓ Optimal pipe path from WWTP to reclaimed water supply point
- ✓ Cost (capital and O&M)
- ✓ Ghg generation
- ✓ Land use
- ✓ Energy requirements

Figure 1-4 DSS' I/O diagram.

## 1.5 CONTRIBUTIONS

The original contributions of the research project are:

1. A methodological framework. The methodological framework defines the series of research steps to be carried out, and documents the arrangement of methods from engineering, operations research, and management. The methodological framework is discussed in Part III. The benefits of the methodological framework are:
    1.1 The means to evaluate SUWWTS as an urban water management alternative.
    1.2 Arguably it could help steer technological change by assisting technological research strategy evaluation. It is a platform to analyse new technologies vs strategies at a system scale, thus it is possible to identify where the biggest needs for technical innovation are or where the technological improvements would give the best benefits.
    1.3 The SUWWTS design automation steps, which saves time in an otherwise very time-consuming process.
2. An application of the methodological framework in a demonstration case.
    2.1 A Decision Support System (DSS) was constructed following the guidelines defined by the methodological framework. The DSS collates relevant contextual information (e.g. population density, topography) and allows decision-makers to provide the contextual requirements of their problem (e.g. their wastewater treatment technological preferences). The DSS is described in detail in Part IV.
    2.2 A demonstration case based on the city of Rio de Janeiro. The empirical data generated by the DSS is used to drive the evaluation process of regional infrastructure management strategy for this important city. The decisions supported by the DSS would compare the key performance sustainability indicators of interest of each strategy for each scenario. The demonstration case is described in detail in Part V.

Overall, it is demonstrated that one can overcome the challenges related to the complex nature of the problem. It helps improve quality of information by (a) dealing with the engineering complexity, (b) proposing an approach to account for the high number of stakeholders, (c) incorporating regional socio political and technological preferences and (d) dealing with uncertainty in future social conditions.

## 1.6 STRUCTURE OF THE THESIS

The subsequent chapters of this Thesis are organized as follows:

Part I The Context. It has two chapters. In Chapter 1 the Definition of the Problem and Goal is presented, the objectives and the motivation of this research. Chapter 2 is a literature survey that links this Thesis to previous research. Its purpose is to place this research in the context of the decision-making process. Also, it provides the rationale that underpins the claims that this Thesis provides an original state-of-the-art contribution to assist urban wastewater management.

Part II Methodological Framework. It has one chapter that describes the first contribution of this research project: the methodological framework, which describes the proposed arrangement of methods. It provides the guidelines for the development of a DSS to aid in the decision-making process for the design of SUWWTS.

Part III Analysis Stage. This Part has two chapters and covers the results of the first development stage. The deliverables of this stage are: the definition of Sustainability and SUWWTS Model, the identification of Sustainability Indicators and the DSS architecture.

Part IV Decision Support System Building. This Part has six chapters and covers the results of the design and development of the DSS. It describes in detail the development, functionality, and application of the framework's guidelines into the DSS. It takes a close look at its architecture, its design, and explains in detail the functionality of each module. That is, the configurable attributes, the mathematical concepts to represent relations, the algorithms used, and the flow of information.

Part V Demonstration Case. This Part has three chapters and covers the results of the third development stage and the second contribution of this research project: experimentation. It describes how to extend the framework's concept from the general goal to a specific case and its functionality. The computer-based tool provides an environment to conduct experiments for sensitivity and scenario analysis. The context is the city of Rio de Janeiro in 2030.

Part VI Summary, Conclusions and Future Work. Consists of a chapter which is a summary of the research conducted: designing a framework and the building and implementation of the DSS. It also provides the concluding remarks of this research examining limitations and capabilities of the methodological framework and DSS. Finally, based on insights gained from the initial experiments conducted, future work is proposed for improving the framework and the DSS.

# CHAPTER 2
# LITERATURE SURVEY

## 2.1 IDENTIFICATION OF THE FOCUS OF THE THESIS IN THE DECISION-MAKING PROCESS

The decision-making process, according to the rational sequential model of decision making, is comprised of the following logical general steps [42]:

1. Identifying the problem. A problem is the visible effect of a cause that resides somewhere in the past. A technique for Problem Analysis is: (a) State the problem, (b) Specify the problem, (c) Develop possible causes from knowledge and experience or distinctions and changes, (d) Test possible causes against the specification, (e) Determine the most probable cause and (f) Verify assumptions, observe, experiment, or try a fix and monitor [43].
2. Generating alternative solutions. In developing alternatives, decision makers must specify the goals that they want to achieve through their decision and determine the criteria that will be used to evaluate the alternatives. Obtaining the necessary information is essential [44].
3. Evaluating alternatives. This step may take two approaches: qualitative or quantitative.
4. Choosing an alternative. The act of making a decision.
5. Implementing the decision. A decision, however sound, can still fail if it is poorly implemented.
6. Evaluating decision effectiveness.

Recycling between steps 6 and 1 may be necessary.

These general sequential steps have been further categorised [45]: (a) by combining the first two steps as “Structuring the Problem” and steps three and four as “Analysing the Problem”, and (b) by referring the six steps as “*Problem solving*”, whereas Decision Making only

encompasses the first four. Problem solving can be defined as the process of identifying a difference between the actual and the desired state of affairs and then taking action to resolve the difference.

Research findings have pointed out a discrepancy between the research focus of decision theory and its practice. Although decision-makers spend more time in intelligence or design activities than in choice activities, the largest part of the literature on decision making has focused on evaluation-choice [42]. In response to such trend this research project focuses on both generating design alternatives and their evaluation. Figure 2-1 illustrates the identification of the focus of this Thesis in the decision-making process outlined in red.

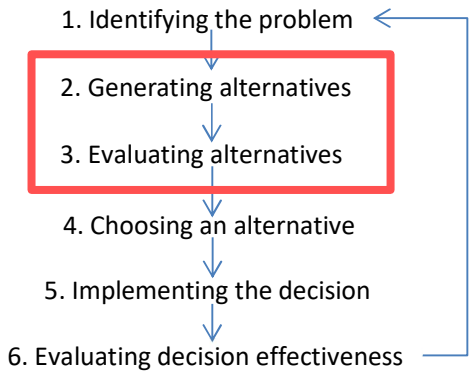



Figure 2-1 Identification of the focus of this Thesis in the decision-making process outlined in red.

## 2.2 Overview of Methods for the Evaluation of Urban Water and Wastewater Treatment Systems

### 2.2.1 Application of Multi-criteria Decision Analysis (MCDA)

*Multi-criteria Decision Analysis* (MCDA) has been used in decision making problems that involve multiple, conflicting criteria and the methods developed have a relatively high level of maturity. MCDA can be defined as ‘‘*an umbrella term to describe a collection of formal approaches which seek to take explicit account of multiple criteria in helping individuals or groups explore decisions that matter*’’ [46].

There are many publications about MCDA methods e.g. [47], from which Mendoza and Martins [48] and Figueira *et al.* [49] are particularly comprehensive. As a result, this subsection will only introduce the method adopted in this research.

Hajkowitz and Collins [50] report a comprehensive review of the application of MCDA in water resource management. Most applications are in water policy, water supply planning and the evaluation of major infrastructure. According to Hajkowicz and Collins the method is a well-suited decision support tool in water management because (1) the problems are multi-objective, (2) the outcomes are often intangible and are measured in a variety of units, (3) it assists with conflict resolution, stakeholder participation and community engagement, and (4) it improves the auditability, transparency, and analytic rigour of water management decisions. Yet, the weaknesses of the MCDA are: (i) that there must be better ways to handle risk and uncertainty, and (ii) the need to structure the MCDA model. That is, selection of criteria and decision options, and to improve decision-maker interaction with the MCDA models. Hajkowicz and Collins suggest the following general classification of MCDA:

1. *Multi-criteria value functions or multi-attribute utility theory* (MAUT).
2. Outranking approaches. Two common approaches are PROMETHEE (Preference Ranking Organization MeTHod for Enrichment Evaluations) and ELECTRE (*Elimination Et Choix Traduisant la Realité* –term in French-).
3. Distance to ideal point methods. A common technique is TOPSIS (Technique for Order-Preference by Similarity to Ideal Solution).
4. Pairwise comparisons. A widely applied technique is AHP (Analytic Hierarchy Process).
5. Fuzzy set analysis.
6. Tailored methods.

The choice of which MCDA method to implement is not as important as training and close collaboration between analysts and decision makers [51].

MAUT needs specified weight and utility or scoring function for each decision criteria. A robust method within MAUT is the Simple Additive Weighting (SAW) which calculates the overall score of an alternative as the weighted sum of the attribute scores. A weakness of the method is that the determination of weighting factors is sometimes difficult. Most MCDA methods study the *deterministic* consequences (trade-offs) of the weights of the criteria with *sensitivity analysis* to reduce the uncertainty in the weight's judgements [52]. An important limitation of the SAW method is that it is assumed constant marginal rate of substitution [53].

This research adopted the SAW method to allow decision-makers to express their preferences on the parameters that will be used to decide where to build a pipe's path. The implementation of the method is described in Part IV.

### 2.2.2 Strategy for Decision Making in the Conceptual Design Phase: Application of Probabilistic Design

Although the conceptual design of a SUWWTS is defined (a network of pipes connecting to several WWTPs) its specific, its details are not. That is, a SUWWTS may be defined by specifying its reclaimed water quality to 99% BOD removal. Such definition might be unambiguous, but is *imprecise*, because there are a large set of wastewater treatment technologies that satisfy such performance characterisation.

Thus, the evaluation and comparison of SUWWTS at the conceptual design stage (the aim of this Thesis) is challenging given that its concept is not a detailed description, but a set of alternatives defined by incomplete specifications. How can it be decided whether it is better to adopt a particular wastewater treatment technology at the general level of conceptual design when specific SUWWTS design details are unknown? Is it possible to reduce the risk of under sizing or oversizing infrastructure which often results from using the traditional deterministic design approach which deals with uncertainties by using safety factors [54]?

The approach adopted in this research was a *probabilistic-specification based* design that models the abstract *multi-attributes* at the preliminary design process [55]. The method

provides designers an intuitive way to define objective functions in multiple-criteria problems to provide a robust design assessment that reduces the risk of oversizing or under sizing.

A probability-based design method has been implemented for the design of wastewater treatment plants [56], so there might be more applications of the method in the water and wastewater sector in the future. The method adopted in this research was developed by Wallace *et al.* (1996) [57]. It uses *specification functions* to translate the designers' subjective probability of finding satisfactory a design's performance. Wallace et al.'s method is described in detail in Section 7.2.1.

### 2.2.3 Stochastic Optimisation Methods

*Stochastic* optimisation is a quite popular approach that has a broad application to problems in statistics, science, engineering, or business, so it plays a significant role in the analysis, design, and operation of modern systems [58]. There are many methods and literature available, thus this section aims to provide a synopsis of the method adopted in this research.

Stochastic optimisation algorithms that *may* find global solutions from among multiple local ones, it can be classified as random search, stochastic approximation, and evolutionary computation algorithms. A special case of the last classification is *Genetic algorithms* (GA), which are quite popular and can be used in general search problems. The algorithm is implemented in this research as a robust search technique in the probabilistic design approach. The algorithm is described in Section 7.2.5.

### 2.2.4 Application of Scenario Thinking and Planning

Scenario Planning is the approach adopted to deal with socio-political and climate future uncertainty. This method has been recently proposed to handle uncertainty about the future in the wastewater sector as an alternative to current design approaches based on forecasts [59,60] and is complementary to analytic methods to aid a robust sustainability science [61,62]. Table 2-1 lists the wastewater management case studies that applied such method.

Table 2-1 Scenario Planning in wastewater management.

| Case study | Scenario technique | Wastewater management | Main contributions | Main limitations |
|---|---|---|---|---|
| Arizona, USA [63] | Three-dimensional matrix (deductive) | • Centralised | • GIS functionality<br>• Identifies possible decentralised wastewater reclamation and sewerage network | Does not explore WWTP technologies |
| Wisconsin, USA [64] | Two-dimensional matrix (deductive) | • Centralised<br>• Decentralised | • Identification of near-term and long-term planning projects | |
| Helsingborg, Sweden [65] | Storylines (deductive) | • Centralised | • Calculates overflow and pollutants released<br>• Models urban sewer network | Does not explore WWTP technologies |
| Lima, Peru [66] | Cross-impact analysis (derived by a software) | • Centralised | • Drinking water and wastewater system in one single model | No GIS functionality |

The method emphasizes future states of the world that represent alternative plausible conditions under different assumptions [67,68] and can be useful in determining the inputs that have the largest effect on the project's value [69,70]. In this Thesis scenario development means the creation of stories, or scenarios, about plausible or likely to be true futures. Scenario analysis is the process of evaluating alternative scenarios [71]. The benefits for taking time in identifying alternative futures are [72]:

1. The decision maker is less likely to be surprised by the future,
2. The decision maker's organization will be better prepared to successfully deal with the future,
3. It encourages decision-makers to think about current assumptions,
4. It allows one to conduct an "if...then" analysis,
5. The decision-makers can plan and act differently now [73],
6. It helps decision-makers to increase their perceived adaptive capabilities when facing turbulent conditions.

It has been proposed that the participatory forms of scenario analysis could be particularly effective in addressing the strategic and normative elements of the sustainability questions by incorporating values and preferences into the scenario analysis process itself [61]. Yet,

scenarios can be used by policy makers as a means of legitimizing rather than informing policy decisions [61].

There is a diversity of methodological approaches to develop scenarios. The selection of a particular method rests on historical and cultural factors. A key aspect is that the method adopted must generate results that decision-makers, who will read the scenarios for a particular use, will consider credible [74] or discomfort them [75].

There are three major types of scenarios: contrasted (possible or plausible futures), trend based (probable futures) and normative (desirable/undesirable futures). Contrasted scenarios can be either *deductive* or *inductive*. The deductive method develops first the framework for comparing the scenarios and then the scenarios. The inductive method develops the other way round. The selected scenario approach in this research is the *matrix approach* of the *deductive* method [76].

Depending on the scenario building tools [77,78], deductive scenarios can be classified as: "*La prospective*" (term in French), *Intuitive logics* and *Future mapping*. The intuitive logics school is the most widely used [79] and is the one adopted in this research. The intuitive logics school develop the initial outline scenarios via brainstorming, future imagining, and scenario matrix to structure stories and generate scenario details [80]. It is very important to clarify that in this method the future is not conditioned by the present.

There are detractors to this method arguing that intuition can lead to misfortune [81] and that intuition is strongly biased against a moment-based view [82]. Others argue that intuition invites further inquiry because plausible imagination provides decision-makers the ability to re-perceive reality, given their mental and social bias, in times of rapid change [83]. Intuition, rather than relying on formal models, is encouraged in courses for managers [84].

Given that a probability is assigned to reflect a person's knowledge about an issue considering any data or other available knowledge [ 85 ] and that there are historical unpredictable events, such as socio-political and climate, the author of this work belongs to the

*futurizing* type of the scenario community. The term accepts limitations to knowing and appreciates and engages intrinsic uncertainty [72]. The author also identifies herself as a *plausibility-centered* planner, for which probability is meaningless in situations when one cannot consider data distributions from the past to be relevant for socio-political and climate uncertain futures [86]. The method is described in further detail in Chapter 13.

### 2.2.5 Application of Decision Support Systems (DSS)

Decision theory is the study of decisions, it focuses on decisions in situations of freedom, with "*goal-directed behaviour in the presence of options*" [87]. It is a research subject characterised by not being unified, having many different research traditions and being interdisciplinary. Researchers in decision theory are from a variety of disciplines, the scope ranges from mathematicians, economists, political scientists, and psychologists to philosophers.

Decision theory is the study of decisions in the face of *uncertainty* [88]. The term uncertainty has different definitions depending on the research area. In this research, uncertainty is defined as "*the incompleteness in knowledge and the inherent variability of the system and its environment*" [89].

From the three theories in decision research, Normative, Descriptive and Prescriptive, this Thesis focuses on the Prescriptive aspects. Prescriptive theory develops and tests methods for aiding people in conforming to desired normative principles (how decisions should be made, the logic of decision making).

A research area with prescriptive benefits, but with linkages to Descriptive and Normative theories, is the development of methods or procedures that aid a decision-maker in structuring a decision problem [90] such as Decision Analysis (DA). "*Decision Analysis will not solve a decision problem, nor is it intended to. Its purpose is to produce insight and promote creativity to help decision makers make better decisions*." [91]. The professional practice of DA is decision engineering because it requires procedures for model building, statistical decision theory and testing principles [92]. Decision Analysis [88]:

- is the formal procedure for the analysis of decision problems in the face of uncertainty,
- puts together knowledge and methods to help make better decisions by replacing confusion with clear insight into a desired course of action,
- has many complementary features with systems engineering (in which key notions are state variables, feedback, stability, and sensitivity analysis).

In alignment with prescriptive theory, there is a need to aid users with tools supporting analytical calculations. A relevant research trend to DA is the development of computer software tools [93]. DSSs are integrative and interactive computer-based tools that support a user or group of users to structure ill-defined problems to achieve higher effectiveness in their decision-making process [94].

A DSS can facilitate the assessment (e.g. sustainability of a strategy), allow the examination and assumptions of the problems' components (quantitative and qualitative data), and enhance communication among stakeholders [95]. DSS can implement a great variety of methods, such as MCDA [96,97]. For instance, users (decision-makers) might reach consensus in a decision when it is built upon a shared vision strategy established with information that is generated and modifiable by the user and displayed by the DSS.

A DSS can be described based on its characteristics [98]:

- It adopts a multiple-pass approach (interactive and recursive).
- It is willing to tackle ill-structured problems. An inability of management to give a fully coherent account of either the problem or the objectives does not impede building a DSS.
- It places a high value on flexibility of system use and adaptability to changing user needs.
- It integrates data sources and models.
- It puts attention to the user interface.

A clear trend in DA is the inclusion of Geographic Information Systems (GIS) in DSS architecture for spatial data manipulation in decision problems that include spatial analysis. GIS capabilities have been used to run scenario analysis for policy making and planning and are well accepted among resource managers who are familiar with map-based reports.

Despite the many DSS developed for water and wastewater management, the success of a DSS to meet the challenge of real-world problems is uncertain [99,100]. Some explanations for the limited practical impact would be:

- These tools oversimplify the problem [101].
- There is a lack of involvement of decision-makers in the process.
- There is a lack of motivation of decision-makers to use the DSS e.g. they could just use the DSS to justify or communicate a choice (such as "policy-based research") [102].
- There could be changes in societal requirements that influence the demand for a DSS e.g. implementation of new policies or unclear expectations from the end-users [103].
- The level of forecast model verification is dependent upon the detail of data available in the given study area [104].
- The quantity and quality of data required are inadequate to put DSS into practice [105].

Given the interest in urban water management practices, an array of DSS have been developed to assist decision-makers in evaluating payoffs. The use a particular method on a DSS depends on the nature of the urban water management problem being solved. The problems can be characterised by their features: temporal or spatial scales, application objectives, the decision-making phase, the number of sustainability objectives, and the number of stakeholders or decision makers involved in the decision-making process.

Tables 2-2 to 2-4 present a comprehensive, yet not exhaustive, list of DSS and approaches in urban water and wastewater treatment systems to illustrate the broad range of applications and to show the relationship among the problem characteristics, the problem definition

strategy/models and the problem-solving methods used. Analysis from these tables indicates that:

- The use of GIS is more important when the spatial temporal scale of the problem addressed increases (e.g. urban area, catchment and strategic), which are sometimes related to an increase in the number of decision makers as well as on the number of objectives.
- It seems there is an increase in the number of objectives when a problem is strategic rather than operational.
- The integration of optimisation tools with simulation models is arguably a standard to solve complex problems. Thus, the combination of these techniques offers a promising approach for use in urban wastewater management.
- The use of MCDM is quite popular in multi objective problems.
- The use of heuristic algorithms (e.g. GA) is linked with the difficulty of mathematical model formulation, but an issue with this approach is the tuning of parameters and the difficulty of benchmarking the results with a mathematical formulation.
- There has not been developed a DSS for SUWWTS.

Thus, the gap that this research is filling is on developing a DSS for SUWWTS. The selection of the preferred models and methods in this Thesis was based on how to deal with the problems being addressed and aware of how such methods have been used.

Table 2-2 Decision Support Systems in Urban Wastewater Management

| Name/ Reference | Objective/ Application | Demonstration case country | Problem definition strategy/model [Problem solving method] | Temporal scale | Decision making project phase | Number of Sustainability objectives | Number of stakeholders/ decision-makers | Compare Technologies | User specify sustainability | Software | Limitations |
|---|---|---|---|---|---|---|---|---|---|---|---|
| EPANET [106,107] | Simulation of hydraulic and water quality behaviour within pressurized pipe networks (arguably the industry's standard) | Any | • Simulation models (hydraulic and water quality)<br>• Optimisation models [Graph theory]<br>• Information systems [GIS] | Operational | N/A | Single | Single | No | No | • C<br>• Java (latest versions)<br>• Public domain | |
| Storm CAD [108] | Design and analysis of storm sewer systems | Any | • Simulation models (hydraulic and hydrology)<br>• Information systems [GIS] | Operational | Design | Single | Single | No | No | • Licensed | |
| WaterCAD [109] | Modelling and management of water distribution | | | | | | | | | | |
| SewerCAD [110] | Design and rehabilitation of sewerage system | | | | | | | | | | |
| AQUASIM [111] | Simulation of wastewater treatment process | Any | • Simulation models [Dynamic modelling] | Operational | Design | Single | Single | No | No | • Licensed | |
| BioWin [112] | | | | | | | | | | • Licensed | |
| EFOR [113] | | | | | | | | | | • Licensed | |
| GPS-X [114] | | | | | | | | | | • Matlab ® simulink™ | |
| SIMBA [115] | | | | | | | | | | • Licensed | |
| STOAT [116] | | | | | | | | | | • Public domain | |
| WEST [117] | | | | | | | | | | • Licensed | |
| UWOT [118,119] | Design and simulation of the urban water cycle by modelling water recycling technologies. | Greece | • Optimisation [Genetic Algorithms] | Strategic | Design | Single & Multiple | Single | Yes | No | • Matlab ® simulink™<br>• Microsoft Excel | |
| [120] | Selection of an appropriate wastewater treatment technology | India | • Multiple criteria decision making [TOPSIS] | Strategic | Feasibility | Multiple | Multiple | Yes | Yes | • No info | Not a DSS |
| [121] | Assessment of hazardous flows in urban water and wastewater systems | Sweden | • Multi-criteria decision making [Multi criteria analysis] | Operational | Feasibility | Multiple | Single | No | Yes | • No info | Not a DSS |

Table 2-3 Decision Support Systems in Urban Wastewater Management (Continuation)

| Name/ Reference | Objective/ Application | Demonstration case country | Problem definition strategy/model [Problem solving method] | Temporal scale | Decision making project phase | Number of Sustainability objectives | Number of stakeholders/ decision-makers | Compare Technologies | User specify sustainability | Software | Limitations |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Watercress [122] | Design and testing of sustainable urban water systems layouts (including water reuse). | Australia | • Statistical method [Forecasting]<br>• Optimisation models [Graph theory]<br>• Simulation models (water quality) | Strategic | Feasibility | Multiple | Single | No | No | • Windows OS<br>• Public domain | |
| IWR-MAIN [123] | Assessing the potential savings of implementing water management practice. | USA | • Statistical method [Forecasting]<br>• Economic models [Cost-benefit analysis] | Strategic | Feasibility | Single | Single | No | Yes | • Licensed | |
| Aquacycle [124,125] | Simulate the daily urban water cycle and investigate the use of stormwater and wastewater | Australia | • Optimisation models (mass balance) | Strategic | Gaming tool | Single | Single | No | No | • Windows OS<br>• Public domain | |
| The Integrated Urban Water Management Tool [126] | Assessment of sustainable water management practices (water reuse) | USA | • Optimisation models (Mass balance)<br>• Statistical method [Forecasting] | Strategic | Gaming tool | Single | Single | No | No | • Visual Basic. NET | |
| Waterware [127] | River basin management information system | Germany, Mexico, Nile river basin, China, Malaysia, Australia, UK | • Information systems [Web-based GIS, real-time data management]<br>• Statistical method [Forecasting]<br>• Simulation models<br>• Optimisation models [Non-linear multi-objective]<br>• Multiple criteria decision making | Operational | N/A | Multiple | Multiple | No | Yes | • Object oriented<br>• Public domain | |
| [128] | Design of regional wastewater pipelines and treatment plant systems | Israel | • Optimisation models [Graph theory, Heuristics search Genetic Algorithm] | Strategic | Feasibility | Single | Single | No | No | • Matlab® GATOOL | Not a DSS |

Table 2-4 Decision Support Systems in Urban Wastewater Management (Continuation)

| Name/ Reference | Objective/ Application | Demonstration case country | Problem definition strategy/model [Problem solving method] | Temporal scale | Decision making project phase | Number of Sustainability objectives | Number of stakeholders/ decision-makers | Compare Technologies | User specify sustainability | Software | Limitations |
|---|---|---|---|---|---|---|---|---|---|---|---|
| WPC-ES [129] | Assess damage or losses caused by municipal water pollution | China | • Information systems [GIS]<br>• Simulation models (water quality)<br>• Economic models [Cost-effective analysis] | Operational | Planning | Multiple | Single | No | No | • Windows OS<br>• Fortran 77<br>• MapBasic<br>• Delphi | |
| [130] | Optimal treatment network of WWTPs and pipes | South Korea | • Economic models [Life cycle assessment and life cycle costing]<br>• Optimisation models [Non-linear programming] (mass balance) | Strategic | Feasibility | Two | Single | No | No | • GAMS | Not a DSS |
| [131] | Selection of wastewater treatment and disposal systems for small communities | Spain | • Information systems [GIS]<br>• Multiple criteria decision making [Rule-based system] | Strategic | Planning | Multiple | Multiple | Yes | Yes | • No info | |
| MULINO [ 132] | Selection of water resource management at the catchment scale | Belgium, Portugal, Romania, UK, Italy | • Information systems [GIS]<br>• Multi-criteria decision making [Multi criteria analysis]<br>• Simulation models [Dynamic modelling] | Strategic | Planning | Multiple | Multiple | Yes | Yes | • Public domain | |
| [133] | Selection of Sustainable Urban Drainage Systems (SUDS) for stormwater runoff management | UK | • Information systems [Web-based GIS]<br>• Multi-criteria decision making [Multi criteria analysis]<br>• Simulation models [Linear additive modelling] | Strategic | Planning | Multiple | Multiple | Yes | Yes | • Public domain | |
| [134] | Evaluation of hybrid water supply systems | Any | • Simulation models (water, contaminant)<br>• Optimisation [Monte Carlo]<br>• Multi-criteria decision making [Multi criteria analysis] | Operational | N/A | Multiple | Single | Yes | Yes | • No info | |
| **This research** | **Design and selection of a SUWWTS** | Brazil | • See Table 2.6 | **Strategic** | **Planning** | **Multiple** | **Single** | **Yes** | **Yes** | • See Table 6.1 | **See Table 14.1** |

## 2.3 INTEGRATED URBAN WASTEWATER MANAGEMENT

The concept of Integrated Water Resources Management (IWRM) was developed to effectively manage water resources. IWRM is defined [135] as:

"*the process of formulating and implementing a shared vision, planning and management strategies for sustainable water resources utilization with due consideration of all spatial and temporal interdependencies among natural processes and water uses"*.

The implementation of IWRM into an urban area is called Integrated Urban Water Management (IUWM). Thus, IUWM integrates the urban water cycle system (water supply, storm water and wastewater) with an organisational framework and the ecosystem [136,137]. According to Georgakakos, [135] some of the challenges of implementing IWRM are a lack of integrative tools to support planning and management decisions, limited participation of stakeholders in decision making process and lack of interdisciplinary training.

## 2.4 BIOLOGICAL WASTEWATER TREATMENT AND ENERGY RECOVERY TECHNOLOGIES

The biological removal of biodegradable organic matter from wastewater is accomplished when bacteria consume it for their processes of respiration and synthesis (production of new bacteria –referred to as biomass-). One of the features of a WWTP is the quantity of removed biodegradable organic matter (BOD), or nutrients (N and P), which serves as an indicator of the efficiency of the wastewater treatment system. Bacterial growth in aerobic conditions is enhanced by providing a suitable environment (for aerobic bioreactors, this involves mixing the wastewater with air). The semisolid material that precipitates is referred to as *sludge*.

The sludge is separated from the liquid portion, or supernatant effluent, through different procedures. This leaves the effluent ready for discharge. The sludge could be treated, reused, or disposed. Options for sludge treatment include stabilisation (aerobic and anaerobic decomposition processes), thickening, watering, drying and incineration [138]. The bacterial decomposition of anaerobic digestion produces bio methane, which can be used to generate

energy by using *Combined Heat and Power* systems (CHP) [139]. Combined heat and power (CHP), also known as cogeneration, is the simultaneous production of electricity and heat from a single energy source (such as natural gas, biomass, biogas, coal, or oil) or from waste heat. CHP is an integrated group of technologies system (rather than a single technology) that increases efficiency of fuel use. Each CHP system must be designed to meet the physical characteristics and operating objectives of the facilities. Some of the available CHP systems are gas-turbine topping cycle, reciprocal engine topping-cycle, combined-cycle, and micro turbine topping-cycle [140].

An issue faced during the development of this research was the lack of publicly available cost and plant design data. The lack of plant design data poses consequences for this research since the plant size is pivotal in assessing the design of a network of WWTP. In order to create a prototype DSS it was necessary to select, in a prudent manner, surrogate values. In view of the data access limitation, this section will only provide a general introduction to and description of a limited selection of wastewater treatment technologies; further details can be obtained in specialised books e.g. [20, 141].

### 2.4.1 Non-Membrane Technologies

These are classified according to where bacteria grow: suspended in water or attached to a surface.

#### *2.4.1.1 Suspended Growth Processes - Activated Sludge*

In suspended growth processes the bacteria population is kept in a liquid suspension. The most common process is activated sludge, which is characterised by raw wastewater flowing into an aeration tank that contains bacteria.

Various modifications of activated sludge treatment are used, the difference being their size, shape and number of aeration tanks. The processes implemented in the DSS are Complete-mix and Sequencing Batch Reactor (SBR).

#### *2.4.1.2 Complete-mix*

Complete-mix reactors are a type of configuration based on the principle that a high food to microorganisms (F/M) ratio favours the predominance of organisms [142]. In a complete-mix process the treatment stage occurs in the reactor, generally square, and the biomass settle in a clarifier/settler, thus it is a technology characterised by requiring large land footprints due to the clarifier. A schematic of a complete-mix process is shown in Figure 2-2. The design parameters and equations [143] used to design the technology in the DSS are shown in Appendix, Section A.I.

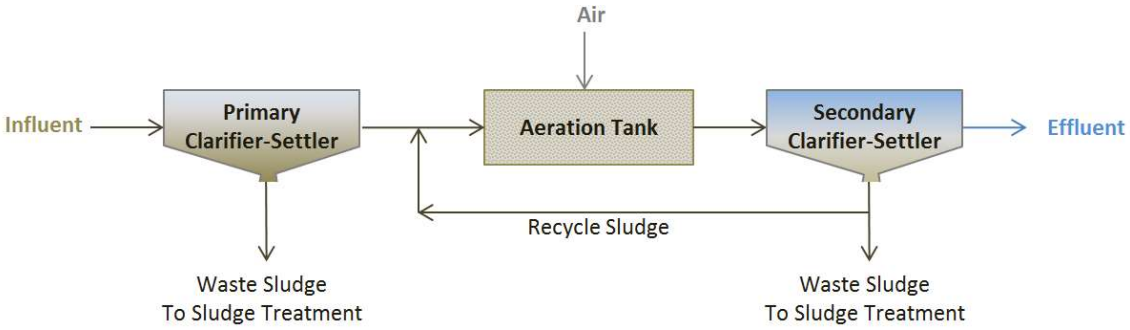



Figure 2-2 Simplified complete-mix activated sludge process diagram.

#### *2.4.1.3 Sequencing Batch Reactor (SBR).*

The SBR process is an intermittent operation system, that is, a fill-and-draw version of the conventional activated sludge. Wastewater is filled into the tank; the metabolic reaction (when the reactor is full it behaves like a conventional activated sludge system) and the biomass settlement takes place in the same reactor at different times. Consequently, it is a process described as a system that operates in "time rather than in space" [144].

The technology is characterised, in comparison with complete mix, by a relatively low land requirement, but with higher level of maintenance requirements (e.g. due to potential plugging of aeration devices). A configuration used in the wastewater sector constitutes two or more SBR tanks used in sequence. An SBR schematic process flow is shown in Figure 2-3. The design parameters and equations [145] used in the DSS are shown in the Appendix, Section A.II.

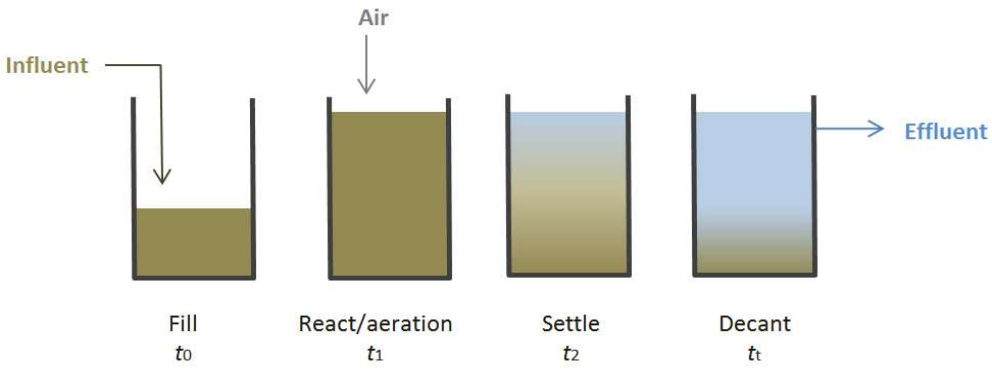



Figure 2-3 Simplified Sequencing Batch Reactor (SBR) process diagram.

#### *2.4.1.4 Lagoons*

Lagoons are a wastewater treatment technology characterised by a large footprint and low O&M costs, particularly if aeration is mainly dependent on wind. In lagoons the removal of biodegradable organic matter is through bacteria and algal activity, as shown in Figure 2-4.

A variation of facultative lagoon is an aerated lagoon, which provides oxygen to the biomass with aerators and achieves complete mixing, hence minimising the anaerobic zone. This is the type of lagoon that the DSS designs. Two key performance parameters for this process are temperature and sunlight intensity; thus, lagoons are better suited for countries with warmer climates.

Facultative lagoons [146] mainly consist of two layers: in the bottom anaerobic bacteria grows, and in the upper layer aerobic bacteria and algae are found. Algae use sunlight and carbon dioxide (produced by bacteria from the lower layer) for photosynthesis, oxygen is produced as a by-product and aerobic bacteria use oxygen to “eat” the waste. The design parameters and equations [147] used are shown in the Appendix, Section A.III.

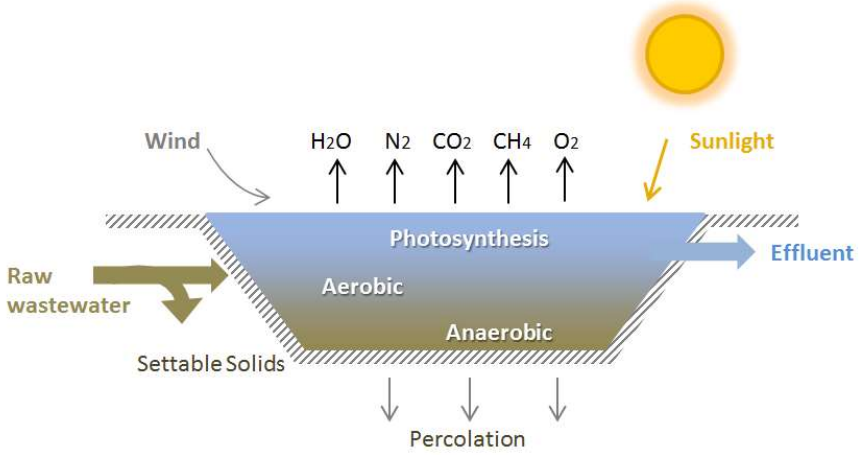



Figure 2-4 Simplified lagoon diagram.

#### *2.4.1.5 Attached Growth Processes – Trickling filter (or biofilter)*

In this type of processes bacteria become attached to a medium's (plastic, wood, or stone) surface and form a biological layer. Trickling filters, or biofilters, are the most used attached growth process. Biofilters, see Figure 2-5, are plug flow reactors, the term 'filter' refers to the basin or tower filled with the support media.

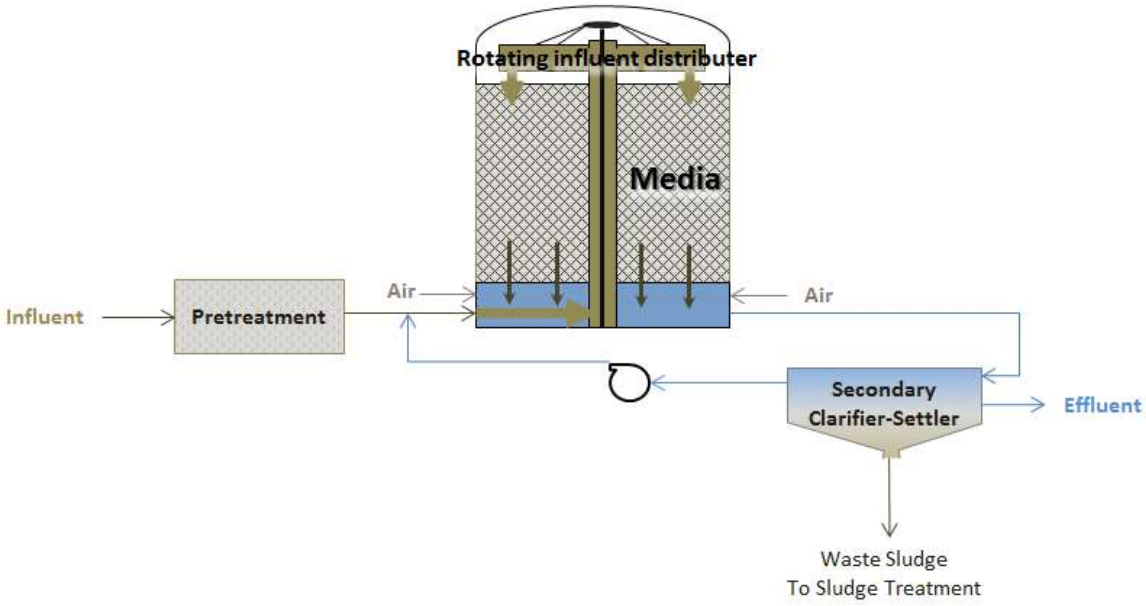



Figure 2-5 Simplified trickling filter, or biofilter, process diagram.

The biological process is the same as in suspended growth systems. Periodically, portions of the film slough off the media, the sloughed material is separated from the liquid in a secondary

clarifier and discharged to sludge processing. Biofilters achieve similar effluent quality as that obtained with activated sludge, but for much less energy. The design parameters and equations [148] are in the Appendix, Section A.IV.

### 2.4.2 Membrane Technologies

A Membrane Bioreactor (MBR) is a wastewater treatment process that uses membranes to separate the treated effluent from the biomass in the reactor. The biological process is the same as in suspended growth systems. Some MBRs types currently used include external membrane systems, immersed membranes, membrane bioreactor with external submerged membranes, and membrane bioreactors with external submerged rotating membranes. The main membrane configurations are multi-tube, hollow fibre, and flat sheet. The MBR designed in the Wastewater Treatment Technologies Library is of the immersed type (iMBR) illustrated in Figure 2-6. MBRs are a very promising technology due to their [141,149]:

- Higher quality effluent. MBRs can operate at higher mixed liquor suspended solids (MLSS) concentrations that increase rates of biological treatment. Moreover, when operating at higher solids retention time (SRT), the growth of targeted microbial communities, such as nitrifying bacteria, is enhanced.

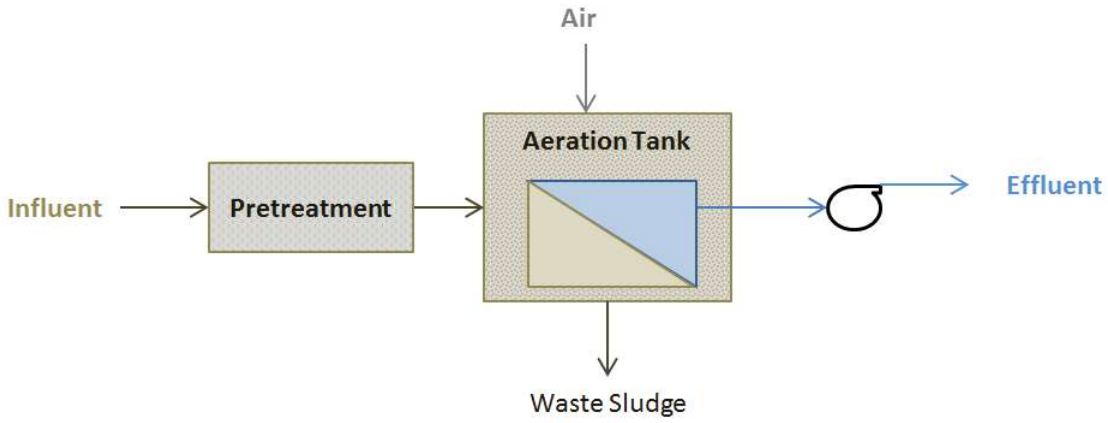



Figure 2-6 Simplified immersed membrane bioreactor (iMBR) process diagram.

- Flexible operating conditions. There are separate controls for solids retention time (SRT) and hydraulic retention time (HRT).
- Smaller footprint. MBR plants have reduced footprints compared to non-membrane activated sludge processes. The reasons are (1) the use of membranes eliminates the need for secondary clarifiers which reduces footprint and construction costs, and (2) MBR systems can operate at higher biomass concentrations (MLSS), that translates to operating at higher SRT, than conventional treatment processes, so smaller process basins are required.
- Lower generation of sludge. This is accomplished when operating at higher SRT.

However, MBRs are an expensive technology in comparison to non-membrane systems, mainly due to high costs associated with operations and management (O&M). It has been reported that between 60 to 80% of the energy consumption by MBR plants is due to aeration for the biological processes and to scouring the membrane filtration system to abate fouling. The higher O&M costs are also due to replacement and maintenance of the membranes, costs of specialized equipment for membrane filtration, and costs for the disposal of the concentrated sludge [141,150].

Typical net flux values for iMBRs in municipal wastewater treatment range between 18-25 LMH (litre $m^{-2}$ $h^{-1}$) [141]. The design parameters and equations [141] used in the DSS are shown in the Appendix, Section A.V.

### 2.4.3 Anaerobic Sludge Digestion: Biogas-to-energy

A method for sludge treatment is Anaerobic Sludge Digestion, a process in which organic matter undergoes bacterial break down into biogas and this is accomplished in the absence of oxygen. Biogas can be used in the generation of renewable energy, so anaerobic digestion can be a net carbon sequestration process [151]. Biogas is comprised mainly of methane (approx

50-75%), carbon dioxide ($CO_2$), hydrogen sulphide, water vapour, nitrogen, siloxanes[a] and particulates. Consequently, biogas must be cleaned before it is used as a fuel in internal combustion engines. Anaerobic Digestion currently treats 66% of the UK's sewage sludge [152].

The anaerobic digestion is a "two-stage" process in which two types of bacteria coexists. The first stage is the one in which acid forming bacteria transforms the organic matter (fats, proteins, and carbohydrates) into organic acids (fatty acids), dropping the pH. Then the methanogen bacteria transform the produced fatty acids (volatile acids) into methane and $CO_2$. The second step is slower that the first one and both steps take place at the same time.

Digester operation depends on maintain a proper environment for methanogens, which are slow growers and very sensitive to changes in: solids loading, pH and temperature [153]. If the digester is over fed, then the system is not in balance: the sludge that has been in the digester for many days might be completing the final step and the new feeding of organics will produce acids, lowering the pH and consequently inhibiting the methane producing reaction. The acceptable pH range for methanogens is between 6.8 and 7.4, being the best value that of 7.0. The two conventional operational temperature levels for anaerobic digesters are determined by the species of methanogens. The methanogens live at temperatures between 35 and 40 °C (mesophilic bacteria) or between 55 to 60 °C (thermophilic bacteria).

The DSS designs a (mesophilic) complete mix reactor, which is illustrated in Figure 2-7. The design parameters and equations used in the DSS are shown in the Appendix, Section A.VI. The biogas heating value is calculated daily. The user has the option to update the value from the commodities value in the stock market at the web.

Finally, although not implemented in this Thesis, it is important to mention that biogas can be burned on-site to generate heat or both heat and electricity in which case it is referred to as

[a] In internal combustion engines, siloxanes are oxidized to silicon dioxide which then forms deposits on moving parts and catalytic oxidation units. Silicon dioxide is insoluble, hard and abrasive; it damages moving parts, including turbine or turbocharger blades, and clogs static filters and catalytic surfaces

a CHP or cogeneration facility. A CHP uses biogas to power a generator to produce electricity (including the emerging technologies of Stirling engines, fuel cells or microturbine technologies [154]). Capturing heat produced in this process provides heat for the anaerobic digesters and the WWTP's buildings.

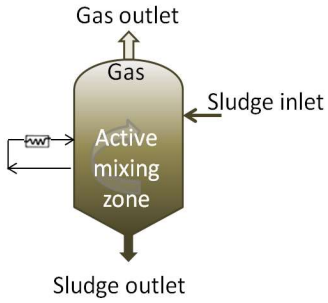



Figure 2-7 Simplified complete mix anaerobic reactor diagram.

### 2.4.4 Nutrient Removal

Biological nutrient removal (BNR) removes total nitrogen (TN) and total phosphorus (TP) from wastewater using microorganisms under different conditions in the treatment process [20]. One technology of P removal is A2/O, which is a configuration including an Anaerobic and Anoxic Tank (A2) and an Aeration (O) tank, as depicted in Figure 2-8. The design parameters and equations [146] used in the DSS are shown in the Appendix, Section A.VII.

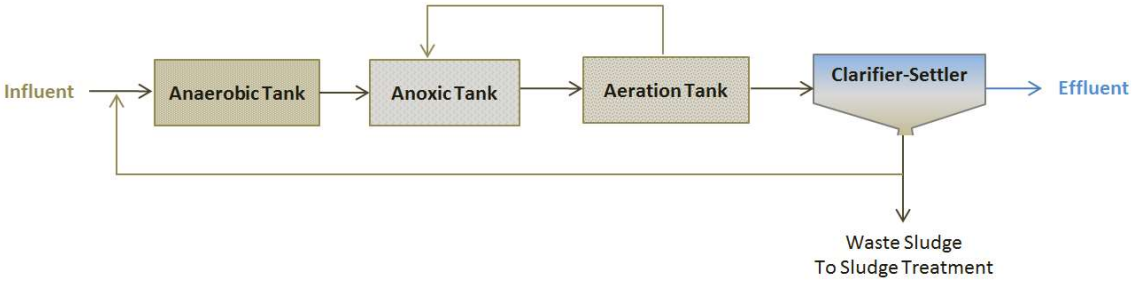



Figure 2-8 Simplified A2/O process diagram.

## 2.5 Criteria for Demonstration Case Selection

The purpose of the demonstration case is to show the implementation of the DSS. Although the application might be specific, it provides an excellent opportunity (1) to provide further insight

about the DSS, (2) to assess the impacts of parameter's values and decision-making implications in SUWWTS design, and (3) to explore the implementation of SUWWTS.

For the demonstration case to provide insights about the DSS it must be representative of a broader set of cases. Table 2-5 shows how the city of Rio de Janeiro met the criteria, which hinges upon issues that experts considered key to have to be representative.

Table 2-5 City of Rio de Janeiro meeting the selection criteria

| Criteria | City of Rio de Janeiro |
|---|---|
| To have sufficient and free information | • The public topographic and socio-economic data available is enough to create a SUWWTS planning stage exercise |
| To have political stability and institutional organisations | • Brazil is a stable democratic country and institutional organisations are set in place |
| To demonstrate the applicability of SSUWTS | • There is an interest in wastewater management. It is a city characterised by generating and implementing tailor-made water and wastewater management solutions<br>• At present current wastewater management solutions are not effective<br>• The city has never been a used in a SSUWTS study |
| To demonstrate the integration of environmental, social and economic benefits in decision making | • Strong water-energy nexus<br>• The city has open-water pollution problems<br>• Uncertainty on the future conditions of the city e.g. impact of climate change in the coastal city and of proposed urban and industrial expansion<br>• Complex urban character |
| To demonstrate usefulness of integrating GIS | • Very interesting topography<br>• Remarkable natural-urban character |
| To transfer lessons to other areas (e.g. build capacity, assess range of impacts, identify attributes) | • Political importance of the city at national and international level<br>• The outcomes will provide information for future management and institution building<br>• Over the next decades the economic importance and population in emerging countries' cities, megacities and in cities of high-income countries will continue to grow, but the pace of urbanisation will be uncertain. The megacity of Rio de Janeiro is a perfect case about the challenges of planning urbanisation or managing a city. Thus, the outcomes of the management approach, applied to such a socio-cultural and geographic complex city, can be particularly relevant and transferable to other cities |

## 2.6 SUMMARY

Table 2-6 is an overview of the approaches adopted in this Thesis.

Table 2-6 Overview of approaches adopted in this Thesis.

| Approach | Reasons for adopting the approach | Advantages | Barriers |
|---|---|---|---|
| Decision Support System (DSS) | • A platform to integrate software tools and methods to translate stakeholder's requirements | • Improve communication and collaboration among decision-makers<br>• Time saving in the decision process<br>• Decision quality can improve<br>• Promote learning among decision-makers<br>• Can enhance understanding of the sector, decision-makers might perceive this useful | • Lack of acceptance from decision-makers to use the DSS, and if they use it they treat it as a "black box"<br>• Failing to meet the challenge of real-world problems<br>• The criteria for judging whether a DSS has been successful or not are often a matter of discussion |
| Geographic Information Systems | • Spatial data manipulation of socio-economic factors | • A means of geographically referencing data to facilitate the generation of information to orient decisions | • Limited analytical problem solving capabilities |
| Probabilistic-based design | • To account for uncertainties in the semi-centralised layout conceptual design stage<br>• To handle incommensurable units<br>• To contextualise the problem: uncertainty is mainly due to randomness of design parameters in the design phase<br>• To provide transparency<br>• To provide flexibility in the framework<br>• A way for account for multidisciplinarity | • Designs can be more robust<br>• Promote learning among decision-makers<br>• Can enhance understanding of the sector, decision-makers might perceive this useful | • Lock-in on traditional design methods in the water industry<br>• Few demonstrations of the benefits of uncertainty-based design in the wastewater sector<br>• Currently this design method is more complex and much more computationally expensive than traditional methods |
| Stochastic optimisation method | • Robust search technique | • Finds a solution | • It is not possible to ensure global optimality |
| Multi-criteria Decision Analysis | • To provide transparency | • Engages decision-makers participation<br>• All decision-makers must explicitly state their preferences | • Determination of weighting factors is sometimes difficult<br>• Better ways to incorporate multiple decision makers<br>• Needs better ways to handle uncertainty |
| Scenario Planning | • To engage socio-economic and climate change uncertainty given:<br>○ Limitations to knowledge,<br>○ Limitations of data quality and quantity,<br>○ Probability is meaningless in situations when one cannot consider data distributions from the past to be relevant for uncertain futures.<br>• To lead better informed decision-making<br>• Provide transparency | • Improve communication and collaboration among decision-makers<br>• Promote learning among decision-makers<br>• Can enhance understanding of the sector, decision-makers might perceive this useful | • Lock-in on traditional design methods in the water industry<br>• Motivation. The audience might dismiss the stories or ignore the exercise |

# PART II
# METHODOLOGICAL FRAMEWORK

# CHAPTER 3
# METHODOLOGICAL FRAMEWORK

## 3.1 DEFINITION

The Oxford Dictionary defines framework as a basic structure underlying a system, concept, or text. Sprague (1980) [95] concludes that a framework is helpful in organising a complex subject by identifying the relationships between the parts and revealing the areas in which further developments will be required. A methodological framework establishes the guidelines on what methods to use and their appropriate sequence implementation. In the context of this research the methodological framework is the basic structure that defines (1) the logic for the development, (2) the selection of different methods used to perform specific functions at different stages in the decision-making process, and (3) the combination of methods in a specific arrangement.

## 3.2 GENERAL APPROACH

Given the limitations of traditional methods identified in the Literature Survey, a concept has been proposed to make decision research useful: *integration*. Integration means linking a qualitative approach (to account for social aspects) with analytical capabilities because such an approach embraces the strengths of each method [48]. Integration offers an option to adequately accommodate the inherent complexity of natural resources management, embracing ecological, biophysical, and social components and capturing the multitude of concerns, issues, and objectives of the decision-makers [48].

The methodological framework addressed the complexity of urban wastewater management challenge by integrating state-of-the-art methods (described in Chapter 2). The development of the method was inspired by works such as the Integrated Methodological Approach (IMA). IMA combines benefit–cost analysis, multi-criteria analysis, and participatory elements based on scientific modelling to support public decisions on complex environmental problems which affect many people, large regions and long periods of time including issues with significant uncertainty [155,156].

Table 3-1 lists the qualitative and quantitative research methods adopted. Doing so incorporates the most relevant information available to enhance the *analytical capacity* [157] of decision-makers. The analytical capacity is defined as the capacity to observe the whole, identify patterns, reflect critically, and understand dynamics and interactions, while remaining open to new ideas and perspectives. Figure 3-1 illustrates the overview of the methodological framework's steps.

Table 3-1 Approach adopted to address the complexity of urban wastewater management challenges.

| Management challenge | Approach |
|---|---|
| Uncertainty in future conditions, e.g. population growth, water demand | ➔ Scenario analysis |
| Complex engineering problem | ➔ SUWWTS Model<br>➔ Sensitivity Analysis<br>➔ Computer-based Tool: Decision Support System (DSS) |
| Decision-makers preferences | ➔ Key Sustainability Management Indicators |
| Regional technological preferences | ➔ Infrastructure Management Strategies |
| Regional socio-economic context | ➔ Geographic Information Systems (GIS) |
| Impact of the wastewater treatment infrastructure and technologies that do not exist yet | ➔ DSS design that allows new technologies to be incorporated in the analysis: Object Oriented Programming (OOP) |
| Feasibility of interconnections of DESAR systems with current infrastructure | ➔ Must be included in the design process without a DSS framework. Thus, outside the scope of this research. |
| Existing technologies are not good enough | ➔ Research strategy evaluation, the use of the DSS potentially could help steer technological change. |

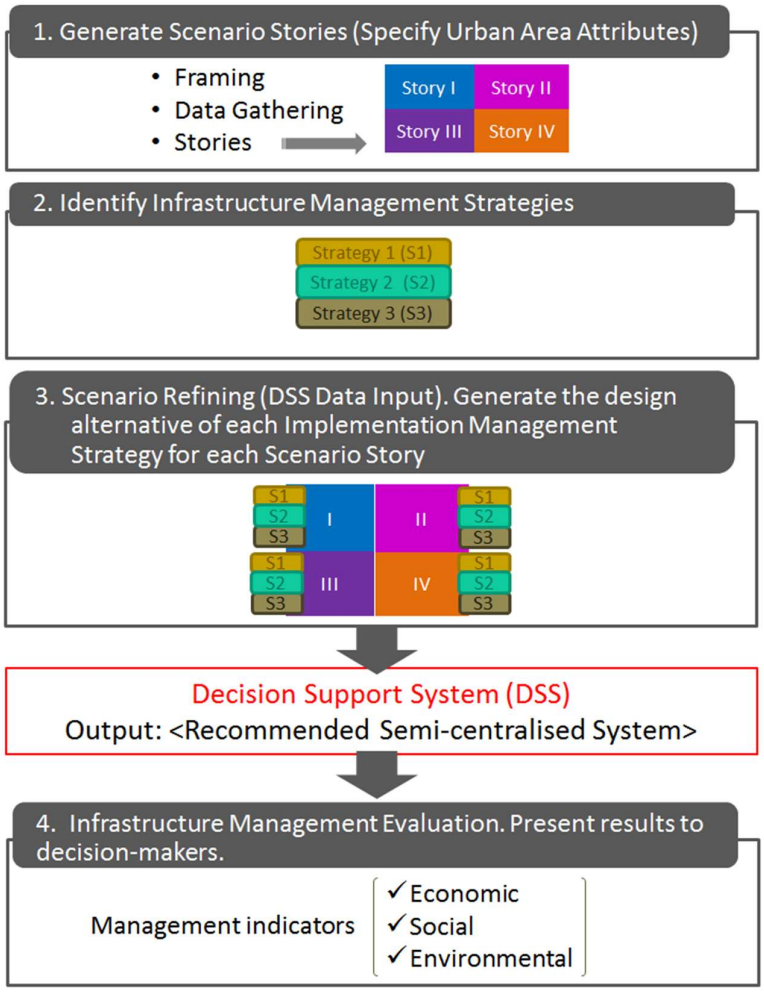



Figure 3-1 Overview of the approach.

The outline of the steps is as follows:

1. **Generate Scenario Stories**. The first step is to develop scenario stories in an urban area with interesting topography, socially complex and from which data is publicly available.

   Three steps are required to generate the stories:

   a. Framing. This first step defines the scope.

   b. Data gathering. Refers to the collection of information of the urban area, its history and context to identify the *driving forces* behind changes.

   c. Creation of plausible futures, or scenario stories.

   Each story specifies the urban area attributes. That is, scenarios are represented as data sets that describe the spatial temporal changes to the key variables of interest and

are used to generate simulation outcomes [71]. The value of the data makes it possible to link with policy-planning implementations e.g. energy mix, electricity tariff (average), water demand management and social factors (monthly income and socio-spatial planning).

2. **Identify Infrastructure Management Strategies**. Contextualised strategies for establishing a SUWWTS for a particular urban area are proposed. Each strategy will explore two organizing principles that decision-makers consider fundamental for assessing potential payoffs. Through this approach it is explicitly accounted subjective value and technological innovation uncertainty [158].

   In this step decision-makers define:

   - The reclaimed resources from wastewater treatment policies that will be explored. In this Thesis it is be an emphasis in water and energy recovery given data availability.
   - The design properties/characteristics/criteria that will be used to determine the acceptability of design alternatives.
   - *The methodological framework arguably can provide technological change recommendations.* It could be possible to identify the technologies that can be included for explicit assessment by asking experts the name of technologies:
     - currently widely used, but subject to improvement
     - technologies not at all or yet used, but that could be adopted within 20-50 years
     - currently used robust technologies

3. **Scenario Refining (DSS Data Input).** Each strategy is analysed against the context of each of the scenarios. The link between infrastructure management strategies and scenario stories increases credibility and acceptance from decision-makers who otherwise would be confused with scenario development [159].

The information retrieved in the previous two steps is inputted to the DSS to obtain the best design of each implementation management strategy for each scenario story. The model-based simulations of scenarios enhance the scenario-planning process by producing quantitative estimates of the effectiveness of various strategies in different scenarios [160].

The scenario construction is accomplished with two research phases: (1) conceptualising the complexity of urban wastewater management and the user requirements, and (2) developing the models, identifying methods and computer-based tools to generate the outcomes deemed important to decision-makers for each scenario.

Conceptual models need to be built to accomplish the first phase, while some issues to be considered for the second phase are whether the DSS is applicable at the resolution, time and spatial scale required by the decision-makers.

It is important to consider the required data is driven by the scenario and the user requirements. Thus, data can be obtained from different sources or derived by models. The data format availability, e.g. resolution, time and spatial scale, should be consistent with the needs. Thus, the following information is required:

a. Sustainability Definition
b. Urban Wastewater System Model Definition
c. Sustainability Management Indicators Identification
d. Computer-based tool (Decision Support System, DSS)

4. **Infrastructure Management Evaluation.** In this step results are presented to decision-makers, trade-offs are identified by examining the implication of each management strategy and a business model is devised.

Sustainability management indicators of each best design are presented to decision-makers. Indicators provide insights of the best design's performance across a wide range

of conditions. The SUWWTS design that performs well in each scenario is deemed to be a robust one.

## 3.3 CONCEPTUAL FRAMEWORK OF THE DSS

As a first step in the development of the methodological framework, its structure was defined as illustrated in Figure 3-2. The blue dotted square encloses the SUWWTS Model. The DSS is the red square, its data input are the black squares, and the green rectangle is its output. The influence of stakeholders is represented with grey dashed arrows. The conceptual framework is illustrated in Figure 3-3.

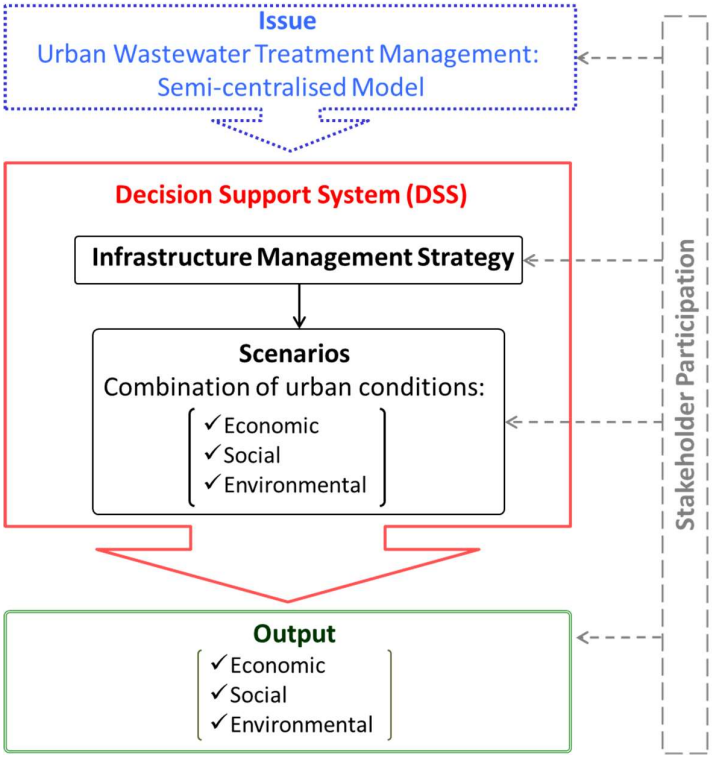



Figure 3-2 Methodological framework structure.

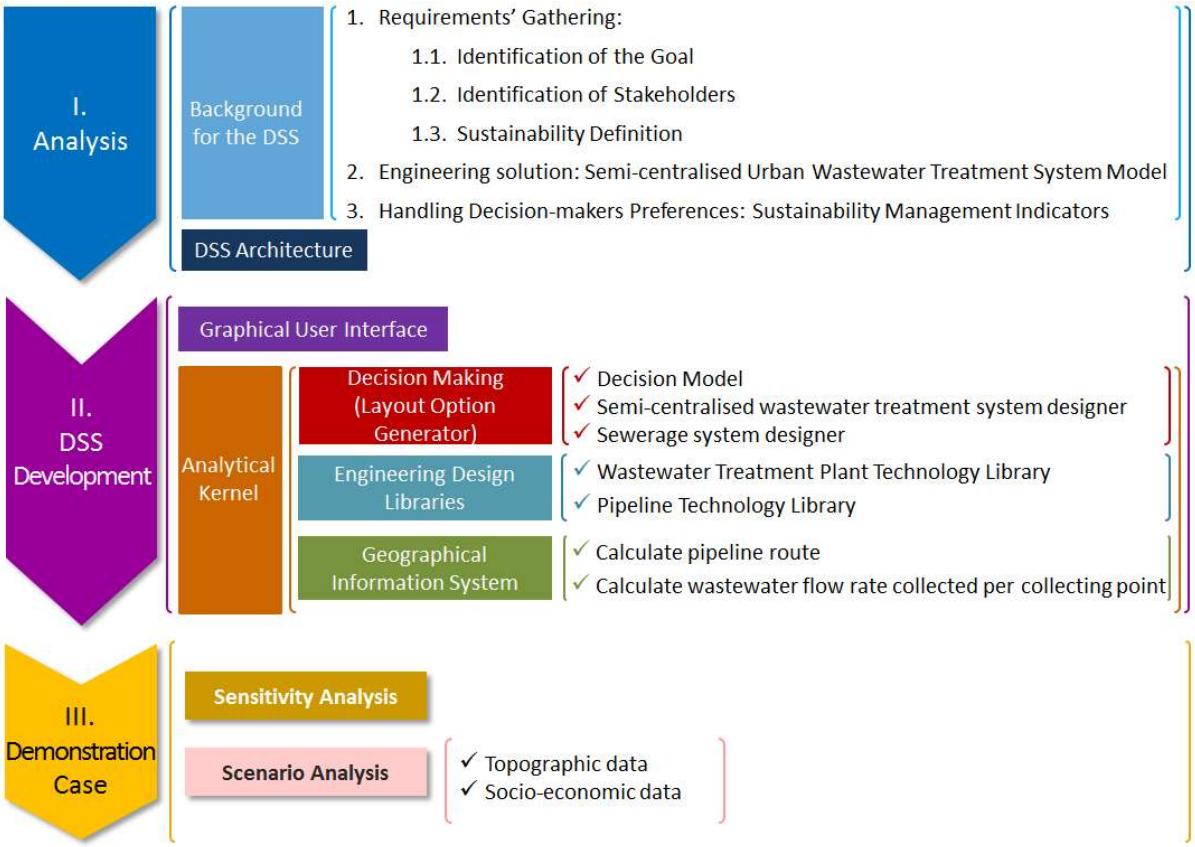



Figure 3-3 A graphical presentation of the conceptual framework of the DSS for the design of SUWWTS.

The conceptual framework of the DSS is comprised of three development stages:

I. **Analysis.** This stage encompasses the following steps:

1. Background for the DSS:

1.1. Requirements Gathering:

- Identification of the Goal. What questions are being answered?
- Identification of Stakeholders involved in the decision
- Sustainability Definition

1.2. Engineering solution: Urban Wastewater System Model Definition. Definition of the system's boundaries (spatial and temporal), data requirements, assumptions, user inputs and outputs.

1.3. Handling Decision-makers' Preferences: Sustainability Management Indicators.

2. DSS architecture. A process which entails the selection of specific computer-based tools and/or methods that will be used to achieve the goals involved with the decision being undertaken. The implementation of a computer-based tool components and/or methods should be verified.

Four key deliverables result from this first stage to be used in the Scenario refining step of Figure 3-1:

2.1 Sustainability Definition. The purpose is to provide alignment of actions with the philosophy.

2.2 Urban Wastewater System Model. The purpose is to identify key socioeconomic and technological interdependencies (either by direct connectivity, policy, procedural or geospatial proximity), key actors and to acquire knowledge of the sector's needs and niches.

2.3 Sustainability Management Indicators. Key sustainability indicators and their importance to assess options.

2.4 DSS architecture. The construction of a DSS entails the selection of specific computer-based tools and/or methods that will be used to achieve the goals involved with the decision being undertaken. The implementation of the DSS components and/or methods was verified.

This stage requires literature review and meetings with experts in the field to gain in-depth understanding.

II. **DSS Development.** The DSS has a modular structure and is comprised of two building blocks:

1. Graphical User Interface (GUI).

2. Analytical Kernel. The functionality of this building block is to design alternatives and their ranking to identify the best SUWWTS candidate design. The module is comprised of three modules:

   2.1 Decision Making (Layout Option Generator).

   2.2 Engineering Design Libraries: Wastewater Treatment Technology and a Pipeline Technology. Both libraries contain a catalogue of well-established technologies.

   2.3 Geographic Information System (GIS). GIS is an instrument that generates information by manipulating spatial data through spatial analysis. GIS allows viewing, understanding, questioning, interpreting, and visualizing data in many ways that reveal relationships, patterns, and trends in the form of maps, globes, reports, and charts. Moreover, GIS provides visualisation of information in a map; a report that includes a spatial dimension which helps the user to comprehend solutions more easily [161].

*Verification* takes place at this stage. Verification is the evaluation that the requirements and design specifications are met.

III. **Demonstration Case**. While conducting this stage it is possible to validate that the DSS meets the needs of the stakeholders. The goals of this stage are: (1) to better understand this novel framework when implemented within a specific environment, (2) to provide insight on the SUWWTS model, and (3) to obtain a deep understanding of the usefulness of the DSS. The framework proposes to develop sensitivity analysis and the scenario analysis in an urban area that is socially complex with interesting topography and for which data is publicly available. The sensitivity analysis is required to differentiate the influence of the factors from systematic error in data from variable outputs from the DSS.

## 3.4 SUMMARY

The methodological framework overview is shown in Table 3-2. Although sustainability problems demand a holistic perspective that unifies across sectors, problems, methods, disciplines, spatial scales, and time [162,163,164], a recurrent theme in studies is the challenge of integration of all these disparate elements [61]. It is precisely meeting the challenge which emphasise the relevance of this Thesis.

Table 3-2 Framework at a glance.

| | |
|---|---|
| **Name** | Framework for the design of Semi-centralised Urban Wastewater Treatment System (SUWWTS) |
| **Description** | A non-standard method to design an integrated SUWWTS with allowance for the socio-economic and geographic context of an urban area. |
| **Audience** | Design engineers |
| **Research Approach** | The Framework implements decision analysis concepts and was developed by having interviews with experts in the field and literature review |
| **Targeted decision-making project phase** | Planning. The useful information is the general knowledge of the system: where the plants will be, the sewerage system and the best option according to criteria |
| **Usefulness** | • Evaluation of SUWWTS strategies to manage urban water<br>• Can help steer technological change.<br>• Analysis of new technologies vs strategies.<br>• Technological research strategy evaluation. The framework could identify where the biggest needs for technical innovation are or where the technological improvements give the best benefits |
| **Approach to deal with social uncertainty** | Integration of scenario analysis and planning strategy initiatives. |
| **Capability** | • Captures the complexity of urban wastewater management and the user requirements<br>• Brings together interdisciplinary knowledge from the regional environmental, social, and economic interdependencies<br>• Integrates different models, methods, and tools to underpin the construction guidelines of a computer-based tool<br>• It enables assessment of semi-centralisation strategies over a range of scenarios |
| **Development stages** | • Model Development<br>• Computer-based Tool Building<br>• Experimentation |
| **Deliverables** | • Sustainability Definition<br>• Semi-centralised Urban Wastewater Treatment Model<br>• Sustainability Indicators Identification<br>• DSS architecture<br>• DSS prototype |

# PART III
# ANALYSIS STAGE

# CHAPTER 4
# BACKGROUND FOR THE DSS

## 4.1 IDENTIFICATION OF THE GOAL

To aid in the design of more integrated wastewater networks across a city as a means of promoting sustainability.

## 4.2 IDENTIFICATION OF STAKEHOLDERS

The importance of identifying the stakeholders involved in the decision is that their needs dictate the way they will assess a SUWWTS. The success of a design of the system is achieved when it meets the stakeholders' expectations such as financial limitations, land availability, energy constraints, or efficiency criteria.

The stakeholders are decision-makers with specialised technical knowledge who are exploring the implementation of a SUWWTS. The involvement of all technically specialised stakeholders is very important because doing so will result in social learning, which is an essential strategy for sustainability: changing values [165]. The targeted decision-making project phase to assist decision-makers is "Planning".

The useful information necessary to reach consensus at this phase is general knowledge of the system. Accordingly, calculations of cost, land use and greenhouse gases generation, are estimates and the detail of the sewerage and wastewater treatment plant unit sizing is that of a bird's eye view.

## 4.3 SUSTAINABILITY DEFINITION

To foster the good management of limited resources and avoid overexploitation, people need to alter their values: to change our lifestyles. Sustainable development is a perspective that stresses long-term compatibility among the economic, environmental, and social dimensions.

The terms *sustainable development* and *sustainability* are used in a wide discourse spectrum, although consensus on their definition has been considerably elusive. The term "development" might imply encouraging economic growth, e.g. institutional incentives on infrastructure policies [166], whereas "sustainability" is a broader concept that encompasses the capacity of humans to live without undesirable consequences, such as social and environmental. In academia, the term sustainability is used in similar contexts as sustainable development [39]. Although there are many definitions of sustainability [167,168,169,170,171], the most quoted definition is the one coined by the Brundtland Report [172],

"*Sustainable development is development that meets the needs of the present without compromising the needs of future generations to meet their own needs*".

- World Commission on Environment and Development (WCED), 1987

The broader, integrative approach of Sustainability has also led to a huge amount of literature. Sustainability aims to reconcile simultaneously the following imperatives encompassed in the triple bottom line concept: Environmental (physical or biological resources); Economic (adequate living standard); and Social (such as the systems of governance that propagate the values that people want to live by) [173].

The term governance describes the process of decision-making and the process by which decisions are implemented or not, and can be applied to corporate organizations, international, national, local governments or to interactions between other sectors of society [ 174 ]. Sustainability also integrates thinking across temporal scales and incorporates spatial analysis. Riley (1992) [169] pointed out that the chosen level of analysis, e.g. production unit or country, has a great influence.

Robinson (2004) [39] stressed that the differences in views about its meaning and value are rooted in the different philosophical and moral conceptions to conceive the relationship between humans and the environment. As such, there is a dilemma of pursuing objective science in a value-loaded and socially charged discourse [175].

## 4.4 SUWWTS MODEL

The goal of creating a model is to identify the key socioeconomic and technological interdependencies of the main components of the urban wastewater system and to refine the spatial and temporal system boundaries seeking advice from experts in the field. The boundaries of the model need to be clearly defined to limit the scope to a manageable one.

### 4.4.1 Conceptual Model

The *conceptual model*, illustrated in Figure 4-1, is a generic and comprehensive approach that integrates the wastewater collection network, treatment plants and treated water receiving body. A conceptual model is a high-level representation of important assumptions, inter-component flows, states, parameters, and uncertainties and it is used as a basis for numerical models [71]. The purpose of the conceptual model is to identify key assumptions, decision factors, the level of model complexity and key variables that represent changes, and to facilitate communication with stakeholders.

The model intends to address long-term planning issues, such as those resulting from potential socio-climatic changes. Hence, an annual time scale was chosen since it matches better the goal of long-term planning decisions. The scope of the SUWWTS is 50 years, or long-term frame [176].

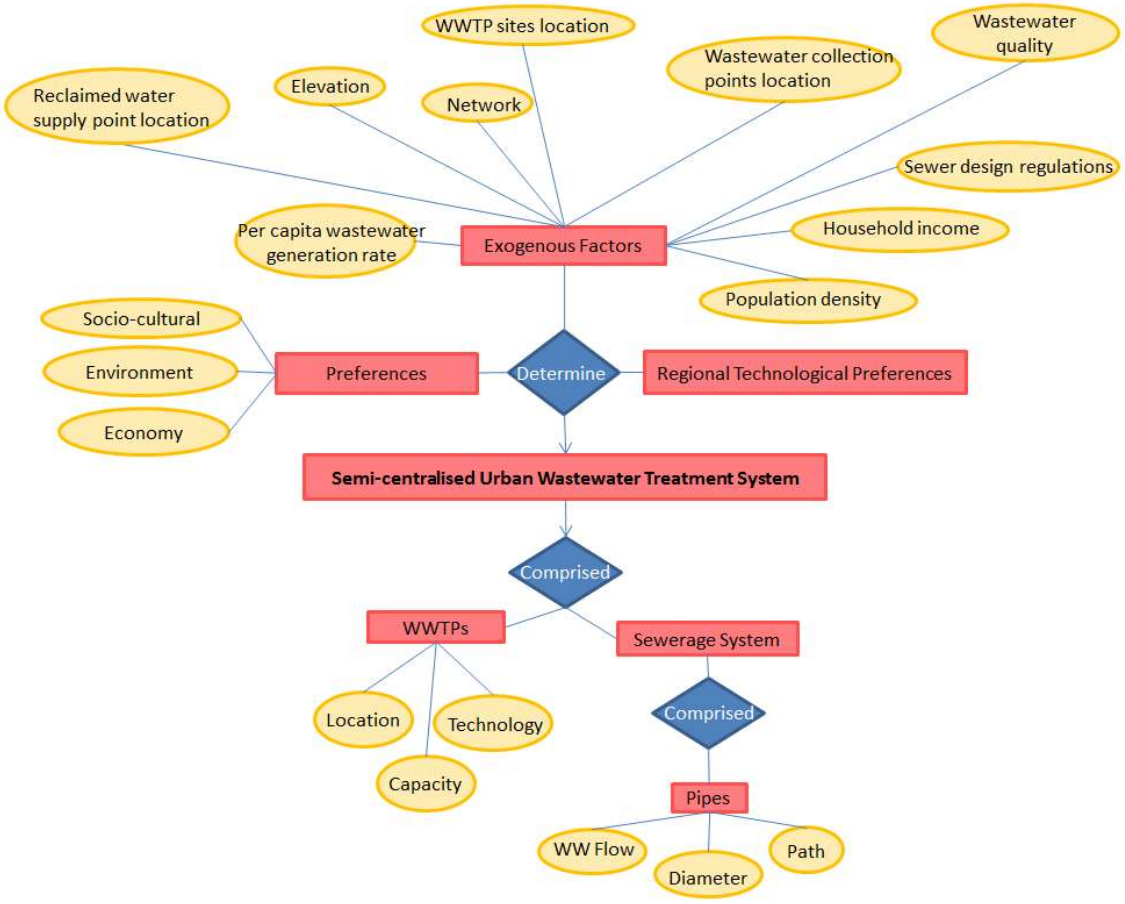



Figure 4-1 Diagram of the SUWWTS conceptual model.

### 4.4.2 Wastewater Network Model

For users that are designing the sewerage system, some of the important spatial inputs are: potential WWTP sites, wastewater collection point sites, reclaimed water demand point sites, and the overall network layout. Network theory is the mathematical means to capture the relations and processes of the components of the SUWWTS Model.

The network model is a flexible way of representing objects and their relationships. The problem consists of a directed graph G, such that $G = (N, A)$, which is a set of nodes, N, connected by a set of feasible directed arcs, A.

A directed graph is determined by the user. By requesting the user to provide it, it is easy to incorporate contextual political motives for connectivity between wastewater collection points. The author of this research acknowledges that the wastewater treatment system will probably

be in a predominantly developed urban area with a prevalent regional political atmosphere. Although from the engineering point of view the optimal WWTP site location and connectivity between points can be calculated, such optimal arrangements may not be politically feasible or desirable.

For example, available WWTP sites might have to be selected from a list of areas classified as "abandoned urban property" or there might be NIMBY movements (Not In My BackYard), which refer to organised opposition to a proposed land use change or infrastructure project.

The set of nodes is divided into two subsets: (a) fixed nodes and (b) potential nodes. The fixed nodes represent wastewater collection or reclaimed water demand points; thus, a fixed node is characterized by either supply of wastewater or demand for reclaimed water. Potential nodes represent available sites in which to build a WWTP. Nodes are characterised by a cost function, a term which is a weighted function of financial, environmental, and social costs determined by the user.

For this research, the term SUWWTS will refer to the solution of connectivity among wastewater collection points, or sewerage system, reclaimed water demand points and wastewater treatment plants. Table 4-1 summarises the terms used in this Thesis.

Table 4-1 Summary of the terms used in the Model

| Term | Definition |
|---|---|
| Graph | A mathematical structure used to model pairwise relations between objects from a certain collection {feasible wastewater treatment plant location, collection points} |
| Network | A directed graph: provided by the user. |
| Node | Fundamental component of graphs formed by potential wastewater treatment plants, wastewater collection points or reclaimed water demand points. A record consisting of one or more fields that are links to other nodes, and a data field |
| Arcs | Representation of the feasible relations and processes between nodes |
| Route | A sequence of vertices of a graph from a destination point to a source, calculated by the Option Generator Module. |
| Path | A sequence of points (x,y,z) from a destination point to a source, calculated by GIS Module. |
| Sewerage system | A connectivity among collection points: a network of sewer pipes. |
| Semi-centralised Urban Wastewater Treatment System | Proposed solution of connectivity among collection points, reclaimed water demand points, and wastewater treatment plants. |

### 4.4.3 Integer-programming Model

The system can be described as an urban region containing several sewage collection points each collection point may be considered as a “wastewater supply point to the SUWWTS”. Each wastewater collection point is characterised by its total composition (carbon loading, nutrients) and flow according to the municipal wastewater produced as a function of household income and population density. The value of wastewater flow collected in each collection point is obtained from the Geographic Information System Module.

Collection points are connected by creating a network of sewer pipes, or sewerage system, illustrated as blue lines in Figure 1-2. Each pipe is characterised by the path from a collection point to another and ultimately to a wastewater treatment plant. The path is obtained from the Geographic Information System Module. Each pipe is characterised by a capacity that bounds the maximum flow over the pipe, which is determined by the maximum available commercial diameter for a particular pipe material recommended by construction codes.

Each potential wastewater treatment plant, orange rectangles in Figure 1-2, is characterised by the upper bound on its corresponding annualised cost. The annualised cost considers investment, operation and management costs. The annualised cost is associated with the plant’s size, location, technology and depends on the land and energy requirements of the plant technology. These parameters are determined by the total flow of wastewater to be treated at the site and the plant technology selected according to the required reclaimed water quality. For example, membrane bioreactors, a technology in which reclaimed water quality is approximately 20% better than that of a lagoon, will have low land and high energy requirements in comparison to a lagoon.

The user specifies the location and use of reclaimed water, shown as yellow tanks in Figure 1-2. For example, reclaimed water could be conveyed to a storage facility due to environmental goals, or to an agriculture or urban water supply point. Each wastewater treatment plant is

connected to the resource recovery point by a pipe. As in the case of the sewers, the pipe is characterised by the path which is obtained from the GIS module.

The problem is to determine the number (the user provides a set of available sites), type of technology and size of the WWTP, the diameter of every pipe, and the path or connectivity between collection points that minimise an objective function e.g. total cost. The identification of the number of semi-centralised wastewater treatment plants can be solved using an integer-programming model: a multi-criteria facility location allocation problem. As such, it is characterised by a set of customers distributed in a geographical area, their demand for services and a set of potential facilities, in which one or more facilities will supply all or a part of the demands, and in which the aim is to minimise costs [177]. The model assumes that decisions are reached between transmission costs and operating costs trade-offs [178].

The basic model formulates the problem as an *uncapacitated* (without restrictions) facility location-allocation for a new urban area. A possible extension is to include capacity limitations, such as available land area to construct a WWTP. The parameters and the decision variables used to formulate the SUWWTS model are shown in Table 4-2:

Table 4-2 Definitions and notation for the SUWWTS model.

| | |
|---|---|
| **Decision Variables** | $y_i$ = whether build a WWTP $i$. Equals 1 if built and 0 not built.<br>$z_{ij}$ = flow from WWTP $i$ to reclaimed water demand point $j$<br>$x_{pi}$ = flow from ww collection point $p$ to WWTP $i$ |
| **Objective Function** | Minimise: fixed costs + variable (transmission and operation) costs from ww collection point to WWTP + variable (transmission and operation) costs from WWTP to reclaimed water demand point |
| **Parameters** | $a_{ij}$ = cost of delivering a unit from WWTP $i$ to reclaimed water demand point $j$<br>$c_{pi}$ = cost of one unit wastewater transmissionfrom the ww collection point to WWTP $i$ plus per-unit operating cost at WWTP $i$<br>$w_i$ = fixed cost of building WWTP $i$<br>$u_i$= capacity of WWTP $i$ (dependent on land availability)<br>$d_j$= demand of reclaimed water $j$ |
| **Sets** | dp = is the set of all reclaimed water demand points $j$<br>cp = is the set of all number of wastewater collection points $p$<br>wwtp = is the set of all number of feasible WWTP sites $i$ |
| **Assumptions** | No economies of scale in neither transmission nor operating costs<br>No capacity constraints in the WWTPs, which are due to land availability |

The facility location allocation model has the following form:

$$Minimise \sum_{i=1}^{wwtp} w_i y_i + \sum_{p=1}^{cp} \sum_{i=1}^{wwtp} c_{pi}\, x_{pi} + \sum_{i=1}^{wwtp} \sum_{j=1}^{dp} a_{ij} z_{ij} \qquad (4\text{-}1)$$

subject to (s.t)

The demand of each reclaimed water demand point must be met from the WWTPs.

$$\sum_{i=1}^{wwtp} z_{ij} = d_j\,, \quad \forall\, j \in \mathbb{Z} \qquad (4\text{-}2)$$

Reclaimed water can only be conveyed from an existing WWTP. When it exists ($y_i$ = 1) the reclaimed water conveyed from WWTP can be no larger than the total reclaimed water demand.

$$\sum_{j=1}^{dp} z_{ij} - y_i \left( \sum_{j=1}^{dp} d_j \right) \leq 0, \quad \forall\, i \in \mathbb{Z} \qquad (4\text{-}3)$$

For future research in which WWTP capacity limits ($u_i y_i$) are included eq. 4-3 will take the form (4-3b)

$$\sum_{j=1}^{dp} z_{ij} - u_i y_i \leq 0, \quad \forall\, i \in \mathbb{Z} \qquad (4\text{-}3b)$$

Flow balance, flow from WWTP to a reclaimed water demand point is equal to the amount of wastewater flowing into the WWTP.

$$\sum_{j=1}^{dp} z_{ij} - \sum_{p=1}^{cp} x_{pi} = 0\ , \forall\, i \in \mathbb{Z} \qquad (4\text{-}4)$$

Wastewater conveyed from collection point $p$ to WWTP $i$ *is* less than the WWTP capacity limits($u_i y_i$).

$$\sum_{p=1}^{cp} x_{pi} \leq u_i y_i\ , \forall\, i \in \mathbb{Z} \qquad (4\text{-}5)$$

Non negativity

$$x_{pi}, z_{ij} \in Z^+ \ \forall\, i,j,p \in \mathbb{Z} \qquad (4\text{-}6)$$

Integrality
(0 = not built, 1 = built)

$$y_i \in \{0,1\}\ \forall\, i, \in \mathbb{Z} \qquad (4\text{-}7)$$

## 4.5 KEY SUSTAINABILITY MANAGEMENT INDICATORS

In the previous sections, the complexity of urban wastewater management and the basic user requirements were covered. Some additional issues arise in practice, such as which are the key

sustainability management indicators? How to evaluate current lifestyle against its desirable future goals and objectives? How to evaluate performance? What criteria to use? How to compare options? How to interpret metrics?

It is especially necessary for detailed engineering analysis to identify suitable methods to assess sustainability [20]. Several ways of measuring sustainability have been developed in which the prevalent idea is the use of *indicators* [179]. Their usefulness is that they can simplify, through quantifying, complex phenomena information so that it can be easily communicated [180]. For example, an indicator might quantify information to explain how a system changes over time.

There is a debate over the use of indicators, at the core of the discussion are three main issues: the decision of using a particular disciplinary approach to generate or identify such indicators, the different views used in defining what are the goals or targets to measure, and how to interpret the indicators [181].

The goal of identifying key sustainability management indicators is to have useful and readily understandable measures of the characteristics of the wastewater treatment system. Sustainability is highly subjective and contextual, that is, what might be considered as sustainable in a given circumstance might not be for another setting simply because the criterion to assess sustainability is developed with the cooperation of key stakeholders in a particular institutional-geographic environment. Hence each urban wastewater treatment system configuration design should be assessed in its specific context.

Although it might be considerably utopian and impractical to identify a universal list of all factors that assess sustainability, it is nevertheless feasible and helpful to have a range of criteria that could be used to assess sustainability. The list of indicators presented on Table 4-3 has been designed as the starting point to assess, from a wider perspective than only a cost-oriented one, the urban wastewater treatment system's adequacy, and to help in making the decision-making process transparent.

Table 4-3 Key Sustainability Management Indicators to be presented to decision-makers.

| Criterion | | Indicator |
|---|---|---|
| Economy | Annual Cost | $ year$^{-1}$ (Capital, Operation and Management) |
| | Recuperated Cost | $ year$^{-1}$ (by resource recovery) |
| Environment (Use of natural resources) | Land Use | m$^2$/person |
| | Energy | kWh year$^{-1}$ person (Operation and Management) |
| Environment (Resources recovered) | Water Recovered | % of reclaimed water |
| | Energy Recovered | % of the consumption of the wastewater treatment system |
| Environment (Discharges) | Greenhouse Gas Generation | ton $CO_2$ eq year$^{-1}$ |
| | Odour | Qualitative |
| | BOD Removal | % |
| Socio-cultural | Ability to Pay | % of average consumption cost with respect to average salary |

## 4.6 SUMMARY

The SUWWTS Conceptual Model is described succinctly in Table 4-4.

Table 4-4 SUWWTS Conceptual Model at a glance.

| | |
|---|---|
| Name | SUWWTS Model. |
| Description | A generic and comprehensive approach that integrates the collection network, treatment plant(s) and receiving body. There is an explicit advocacy of the closed loop ecological sanitation viewpoint and to accounting for the water-energy nexus. |
| Components | • Sewerage system<br>• Wastewater treatment plants<br>• Water supply pipeline network<br>• Reclaimed water and energy demand points |
| Lifetime | 50 years |
| Model driving forces | • Population growth<br>• Greenhouse gas emissions |
| Key model factors | • Socioeconomic change: population density, average annual population growth, average water consumption, land-use<br>• Wastewater treatment technologies<br>• Energy recovery from wastewater treatment technologies |
| Policy targets that could be analysed | • Reclaimed resources from wastewater treatment (water and energy)<br>• Energy mix<br>• Electricity tariff (average)<br>• Water demand management<br>• Social factors (monthly income, socio-spatial planning) |

# CHAPTER 5
# DSS ARCHITECTURE

## 5.1 SOLUTION DOMAIN

A *solution domain* is defined as the abstract environment where the solution is developed [182]. It involves transforming stakeholder requirements into a set of computer-based system's requirements (what the computer-based system must do), creating a computer-based system model that enables the required functionality and defining the architectural design [183]. The computer-based tool has the following requirements (in **orange font**):

- An **interactive system that helps decision-makers** systematise decision making.
- The capability to **integrate expert knowledge.**
- The ability to **support political dialogue** and to **enhance participation.**
- The capacity to **capture the goals of decision-makers/users in a transparent way.**
- The ability to **enable scenario-based analysis.**

and the following functionalities:

- The users will be decision-makers with technical knowledge.
- To enhance the analytical capacity of decision-makers the system will translate the expert knowledge on the urban system components and their interdependencies, knowledge which is held by experts from different technical and scientific areas.
- To systematise and structure on ill-defined problem of an integrated urban wastewater system, geographical dependence and socio-technological factors should be inputs to the underlying model. The reason for this is that an optimal integrated water and sanitation service provision is contextually dependant on regional variables (e.g. water use) and on climate change impacts (such as flood or drought, which are characterised by inherent variability and lack of accurate data).

- To foster an informed dialogue, it is necessary to stress the importance that the social, economic, and environmental goals of the stakeholders should be inputs to the underlying model *in a transparent way* [184,185].
- *To adapt to future needs*:
    - To ease the incorporation of new data and/or applications to contextualize the problem.
    - To integrate the main components of urban water systems and interconnected sectors, of relevance for the water-energy nexus.
    - To incorporate the exploration of new technological solutions, such as decentralised sanitation and reuse.
    - To identify sustainability indicators, how they are interpreted and, ideally, to allow the user to define them.

## 5.2 CONCEPTUAL SOFTWARE ARCHITECTURE

The architecture of a software development refers to the highest level of abstraction and is related to the choice of programming paradigms. That is, a way of building the structure and elements of computer programs, interaction between components, timing, and high-level methods. As a result, the architecture underpins further design [186]. A bottom-up approach of dynamic programming was implemented. Dynamic programming, DP, is an optimisation approach that transforms a complex problem into a sequence of simpler problems [178]. It is important to mention that it cannot ensure global optimality.

Given the complexity of the problem and the DSS requirements, several computer-based tools and information (or knowledge) produced must be assembled in a cohesive fashion. Thus, an integrated structure is necessary to manage the information flow between various process phases (e.g. data exchange, databases, visualisation components, and simulation models). The configuration consists of the following interconnected modules:

- **Graphical User Interface (GUI).** Its functionality is to enable user interaction. The functionality of this module is to allow users to convey information and to display results (e.g. spatial data display, graphs and tables). It is through the graphical features that the user communicates with the back end of the computer system (Analytical Kernel). The DSS is comprised of a Microsoft C# GUI that builds an add-in for ArcMap 10™. Given that the DSS was not meant to be a released version its usability was not examined, rather it was an exercise to implement the design guidelines.
- **Analytical Kernel**. Its functionality is to integrate the models necessary to design and evaluate a wastewater treatment system given a geo-social context. Such as the exploration of the degree of decentralisation and/or wastewater treatment resource recovery strategies. It is comprised of three modules:
    - **Decision Making (Layout Option Generator).** The goal of the module is to generate semi-centralised layout design alternatives and rank them to identify the best one. It uses the set of decision–makers' preferences.
        - Decision model
        - Semi-centralised wastewater treatment system designer
        - Sewerage system designer
    - **Engineering Design Libraries**
        - Wastewater Treatment Technologies Library
        - Pipeline Technology Library
    - **Geographic Information System (GIS).** A GIS integrates hardware, software, and data for capturing, managing, analysing, and displaying all forms of geographically referenced information. The inclusion of GIS in the DSS responds to the necessity of spatial knowledge in the decision problem; spatial analysis capabilities are useful to run scenario analysis for policy making or planning [187,188]. The Module is comprised of two sub modules:

- Path Calculator
- Wastewater Allocator

The modular conceptual design of the computer-based tool is illustrated in Figure 1-3. The relationship between the identified requirements of the framework, described in section 5.1, and the conceptual design of the computer-based tool is illustrated in Table 5-1.

To generate the SUWWTS the required data can be provided by the user, and/or generated by the Analytical Kernel. Data can be broadly divided into two types: spatial (geo-referenced) and non-spatial. Each type was managed by adequate data repositories (or databases). The DSS has as inputs contextual socio-economic-geographic data and design specifications (performance variables, design variables, specifications and data required to compute the values of the performance variables). The outputs are the number of wastewater treatment plants, the technology of each plant, the sewerage system, and the associated reclaimed water distribution networks.

Figure 5-1 is a simplified data flow chart of its architecture and data flow. The colour coding refers to the DSS architecture (see Figure 1-3). Tasks are represented as rounded rectangles, input data as hollow ellipses, and outputs as filled ellipses. The DSS is built using *Object-Oriented Programming* principles with the aim of representing the physical world more faithfully and for facilitating code-reuse and the incorporation of new data and/or applications, e.g. novel technological approaches [189].

The GIS software package used in this research was ArcGIS, which is a platform for designing and managing solutions through the application of geographic knowledge. ArcGIS is developed by the ESRI company, and is a popular suite of software products, each with its own pricing and licensing [190]. ArcMap is the primary application used in ArcGIS and is used to view, edit, create, and analyse geospatial data [191]. Technical details are described in Chapter 10, Part IV.

Table 5-1 Relationship between the computer-based tool's requirement (in orange font) and its conceptual architecture. Newly introduced terms are in violet font.

| Task | Required functionality | Term | Description | Module | Sub module |
|---|---|---|---|---|---|
| Input of data<br>Capture the goals in a transparent way | Record urban water policies | Infrastructure Management Strategies* | Water and energy recovery from wastewater treatment policies<br>(Water Reuse, Energy Recovery, Nutrient Recovery) | Graphical User Interface | |
| | Record quantitative data<br>Enhance participation & Goals of decision-makers | Sustainability Goals*<br>Aspiration values of the Sustainability Goals* | Economy<br>Environment (use of natural resources)<br>Environment (resources recovered)<br>Environment (discharges)<br>Socio-cultural | Graphical User Interface | |
| | Record scenarios: contextualisation uncertainty and constraints | Data required to compute the Sustainability Goals* | Spatial Data: Topography<br>Urban Area map, Wastewater collection points location map, Elevation (Digital Elevation Model, DEM), Roads map, Exclusions zones map, Network, Wastewater treatment plants potential sites, Reclaimed water supply point<br>Spatial Data: Socio-economic<br>Household income map, Population density map, Per capita wastewater generation rate<br>Wastewater quality, Sewer design regulations, Electricity supply mix | Graphical User Interface | |
| Simulation to compute performance variables<br>Expert knowledge integration | Design wastewater treatment plant | | | Analytical Kernel | Wastewater treatment technology library |
| | Design pipe | | Pipe diameter calculation | Analytical Kernel | Pipeline design library |
| | | | Path of a segment of pipe | Geographic Information System | Path Calculator |
| | | | Flow collected in a wastewater collection point as a function of population density and average monthly income | Geographic Information System | Wastewater Allocator |
| | Design sewerage system | Hao-Kocur labelling algorithm | Connectivity among wastewater collection points | Analytical Kernel | Option Generator |
| | Design Semi-centralised wastewater treatment system | Branch and Bound | Number and location of wastewater treatment plants & sewerage system | Analytical Kernel | Option Generator |
| Support political dialogue | Ranking of options | Genetic Algorithm (Search technique) | Facilitate the interpretation of results | Analytical Kernel | Option Generator |
| Presentation of results | Tables, files, graph | | Number, location and technology of wastewater treatment plants and the sewerage system | Graphical User Interface | |

* Terms that comprise the Probabilistic Specification-based Model.

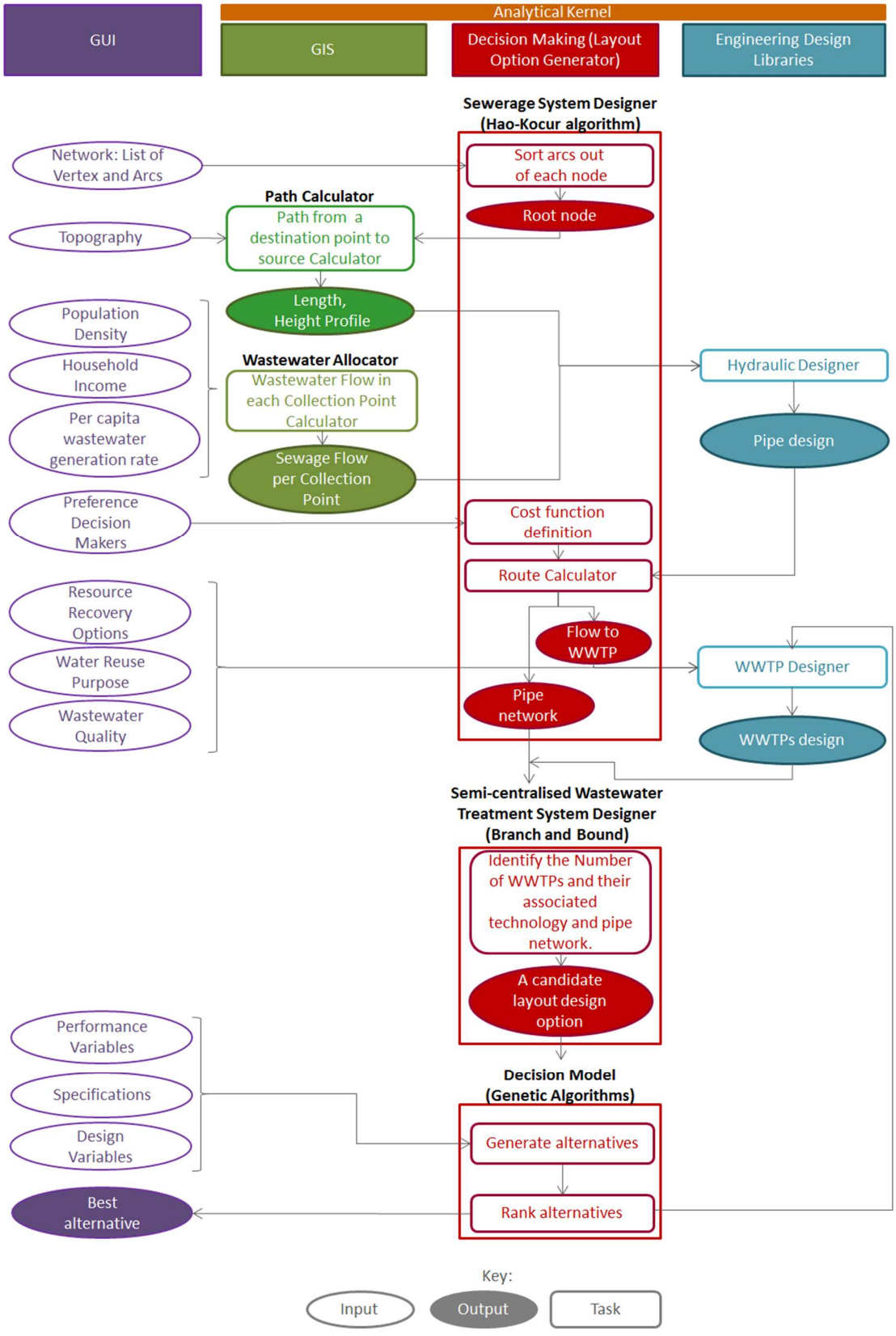



Figure 5-1 Simplified flow chart of the DSS. The colour coding makes reference to the DSS architecture (see Figure 1-3). Tasks are represented as rounded rectangles, input data as hollow ellipses, outputs as filled ellipses.

As mentioned previously, this work depended on information publicly available, yet reliable cost and technology data are companies' secrets. Given the data limitation issue, a feature of the DSS is that it contains default parameter values and equations that make non-specific *a priori* assumptions, which make the output too general for local applications.

Technical expertise is required in the design of wastewater treatment plants and sewer system, so it would have been ideal to have collaborated along a design, engineering, and consulting services company to access accurate data. However, such assumptions were necessary to provide an example of the logic of the approach and a starting point to move forward.

Default parameter values, cost, and design equations of six wastewater treatment plant technologies and two pipe technologies are found in Chapter 2, 8 and 9. GIS default parameter values are described in Chapter 10. A discussion about the limitations of data is discussed in Chapter 14.

## 5.3 SUMMARY

The outlines of the DSS' architecture are presented in Table 5-2.

Table 5-2 Computer-based tool outlines.

| | |
|---|---|
| **Name** | Decision Support System for SUWWTS. |
| **Description** | A computer-based tool to assist decision-makers in the generation and analysis of SUWWTS alternatives. |
| **Modules** | • Graphical User Interface (GUI)<br>• Analytical Kernel Module<br>• Geographic Information System (GIS) Module<br>• Manager Module |
| **Input** | • Decision making rules<br>• Socio-economic and geographical urban context<br>• Network of node connectivity |
| **Features and Output Highlights** | • Semi-centralised Wastewater Treatment System layout assessment<br>• Design assessment criteria integration<br>• Socio-spatial change impact e.g. population density, water demand, monthly income<br>• Greenhouse gas emissions life-cycle assessment: direct and indirect $CO_2e$ emissions from the wastewater treatment technology |

# PART IV
# DECISION SUPPORT SYSTEM DEVELOPMENT

# CHAPTER 6
# DSS DESIGN

## 6.1 SOFTWARE DEVELOPMENT METHODS

Software Design is the proposed implementation of the algorithms, procedures, design patterns (e.g. abstract factory) and programming languages [163]. As mentioned in the previous chapter, one of the functionalities of the DSS is to ease the incorporation of new data and/or applications to contextualize the problem. The aim of this section is to briefly describe the software development methods to ensure the implementation of the required functionality and to introduce the terminology that will be used throughout this Part.

The software development methods employed were the *Unified Modelling Language* (UML) and *Object-oriented Programming* (OOP), both well-established methods within the software development community.

OOP is a programming methodology that uses *objects* to represent the things being modelled, which might be physical (e.g. pipe) or intangible (e.g. arc). The OOP objects are a representation, or *abstraction*, of real-world objects. In the abstraction exercise it is necessary to understand the real-world object to represent it in the software. Several programming languages, such as Java, C# (pronounced as see sharp) and Python support this programming paradigm.

In OOP it is important to identify the objects to be manipulated and their interactions with other objects. A *class* is the generalised definition of an object, it is like Plato's abstract objects,

that defines its characteristics (*parameters* or *variables*) and logical functions to manipulate or describe its behaviour, the logical functions are called *methods*. Consequently, an object is the instantiation of a class (like a concrete object of a Plato's abstract object) it is a data structure that stores inside its properties its state, and its behaviour is represented through its methods.

The concept of *encapsulation* in OOP refers to how objects will be manipulated by other objects. That is, it sets the rules for restricting access to some of the object's components to avoid data corruption. Objects interact, or communicate, via *interfaces*. Typically, an object has a public and a private interface. The public interface refers to what is available to use from the object, whereas the private interface refers to what makes the object work.

UML is a standardized representation of software systems that helps to specify, visualize, and document software models [192,193]. UML notation can be divided in two parts: (1) that which is for modelling the static elements of a design (the class attributes and its interactions with other classes), and (2) that for modelling the dynamic elements of a design (objects and messages).

Figure 6-1 displays a UML notation for the class Pipeline_Route. From this point onwards whenever referring to a class the word font will change e.g. Class_Name. The class icon is comprised of three rectangles. The top one shows the name of the class, the middle one shows its properties and the bottom one shows its methods. The symbol at the left of the properties and methods indicates the nature of the interface. The plus sign (+) indicates "public" and the minus sign (-) indicates "private". In general, it is not necessary to show every property or method, the purpose of a UML representation is to give insight into the general workings of the system.

An additional concept in OOP is *modularity*, which refers to the notion of building components that can be re-used and put together to construct complex systems [194]. The DSS has been constructed from a series of object modules that can communicate with each other to simulate the similar workings of a real-world wastewater system.

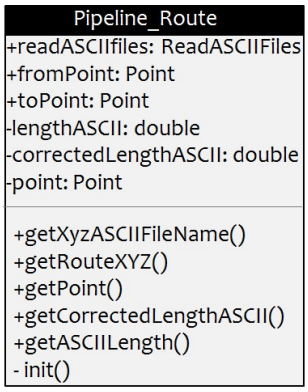



Figure 6-1 Class icon example.

Another way of using abstraction in OOP is through the concept of *inheritance*. It is a functionality through which an object (called the "child object") is based, with some exceptions, on another object (called the "parent object"). The implementation of inheritance allows code re-use and is a way to add features to an existing class without having to modify it. This feature is one of the main reasons for using OOP in this project, particularly in the deployment of alternative wastewater technologies that can be added, subtracted, and swapped from the libraries without having to change their code. The concept of inheritance was also used to enhance the DSS by generating a parent class of "Decision Models" that allow the user to select the method to obtain the best layout design.

## 6.2 UML CLASS DIAGRAM

The class diagram is a static modelling notation that depicts the classes and their relationships in a software model. Figure 6-2 is the class diagram of the DSS. As mentioned earlier it is not necessary for this diagram to show every property or method. The following chapters will provide more detail on these classes.

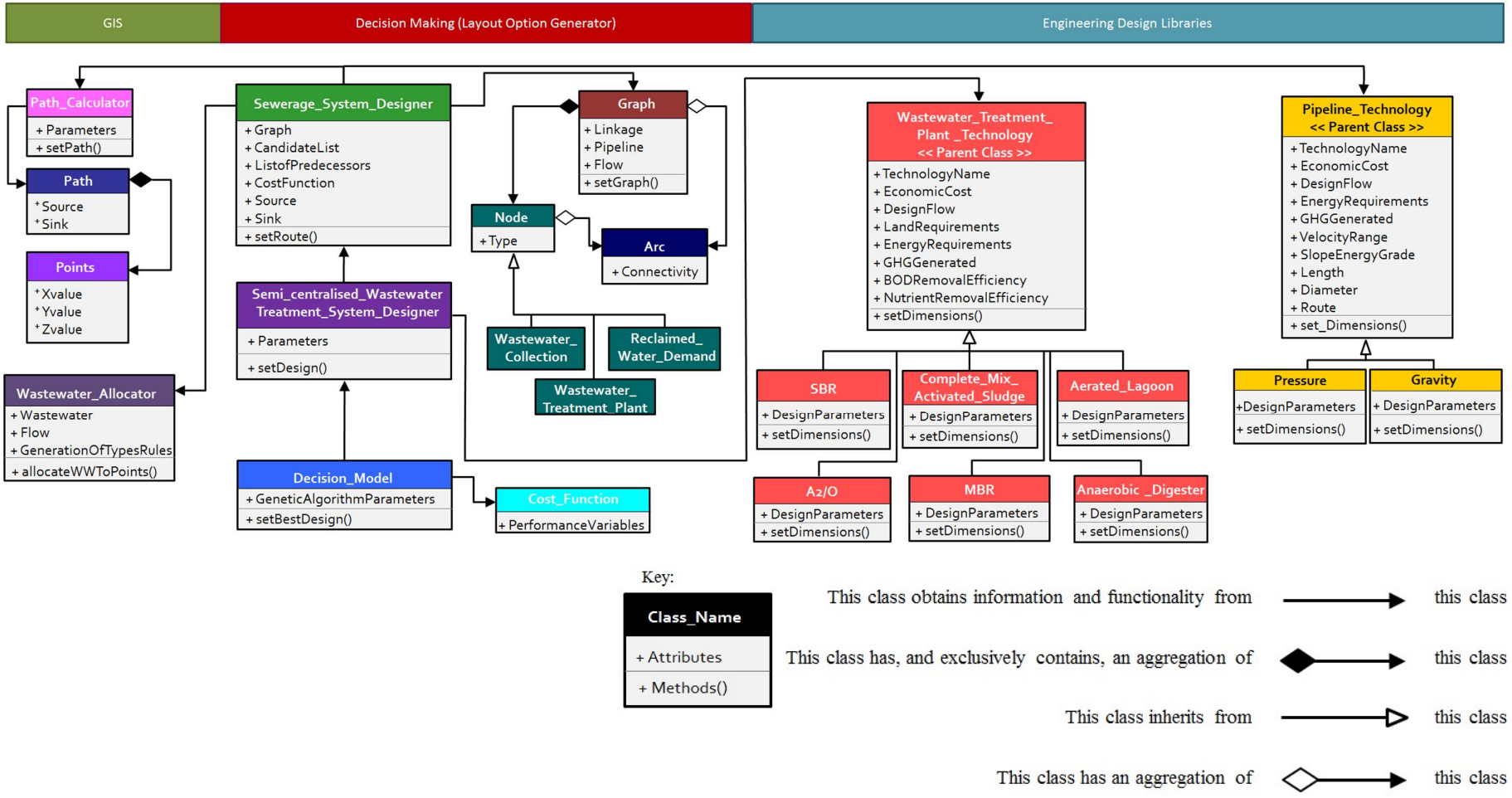



Figure 6-2 UML class diagram. High level representation of the different classes and their connections.

An explanation of the main elements of the figure is as follows:

- Class. The icon that represents a class is a box comprised of three rectangles. The classes are colour-coded to make it easier for the reader to grasp relationships with the aid of colours. It should be noted that the class colours are not related to the module's colour scheme used in Figure 5-2.
- Inheritance. The solid line and a hollow triangle connecting the Wastewater_Treatment_Plant_Technology and the MBR or SBR classes indicate an inheritance relationship. The use of inheritance allows new technologies to be easily incorporated into the Library.
- Association. The solid line with an arrow connecting the classes Decision_Model and Semi_centralised_Wastewater_Treatment_Designer indicates a directional association between them. That is, the class Decision_Model knows about Semi_centralised_Wastewater_Treatment_Designer and interacts with its interface, but the opposite is not true.
- Aggregation. A solid line with a void rhombus indicates an aggregation relationship: Node and Graph both contain a collection of Arc. A solid line with a filled rhombus indicates an "exclusive" aggregation relationship: Graph exclusively contains a collection of Node.

## 6.3 GUI DESIGN

It is extremely important to take into consideration the user's experience and interaction with the system, otherwise poorly design interfaces can lead to perceived uselessness and a failure of the intended purpose to help decision-makers. The problem requirements were translated into the features of the GUI [195]. Having in mind the *Human-Computer Interaction* and *Usability* concepts, the GUI architecture employed good design principles [196]. Software

usability refers the assistance provided to a user to accomplish a task. Human-computer interaction refers to the user-oriented approach on the design of interactive systems [197].

## 6.4 DSS FACT SHEET

Table 6-1 displays the *Fact Sheet* (presentation of data in a format which emphasizes key points concisely) of the DSS.

Table 6-1 DSS Fact Sheet.

| | |
|---|---|
| **Name** | Decision Support System, DSS. |
| **Description** | A computer-based tool to assist urban water managers in the design of an integrated SUWWTS as an urban water management option. |
| **Hypothesis** | The integration of a Geographic Information System (GIS), with a set of wastewater treatment technology models that explore the expediency of resource recovery solutions from wastewater treatment processes and the degree of semi-centralisation designed to enhance the analytical capacity of decision-makers. |
| **Underlying model** | Analytical model and methods module to generate design parameters: Optimisation engine, Wastewater treatment technologies libraries (treatment plant technologies, pipelines, reservoirs, energy recovery technologies) and a Geographic Information System module (to store, manipulate and analyse spatial data as well as an interface for the user). |
| **Development Goal** | To demonstrate a realisation of the Framework guidelines. |
| **Features** | • Sourcing together multidisciplinary knowledge, integrating engineering models and independent software tools<br>• Automation, thus a reduction in human and time resources |
| **Relevance** | • The development of the first decision support system that provides core functionality for assisting in the evaluation of the degree of wastewater treatment semi-centralisation in urban areas.<br>• The availability to decision-makers of integrated simulation models with expert knowledge. The DSS compiles multidisciplinary expertise, from Geographic Information Systems to the water sector knowledge domain. |
| **Intended Users** | Design engineers |
| **System I/O data format** | • GIS data files<br>• Text files |
| **Maturity** | Experimental prototype. |
| **System Requirements** | Windows 7, JDK 1.7, .NET Framework 3.5 SP1, Python 2.7.x and Numerical Python 1.6.x, ArcGIS 10. |
| **Required Licenses** | ArcGIS 10 Engine |
| **Underlying technologies** | • Java, C# and Python programming languages<br>• JFreeChart (version 1.0.13) displaying charts library<br>• JCommon (version 1.0.16) displaying charts library<br>• Watchmaker (version 0.7.1) genetic algorithms library<br>• Integrated Development Environments (IDEs): Microsoft Visual Studio 2010, PythonWin for ArcGIS 10 and NetBeans (version 7.2.1) |

# CHAPTER 7
# DECISION MAKING (LAYOUT OPTION GENERATOR)

The Decision Making (Layout Option Generator) module is integrated by three key classes:

- **Decision_Model**. The functionality is to generate options, rank options and facilitate the interpretation of the result, that is, which semi-centralised design is better.
- **Semi-centralised_Wastewater_Treatment_System_Designer**. The functionality is to determine the number, location, type of technology and final sewerage system of the semi-centralised wastewater treatment plant system.
- **Sewerage_System_Designer**. The functionality is to determine the sequence of vertices of a graph from a destination point to a source.

To facilitate the explanation, the order adopted is top-down. Thus, the explanation begins with the highest conceptual level and then continues with details of the smaller components. The figures that illustrate the relationships among the classes at the beginning of each section should be particularly useful.

## 7.1 SOLVING TECHNIQUES OVERVIEW

This subsection uses terms introduced in Table 5-1, thus are in **violet font**.

The **Hao-Kocur labelling algorithm** solves the connectivity between fixed nodes and a potential node (as defined in the Network model in Chapter 4). The *Simple Additive Weighting Method* is used as a criterion for evaluating connectivity alternatives. That is, to decide whether connecting node A with node B or C. The Simple Additive Weighting "cost function" encapsulates the triple bottom line concept of financial, environmental, and social costs. The "cost function" will depend on the flow of wastewater conveyed and the pipe path. The

algorithm is the core of Sewerage_System_Designer class, which will be described in Section 7.4.

The minimisation of the objective function of the integer-programming model (equation 4-1) is solved employing the **Branch and Bound algorithm**, which is described in detail in Section 7.3.1. The output from this technique is *a candidate layout design option* of a SUWWTS (the number of WWTPs), their associated wastewater collection and reclaimed water points, and the pipe network. The solution of the Hao-Kocur algorithm for each potential node is an input data for the Branch and Bound method. The algorithm is the core of Semi-centralised_Wastewater_Treatment_System_Designer class, which will be described in Section 7.3.

Yet, to find the best design candidate it is necessary to generate alternatives and to rank them in terms of the stakeholders' prioritisation criteria (in terms of cost, energy requirements, etc.). The best design is the one with the highest ranking.

The approach for generating many design alternatives and their ranking to identify the best candidate is using the **Probabilistic Specification-based Design Model**. As mentioned in Chapter 2 this model was developed by Wallace *et al.* [57] and uses the **search technique** of ***Genetic Algorithms (GA)***. A search technique is an optimisation method used to search different candidate design solutions to improve a SUWWTS. The combination of Branch and Bound to generate some information to be used to guide a GA search for optimal or near-optimal solutions has been used in the literature [198,199].

The model and search technique are the core of Decision_Model class, which will be described in further detail in Section 7.2. Figure 7-1 is a simplified visualisation of the approach to identify the best SUWWTS design. It is important to mention that with these techniques it is not possible to ensure global optimality.

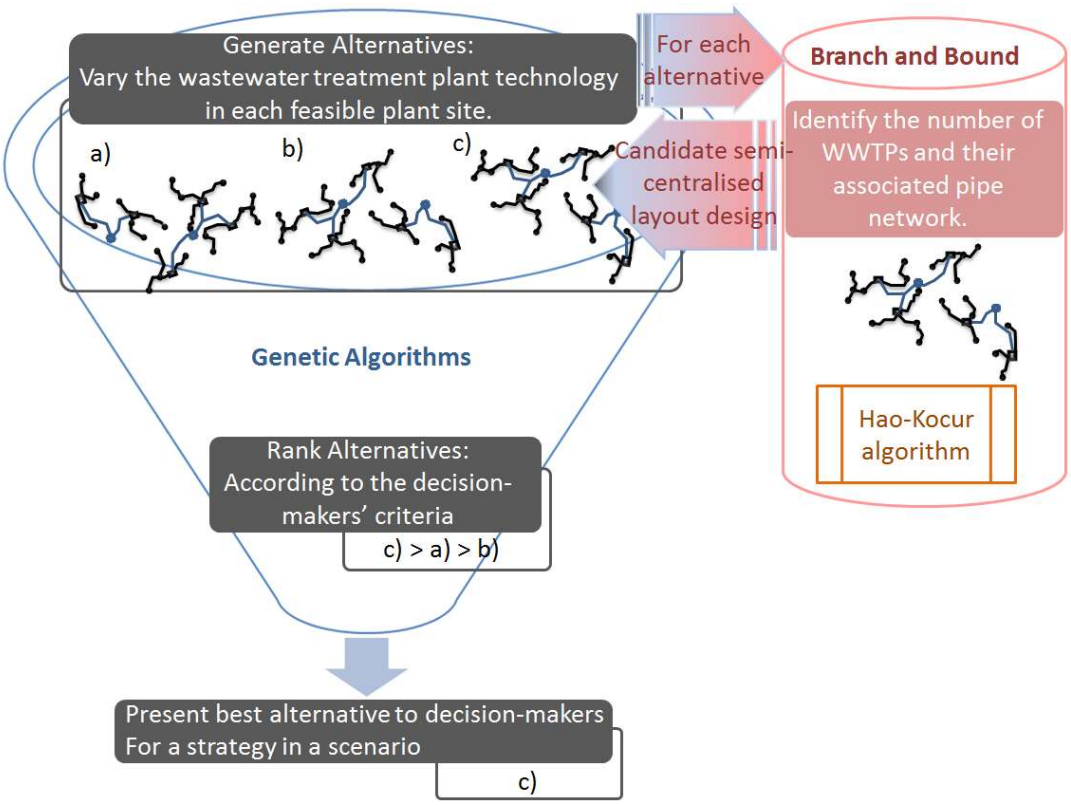



Figure 7-1 Visualisation of the programming techniques used to identify the best SUWWTS layout design.

1. GA generates alternatives by varying the wastewater treatment plant technology in each feasible plant site according to the infrastructure strategies (reclaimed resources from wastewater treatment policies) that the decision-maker wants to explore.
2. For each alternative Branch and Bound will compute the candidate design options, it requires the Hao-Kocur algorithm to determine the sequence of vertices of a graph from a destination point (possible wastewater treatment plant) to a source (each wastewater collection point).
3. The alternatives will be ranked according to the Probabilistic Specification-based Design Model and after a series of iterations the best design is presented to the decision-makers.

## 7.2 DECISION MODEL CLASS

The Decision_Model class is the master level class that orchestrates the decision making process. Figure 7-2 illustrates the relationship between the Decision_Model class with Semi-centralised_Wastewater_Treatment_System_Designer and Cost_Function classes.

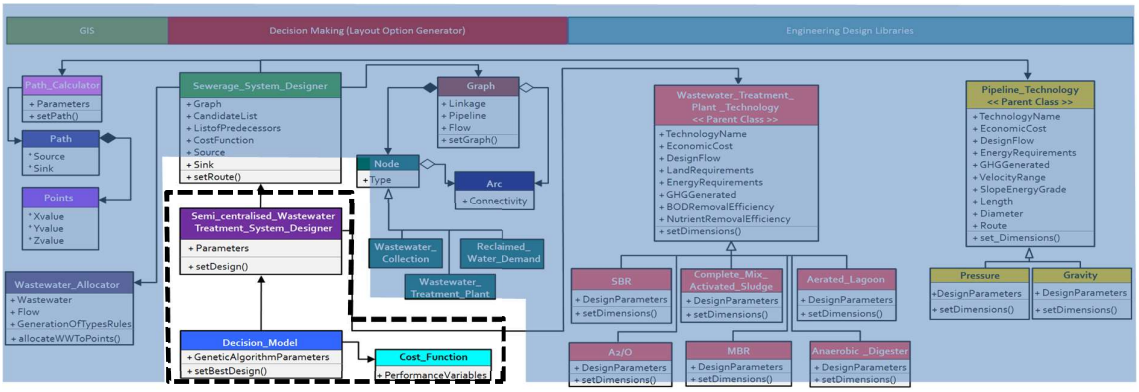



Figure 7-2 Relationships between the Decision_Model class with the Semi-centralised_Wastewater_Treatment_System_Designer and Cost_Function classes.

The Decision_Model class is the implementation of a GA algorithm, thus in its fundamental method the following steps are implemented:

1. An initial list of WWTP technologies is seeded; the technologies evaluate the resource recovery targets selected by the user. This population is said to be the first generation. Semi-centralised_Wastewater_Treatment_System_Designer class designs a candidate semi-centralised layout design for each population.
2. Each member of the population is evaluated with the fitness function defined by the user. The fitness function parameters are retrieved from the Cost_Function class, which stores the performance variables defined by the user.
3. Members of the population are evaluated for their fitness scores. The best or "fittest" are used as the "parents" for the next generation.
4. A new generation is created by combining or altering the fittest parents. The two operators implemented are *cross-over* followed by *mutation*. Cross-over refers to

dividing the list of WWTP technologies of two parents and recombining the cut lists to create an "offspring". Mutation refers to copying the list of WWTP of a parent, but with a small, random change (such as changing one technology), to create the offspring. Finally, via *elitism* some offspring are the copy of a parent.

5. Several generations or iterations are performed. The algorithm terminates either when: (a) It converges to the highest-ranking solution's fitness, (b) The maximum number of generations defined by the programmer has been reached.

### 7.2.1 Probabilistic Specification-based Design Model

This approach assists in managing the complexity faced by decision-makers: a sustainable Semi-centralised Urban Wastewater Treatment System (SUWWTS) can be considered acceptable or satisfactory in terms of many socio-technical objectives/specifications, which usually are incommensurable and conflicting.

The need to integrate value judgements, or qualitative information, with quantitative data results in two important challenges: (a) How to combine/aggregate multiple objectives into one figure of merit? and (b) How to search for an optimal solution? The first question will be discussed in this subsection, whereas the second in the following subsection.

From the myriad of ways in which multi objective optimisation can be conducted [200] the acceptability functions were selected. The method, developed by Wallace *et al.* [57,201], stems from engineering design and is a goal/targets-oriented design model to evaluate the performance of each design solution.

Under the premise that design is a satisfaction process the value of the acceptability function (or specification) represents the subjective probability that a designer will accept a design, capturing the uncertainty about finding a design "acceptable" or "not acceptable". The acceptability concept holds the notion of "good enough" and is linked to the designer's decision on a course of action: if a design is acceptable then it does not require improvement.

In the probabilistic specification-based design model, in order to perform an optimisation, the problem is defined in terms of probability distributions of design variables, performance variables and specifications, terms introduced in Table 5-1 (in **violet font**).

- **Infrastructure Strategies** are the characteristics of the SUWWTS design to be optimised.
- **Sustainability Goals** are the design's properties/characteristics/criteria that will be used to determine the acceptability of design alternatives. They are the result from calculations using the infrastructure strategies. Sustainability Goals must be probability distributions: the delta function is used for a deterministic characteristic (exists at a point with complete certainty). The user must provide the **data required to compute the Sustainability Goals**.
- **Aspiration values of the Sustainability Goals** are acceptability functions and are the distributions against which Sustainability Goals variables are measured.

The importance of a characteristic is expressed by its ability to influence on the overall acceptability and is reflected in the shape of its acceptability function (or specification), see Figure 7-3.

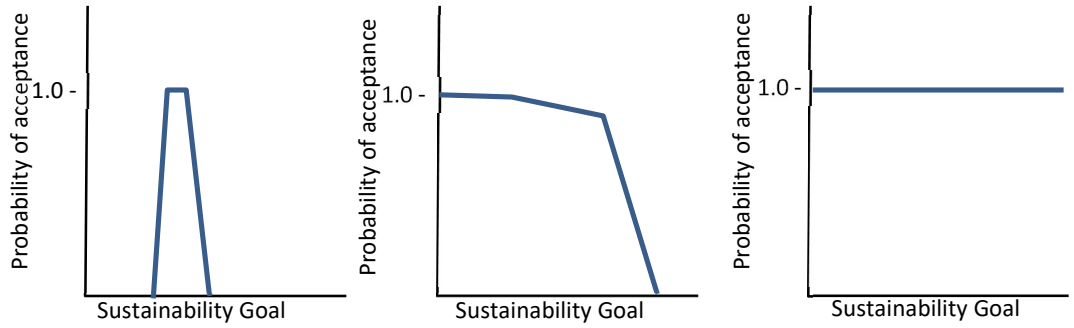



Figure 7-3 Importance of a specification expressed in the shape of acceptability functions: (a) likely to drive design, (b) less likely to drive design, (c) never drives design.

The Sustainability Goal on Figure 7-3 (a) may be more important because the region of acceptability is narrow and might influence the overall acceptability. In contrast Figure 7-3 (b)

might not be as important as its region of acceptability is very wide, that is, the criterion will be satisfied with a wide range of performance levels. Figure 7-3 (c) can be interpreted as an "optimism level", when there is lack of information or a failure in identifying when a criterion could be important. The optimism level is a value used as the subjective probability of acceptance.

If during an analysis the distribution data for a variable is missing, the optimism level is used as the subjective probability that, if available, the data would have values that would be satisfactory for the design. The value is called an optimism level because the pessimist would assign a probability of 0 (which disqualifies any design with missing data), while a pure optimist would assign a probability of 1.

### 7.2.2 Data Input

Table 7-1 shows the variables and Table 7-2 shows the data required to compute the Sustainability Goals. The values of both tables are entered into the DSS by the user. It is important to observe that for an application of the DSS the values of the parameters of Table 7.2 are rarely available in the public domain. In the absence of more site-specific data, it is useful for the purpose of this research to use in a prudent manner surrogate values.

On ArcGIS for Desktop ArcMap 10.1, the user must click the button that will launch the DSS. ArcMap is the map display and editing workhorse for the Esri ArcGIS Geographic Information System (GIS) software package.

Certainly, wastewater parameters (e.g. BOD, COD) values are site specific, yet a certain extrapolation of composition values of an urban area with similar characteristics can be used judiciously as a first estimate [142]. The production of domestic sewerage corresponds generally to water consumption; indeed, the hourly variations of wastewater flow must be taken into consideration when designing a SUWWTS, yet this work is intended as a design guide.

Table 7-1 Types of variables in the Probabilistic Specification-based Design Model. All provided by the user.

| Input | Comments | Description |
|---|---|---|
| Infrastructure Strategies | The types of wastewater treatment plants technologies are governed by resource recovery from wastewater treatment policies. | Water Reuse<br>Agricultural irrigation<br>Groundwater recharge<br>Urban Landscape Irrigation<br>Industrial<br>Environmental enhancement<br>Potable use<br>Nutrient Recovery<br>Energy Recovery |
| Sustainability Goals | The design properties/characteristics/criteria that will be used to determine the acceptability of design alternatives and are calculated by stored methods.<br>The performance variables are the Key Sustainability Management Indicators (see Section 4.5).<br>The user provides the data required to compute the values of the performance variables.<br>As future work the functionality to provide the user with various methods to compute performance variables could be incorporated.<br>In the description column the options currently available to the user are shown. | See Table 4-3 |
| Aspiration values of the Sustainability Goals | These are the goals that the decision maker is aspiring the semi-centralised system should have. | The distributions against which performance variables are measured.<br>The user defines the shape of specifications: through either beta distributions or piecewise linear distributions. |

The location of wastewater collection points, feasible wastewater treatment plants and network of central nodes maps are generated from available public information to symbolize socio-political issues. See Chapter 11 for a detailed description of the input parameters in an application of the DSS.

Table 7-2 Data required to compute the Sustainability Goals. All provided by the user.

<table>
<tr><th colspan="3">Input</th><th>Comments</th><th colspan="4">Description</th></tr>
<tr><td rowspan="3">Data required to compute the Sustainability Goals<br><br>(Record Urban Area Attributes)</td><td>Wastewater Data</td><td></td><td>Wastewater flow rate and composition are influenced by socio-economic factors and water availability, depending on the geographical location.</td><td colspan="4"><table>
<tr><th>Parameter</th><th>Units</th><th>Parameter</th><th>Units</th></tr>
<tr><td>Flow rate</td><td>$m^3s^{-1}$</td><td>Phosphorous (P) total</td><td>$g\ m^{-3}$</td></tr>
<tr><td>Biological Oxygen Demand (BOD)</td><td>$g\ m^{-3}$</td><td>Total Suspended Solids (TSS)</td><td>$g\ m^{-3}$</td></tr>
<tr><td>Chemical Oxygen Demand (COD) total</td><td>$g\ m^{-3}$</td><td>Volatile Suspended Solids (VSS)</td><td>$g\ m^{-3}$</td></tr>
<tr><td>COD soluble</td><td>$g\ m^{-3}$</td><td>pH</td><td>-</td></tr>
<tr><td>Ammonia-N ($NH_3$)</td><td>$g\ m^{-3}$</td><td>T</td><td>$^oC$</td></tr>
<tr><td>Total Kjendahl N*(Ammonia, organic and reduced nitrogen)</td><td>$g\ m^{-3}$</td><td></td><td></td></tr>
</table></td></tr>
<tr><td>Spatial Data</td><td>Topography<br><br>Socio-economic</td><td>Urban Area map<br>Wastewater collection points location map<br>Elevation (Digital Elevation Model, DEM)<br>Roads map<br>Exclusions zones map<br>Network of central nodes<br>Wastewater treatment plants potential sites<br>Reclaimed water demand points map<br><br>Household income map<br>Population map<br>Per capita wastewater generation rate (water consumption)<br>Minimum monthly wage<br>Classification values</td><td colspan="4">For the network, potential wastewater treatment plant's sites, reclaimed water demand points and wastewater collection points the user must provide the following information:<br><br>• Map of the location of feasible wastewater treatment plants. The map is in point shapefile format[b]<br>• Map of wastewater collection points. The map is in point shapefile format<br>• Map of reclaimed water demand points. The map is in point shapefile format<br>• The connectivity between points is expressed as pairs of numbers e.g. (2, 39) in Text File format<br>The DSS calculates the path between the pair of numbers via a method housed in the GIS Module</td></tr>
<tr><td>Electricity supply mix</td><td></td><td>The electricity mix is contextual to the urban area.</td><td colspan="4"><table>
<tr><th>Data</th><th>Units</th><th>Data</th><th>Units</th></tr>
<tr><td>Hydropower</td><td>%</td><td>Oil</td><td>%</td></tr>
<tr><td>Gas</td><td>%</td><td>Coal</td><td>%</td></tr>
<tr><td>Biomass</td><td>%</td><td>Wind</td><td>%</td></tr>
<tr><td>Nuclear</td><td>%</td><td>Tariff</td><td>$\$\ kWh^{-1}$</td></tr>
</table></td></tr>
</table>

[b] A vector data storage format for storing the location, shape, and attributes of geographic features. A shapefile is stored in a set of related files and contains one feature class. A shapefile stores nontopological geometry and attribute information for the spatial features in a data set. The geometry for a feature is stored as a shape comprising a set of vector coordinates. Shapes can be points, lines, or polygons (areas).

### 7.2.3 Acceptability Function

The probabilistic specification-based method assumes that the acceptability of a design may be determined through the evaluation of its components. The probability, $p_i$, of accepting a design based upon the $i^{th}$ characteristic is:

$$p_i = \int_x a(x)p(x)dx \qquad (7\text{-}1)$$

$$\text{s.t} \quad a\,(x) \in [0,1]$$

Where

*$i$ = number of design characteristics/attributes to be evaluated vs acceptability functions*
*$x$ = performance variable*
*$a(x)$ = acceptability function or specification which defines the probability that different levels of the performance variable will be acceptable*
*$p_i(x)$ = probability density function (pdf) of unit area which quantifies the design's performance for characteristic x.*

It is important to observe that at this stage of research p(x) has only been implemented in the DSS as a Dirac delta function, or δ function, mainly because of difficulty in accessing data. Certainly, further research effort is required to implement other functions. The Dirac delta function can be defined as

$$\delta(x) = \begin{cases} +\infty, & x = 0 \\ 0, & x \neq 0 \end{cases}$$

and satisfies the identity

$$\int_{-\infty}^{\infty} \delta(x)dx = 1$$

When evaluating a multi-attribute design the overall probability of accepting a design alternative is the probability that the design will be acceptable according to all objectives. The overall probability value is, thus, the multiplication of individual probabilities:

$$p_{acceptable\ based\ on\ all\ characteristics} = \prod_{i=1}^{k} p_i \qquad (7\text{-}2)$$

Where

*k = number of design characteristics/attributes to be evaluated*
*$p_i$ = probability of accepting a design based upon the ith characteristic, Eqn. (7-1)*

In this way the acceptability metric combines multiple attributes into a single objective function. Consequently, when comparing different design alternatives, the ideal goal is to find one with certainty to be accepted $P_{acceptable}$ = 1.0; that is, higher $P_{acceptable}$ values will be preferred.

Figure 7-4 exemplifies an acceptability function of reclaimed water quality (g BOD $m^{-3}$) obtained from a wastewater treatment plant technology, where:

- The performance characteristic is the reclaimed water quality, RWq.
- *a*(RWq) is the acceptability function which defines the probability that different qualities of reclaimed water will be acceptable. For instance, a reclaimed water quality of less than 25 mg BOD $m^{-3}$ has a probability of 1.0 of being accepted. However, a reclaimed water quality of 30 mg BOD $m^{-3}$ will be rejected for sure. Since an absolute scale is being used, the slope implicitly captures the designer's substitution or trade-off preferences.
- *p*(RWq) is a probability density function; in this example the value was obtained from the design variable (wastewater treatment technology) and is deterministic (delta function).
- Consequently, if a reclaimed water quality is known to be exactly 28 mg BOD $m^{-3}$, it has a probability of acceptance of 0.4.

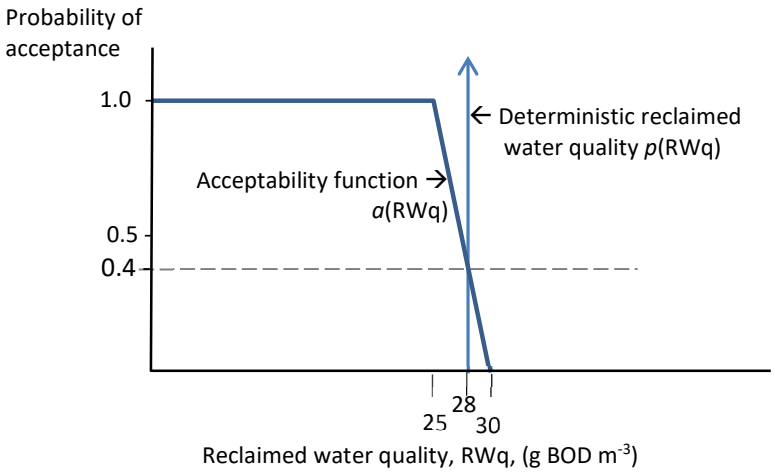



Figure 7-4 Piecewise linear Acceptability function and Probability density functions (delta function) for a reclaimed water quality achieved by a wastewater treatment plant technology.

It is important to observe that there is uncertainty in reclaimed water characteristics, usually WWTPs always operate over ranges (e.g. 20 to 35 ppm) during normal operations (not points). As mentioned earlier mainly because of difficulty in accessing data, this issue is required to be implemented. Additionally, on occasions single factors often define decisions in wastewater treatment plant designs or choices; sometimes not related to optimisation or operational considerations. The approach to incorporate such subjective issues was via the Scenarios method and Strategies since these capture judgement values (see Table 7-2).

### 7.2.4 Advantages

The model provides a straight-forward way of combining multiple attributes into a single objective function to assess performance and provides a structured way to handle preferences in design. Some of the advantages are:

- the problem is modelled in terms of a language that designers or decision-makers are familiar with, they just must decide the acceptable levels of performance for each evaluation category.

- the decision-makers, or users, decide the shape of the acceptability functions in their internal negotiations.
- the model addresses the data-completeness problem by allowing analysis to proceed using incomplete data or approximations.
- the use of weighting factors is not needed.
- since the evaluation is based upon subjective probabilities in an absolute scale, it is possible to compare the overall probabilities of different design options even though each might not have identical requirements.

### 7.2.5 Search Technique: Genetic Algorithms

This subsection describes the **search technique** which is an optimisation method used to search different candidate design solutions to improve a SUWWTS. Candidate solutions are combinations of components (wastewater treatment plants –with their associated type and location-, sewerage system and reclaimed water network) that have been encountered but may not satisfy all given conditions. Solutions are candidate solutions that satisfy all given conditions [202].

Since our problem consists of a mixture of numerical simulations, analytical calculations and catalogue selections, there is no easy and accurate way of calculating derivatives of an objective function, assuming it could be feasible to define one. For our problem, therefore, it is suitable to use one of the most popular heuristic methods applied in a broad range of engineering problems: Genetic Algorithms (GA) [203,204].

A GA is often considered a baseline approach because it provides a robust search. GA are a type of evolutionary algorithm that imitates natural evolution using stochastic [c] [205] transformations to undergo reproduction, mutation, recombination, e.g. cross-over, and selection. The fitness function is used to determine the selection condition (a way to rank the

[c] Having a random probability distribution or pattern that may be analysed statistically but may not be predicted precisely.

design candidate solutions) to assess the survival (through selection –a force that drives convergence- or crossover –one that drives exploration-) of a candidate solution.

A GA is an iterative process that starts from a randomly generated initial population of candidate/potential solutions (also called individuals or phenotypes) $C(t)$, for each iteration $t$ of the problem. Each candidate solution has a set of properties (also called chromosomes or genotype). The population at each iteration $t$ is called a generation. In each generation the fitness of every individual in the population is evaluated. The fitness is usually the value of the objective function to be optimized (e.g. maximized or minimized). The fitter individuals (with the better fitness/objective values) are stochastically selected to form a new generation with a new population, $C(t+1)$. The algorithm terminates either when a maximum number of generations have been produced via a parameter determined by the programmer or converges to an optimal or sub-optimal solution of the fitness/objective function.

Since GA manipulates a population of individuals it can quickly locate feasible regions without getting trapped in local optima. However, since it is a heuristic algorithm, it cannot to assure optimality and uniqueness of the final solution. The GA library used in this Thesis was developed by Daniel W. Dyer [206].

The use of GA requires the definition of several parameters that affect search performance and efficiency. Several runs of the program were conducted to determine the best values for each these parameters.

#### *7.2.5.1 Fitness Function*

To identify the best candidate solution a fitness function is required. The fitness function[d] [207] is a criterion for determining which design alternatives are the most suitable parents. The goal of the fitness function is to identify the potential of individual characteristics (genotype) even if the potential solution (phenotype) is not good enough. Wallace *et al.* (1996) [57] resolved the

[d] The fitness function estimates how close a candidate is to being a solution.

problem of estimating desirable "genetic material" using the Information Content[e] [208] concept as the logarithm of the inverse of the Probability of Acceptance:

$$I = \sum_{i=1}^{n} log_2\left(\frac{1}{p_i}\right) \qquad (7\text{-}3)$$

Where

*I = design information content*
*n = number of design specifications or criteria*
*$p_i$ = probability of accepting a design based upon the $i^{th}$ characteristic, Eqn. (7-1)*

A candidate's information content is initialised setting the maximum value ($I_{max}$). All specifications (or performance variables) are set to zero equivalent probability acceptances (0.001)[f] to obtain the maximum value of information content ($I = \log_2(1/0.001) = 9.96$) and then adds the information contents for all specifications. For example, a candidate with ten specifications will have $I_{max} = 99.6$.

An iterative process follows for each specification in which the information content is computed, and this value is subtracted from the candidate's information content $I_c = I_c - I_{specification}$ (at the beginning of the iteration the $I_c = I_{max}$). A specification with an acceptance probability of 1.0 has the smallest information content value $I_{specification} = \log_2(1/1) = 0$, consequently it will not reduce the candidate's information content ($I_c = I_c - 0$). The best design has the smallest $I_{specification}$ since it requires the least amount of information to achieve the design goals [209]. On the contrary, a specification with an acceptance probability of less than 1.0, such as 0.5, will reduce the candidate's fitness function value by 1 unit ($I_{specification} = \log_2(1/0.5) = 1$).

The goal of the optimisation is to maximise the value of the candidate's Information Content. It is an indirect way to maximise the probability of having an acceptable specification and an effective way to identify acceptable candidates with desirable genetic material.

[e] Information: the probability of achieving the Functional Requirements or goals. Information Content: the logarithm of the inverse of the probability of fulfilling the specified Functional Requirements.
[f] Wallace *et al.* [57] reported that the value of the zero equivalent does not have a significant impact on the performance of the algorithm.

## 7.3 SEMI-CENTRALISED WASTEWATER TREATMENT SYSTEM DESIGNER

The Semi-centralised_Wastewater_Treatment_System_Designer class identifies the number of wastewater treatment plants that are worth building from the set of feasible WWTPs sites and the wastewater collection points to be connected to each WWTP.

Figure 7-5 illustrates the relationships between the Semi-centralised_Wastewater_Treatment_System_Designer and Sewerage_System_Designer and Wastewater_Treatment_Plant_Technology classes. These are fundamental components because the first one designs the sewerage system and the second designs the treatment plants.

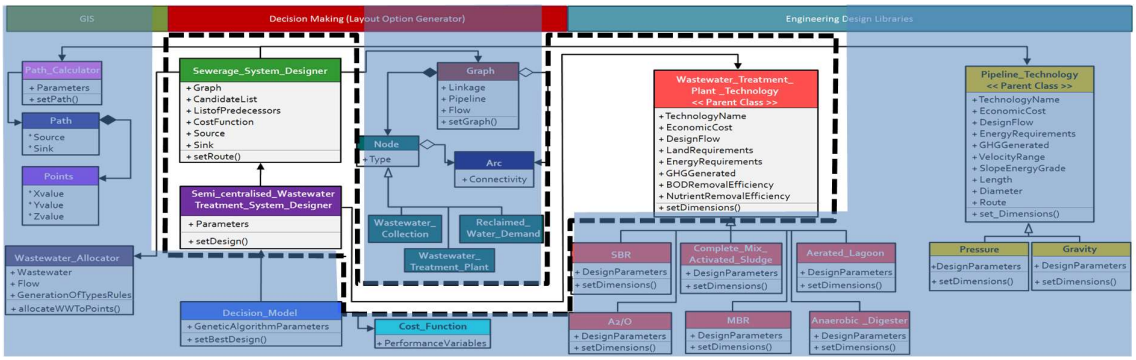



Figure 7-5 Relationships between the Semi-centralised_Wastewater_Treatment_System_Designer and Sewerage_System_Designer and Wastewater_Treatment_Plant_Technology classes.

### 7.3.1 Branch and Bound Method

The Semi-centralised_Wastewater_Treatment_System_Designer class identifies the number of wastewater treatment plants that are worth building from the set of feasible wastewater treatment plant sites using the **Branch and Bound algorithm** (see Section 7.1). Branch and Bound algorithms are methods used for solving mixed (or pure) integer programming problems and for finding global optimum in non-convex problems. Branch and bound algorithms are non-heuristic. As such they maintain provable lower and upper bounds on global objective values; terminate with certificate proving sub-optimality; and although often slow, they provide results

[210]. When it is not possible to obtain (prove) a globally optimal solution, then it is necessary to use an approximation: a sub-optimal solution.

The basic idea of the method is based on a *branch and bound tree* search that uses upper and lower bounds to limit the number of combinations examined while looking for the solution [211]. Figure 7-6 shows a branch and bound tree.

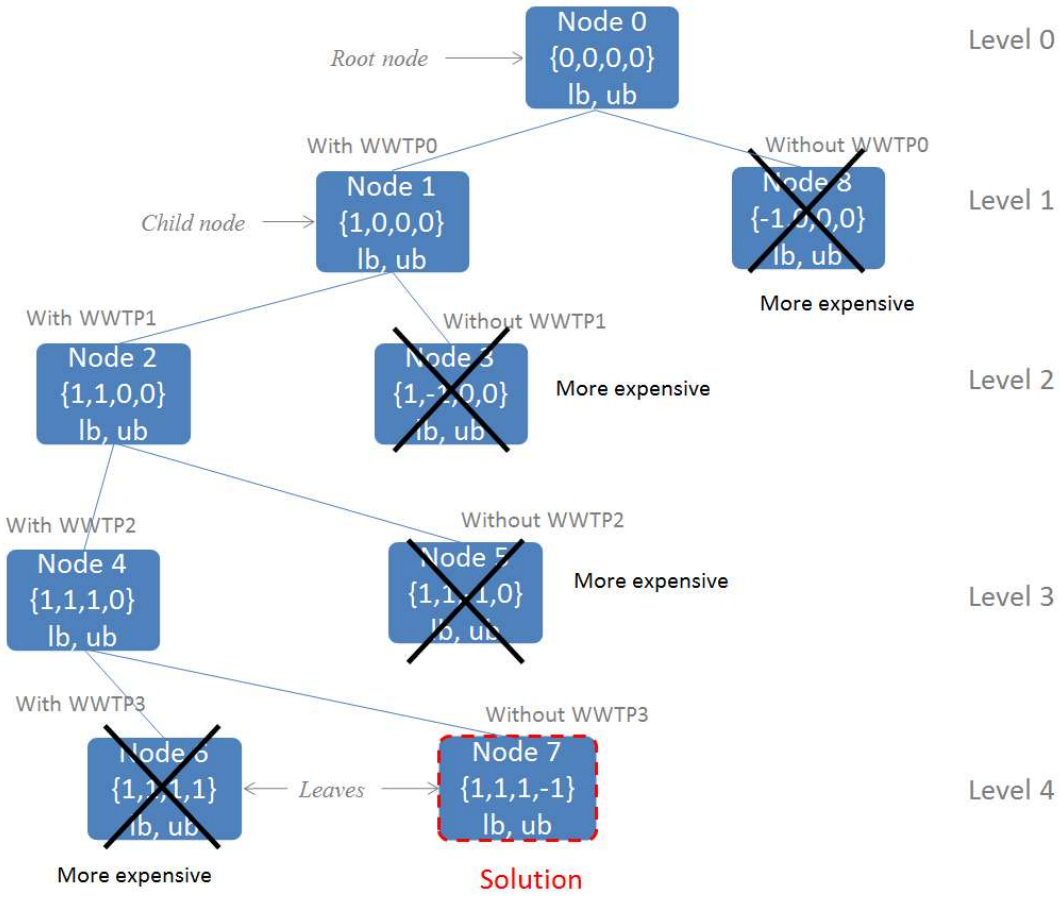



Figure 7-6 Simplified illustration of the branch and bound tree.

An explanation of the main elements of the figure is as follows:

- Tree. Is a directed graph of linked *decision nodes* that does not contain cycles and has an initial decision node called *root*, said to be on *level 0*.
- Branch. It represents a *decision alternative* that emanates from a decision node.
- Leaf. Is a termination node, so no further alternatives are made.

- Decision node. Is a node where a decision between alternatives can be made. Any other decision node *i* is said to be a "child node" on level *l* and is a partial solution, or part of the solution space. Each decision node, depicted as a blue rectangle, is a problem state which, in the example shown in Figure 7-6, contains a solution of wastewater treatment plants {WWTP0, WWTP1, WWTP2, WWTP3} and the pruning values.
- Decision variable. Whether or not to open a wastewater treatment plant from the set of available treatment plant sites. To indicate the state the convention used is: 1= the WWTP is opened, -1 = the WWTP is not opened, and 0= unknown state.
- Pruning values. Lower bound (lb) and upper bound (ub). The lower (or optimistic) bound is the sum of the minimum transmission costs over all WWTPs (either built or being evaluated) and the fixed costs of the WWTPs built. The upper (or pessimistic) bound is the sum of the minimum transmission costs over all built WWTP and their corresponding fixed costs.
- Pruning rules. These determine that it is not worth exploring the "children" of the node being evaluated. The rules are [212]: if the minimum savings from building a WWTP are greater than the WWTPs' fixed cost then build the WWTP, and if the maximum savings from building a WWTP are less than the WWTPs' fixed cost then do not build the WWTP.
- Bound function. It determines that it is not worth exploring the "children" of the node being evaluated. Since the problem is a minimisation problem a node is bounded when its lower bound is greater than the "best solution so far".
- Solution. Since the problem is a minimisation problem it is the node with the upper bound with the lowest value found "so far".

The algorithm begins at the root of the decision tree and explores the decision nodes. The search strategy used in the DSS to evaluate the decision nodes is *breadth first search*. In breadth

first the decision node to be evaluated stays live until all its children have been generated[g], the order of nodes to be evaluated is stored in a *data structure* called a *queue*. A data structure is an efficient representation of data which has applicable rules. Some data structures are queue (first in, first out), stack (last in, first out) and heap (priority queue). Queue is a list that manages data in a *first in, first out* (FIFO) way.

It is assumed that there are no feasibility constraints, e.g. land area, financial or greenhouse gas generation (GHG). In this research the multicriteria selection is accomplished by the Decision_Model class, given that one of the Framework's requirements was that users directly define the shape of the Specification functions, and they are not expected to be experts in deriving mathematical equations (multi-objective functions). The algorithm terminates when there are no more decision nodes to be evaluated either by being pruned or bounded. The solution is the "best solution so far".

Figure 7-7 illustrates the identification of the number of wastewater treatment plants to be opened, and their related sewerage system, under the assumption that the only criterion is the financial cost, and all plants are of the same technology.

On the left-hand side of the figure is the given network, or directed graph, provided by the user. The patterned triangles represent the feasible wastewater treatment plant location, circles represent wastewater collection points, and the blue-dashed lines represent a feasible connection between wastewater collection points. The solution is on the right-hand side: the blue triangles represent wastewater treatment plant sites to be built, and the black lines with an arrow represent the direction of the designed sewerage system, to be precise, the optimal connectivity. The sewerage system is designed by the Sewerage_System_Designer class.

[g] Another strategy is "*depth first*" search in which as soon a child of the node being evaluated is generated, the child becomes the new evaluated node.

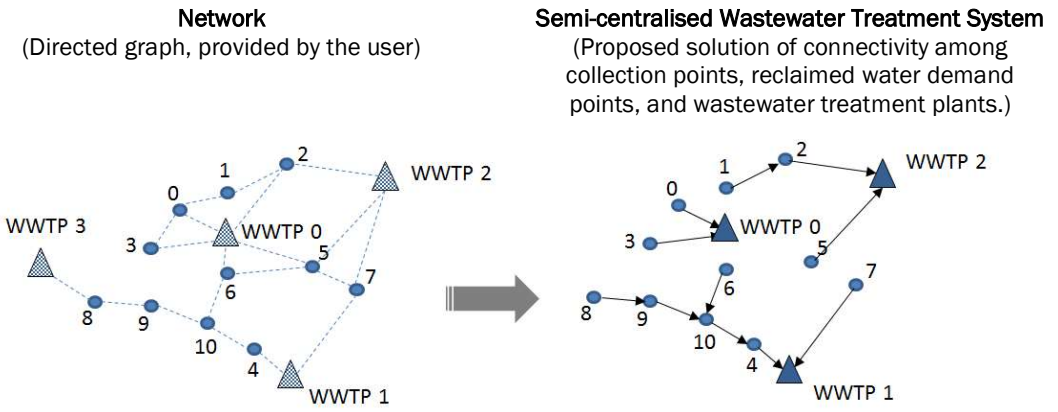



Figure 7-7 Result obtained with Semi-centralised_Wastewater_Treatment_System_Designer.

## 7.4 SEWERAGE SYSTEM DESIGNER

Figure 7-8 illustrates the relationship between the Sewerage_System_Designer class with Graph, Pipeline_Technology, Path_Calculator and Wastewater_Allocator classes. The last two classes are embedded in the GIS module.

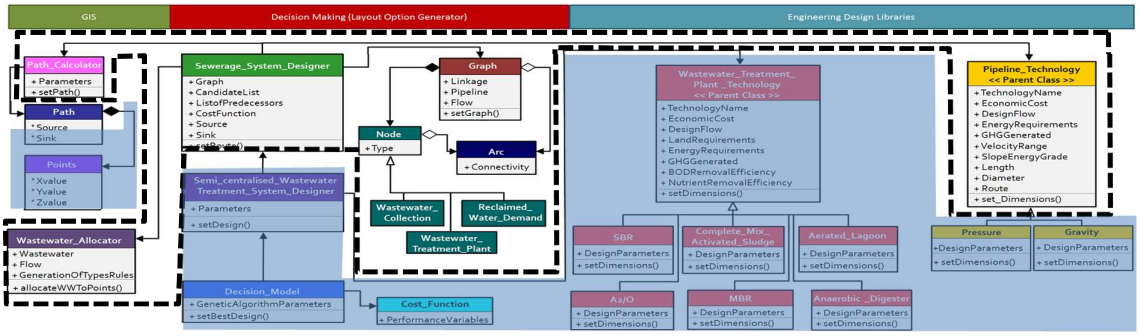



Figure 7-8 Relationships between the Sewerage_System_Designer class with Graph, Pipeline_Technology, Path_Calculator and Wastewater_Allocator classes.

A key parameter of the Sewerage_System_Designer class is Graph. This class is a data structure which is comprised of a collection of Nodes and a collection of Arcs. The solid line and a hollow triangle connecting to Node indicates an inheritance relationship, a feature that allows adding types of nodes. For instance, potential wastewater treatment plants, wastewater

collection points or reclaimed water demand points (see Chapter 4), without having to change the code

### 7.4.1 Hao-Kocur Labelling Algorithm

The Sewerage_System_Designer class computes the shortest route in the network using the **Hao-Kocur algorithm** [213] (see Table 5-1) that builds a shortest path *tree* from a *root* node (a potential wastewater treatment plant facility location) to all other nodes (sewage collection points or reclaimed water demand points) in the network (a directed graph provided by the user). A tree is a directed graph (linked nodes) that does not contain cycles and has an initial node called root. There is a directed route from the root node to all other nodes. The nodes on the route from a given node *i* to the root node are called *predecessors* of node *i*.

The principle of shortest route algorithms is *labelling*. This term refers to defining (1) the value of the cost function from the root of the tree to each node and (2) the predecessor node on the route from the root of the tree to a node.

To identify the predecessor of a node, it is essential (1) to know the arcs out of each node and (2) to keep track of the candidate nodes to add to the shortest route tree as they are discovered or revisited (to *back-track*).

Once the shortest route tree is identified, the sewerage system is generated by tracing back predecessor nodes, a process known as back-tracking. This method is used given the fact that the cost function is not linearly proportional to the flow of wastewater and, consequently, the superposition principle does not apply.

The Hao-Kocur is a label correcting algorithm whereby if an arc is added to the tree, it may be altered later when a better path is found. The algorithm puts the new node at the front of the candidate list if it has been on the list before. It is put on the back of the list if the label is greater than the value of the front node and on the front if the value is smaller than the former front node. Figure 7-9 illustrates the design of a sewerage system (right hand side) given a network, provided by the user (left hand side). Symbols are as used in Figure 7-8. Details of a label

correcting step in the Hao-Kocur algorithm to identify the optimal connectivity are shown in Figure 7-10.

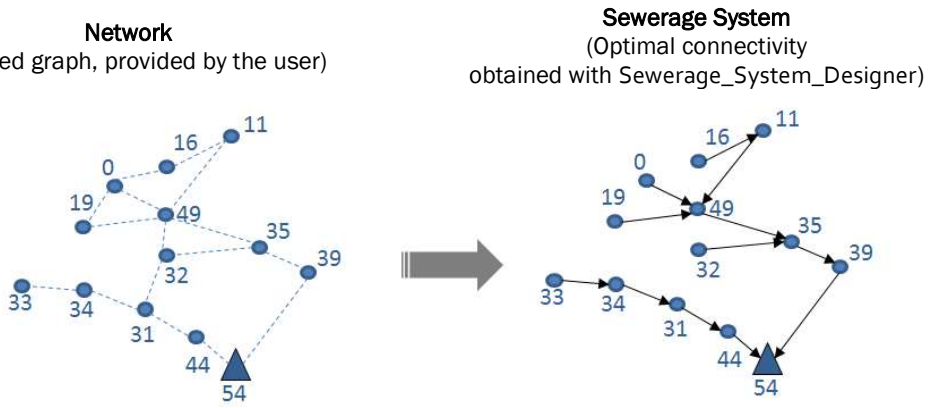
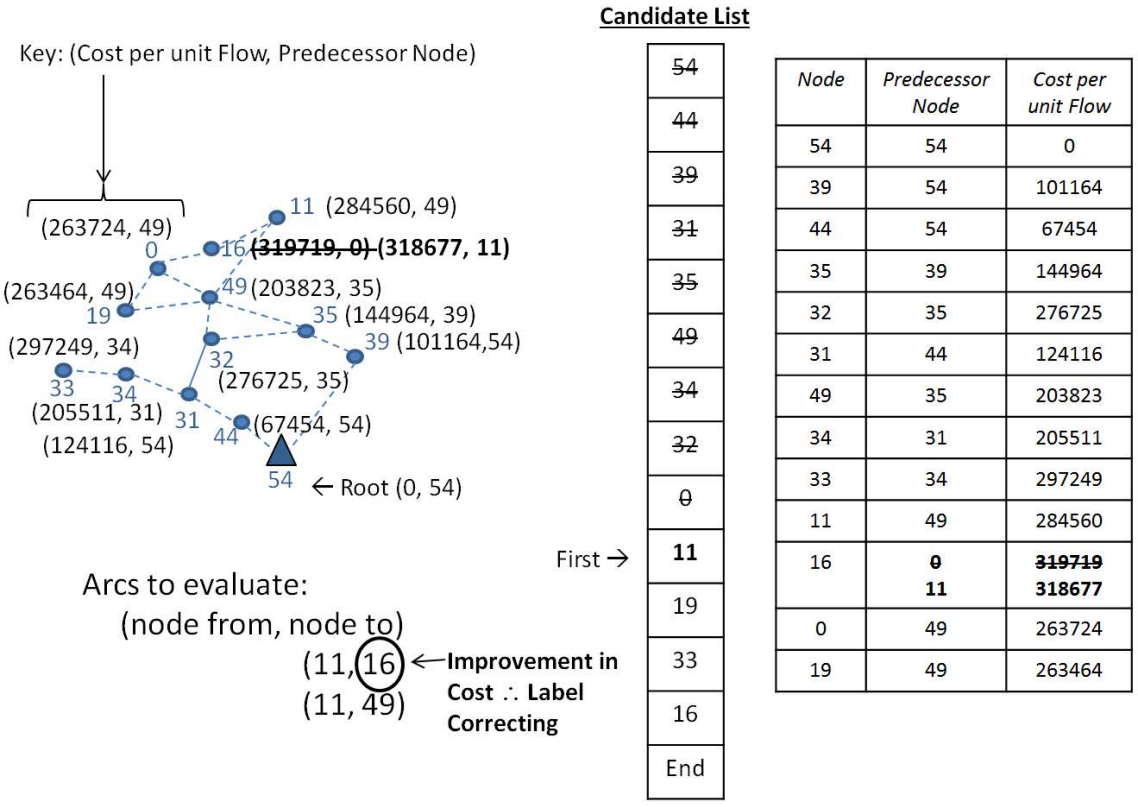



Figure 7-9 Result obtained with Sewerage_System_Designer. Given a network the class identifies the optimal connectivity to design a sewerage system.




| *Node* | *Predecessor Node* | *Cost per unit Flow* |
|---|---|---|
| 54 | 54 | 0 |
| 39 | 54 | 101164 |
| 44 | 54 | 67454 |
| 35 | 39 | 144964 |
| 32 | 35 | 276725 |
| 31 | 44 | 124116 |
| 49 | 35 | 203823 |
| 34 | 31 | 205511 |
| 33 | 34 | 297249 |
| 11 | 49 | 284560 |
| 16 | ~~0~~ **11** | ~~319719~~ **318677** |
| 0 | 49 | 263724 |
| 19 | 49 | 263464 |

Figure 7-10 Detail in the Hao-Kocur algorithm when the label correcting step occurs.

When evaluating the arc connecting nodes 11 to 16 a cheaper connectivity cost between nodes 16 to 11 has been identified (in comparison to the previous connectivity cost between

nodes 16 to 0). Since node 16 is at the rear of the Candidate List and has not been evaluated it stays there, but if it would had already been evaluated, Node 16 would have been placed at the front of the candidate list to re-evaluate connectivity.

### 7.4.2 Multicriteria Decision Analysis - Simple Additive Weighting Method (SAW)

The cost function used in the Hao-Kocur algorithm to identify the shortest route is the Simple Additive Weighting Method (SAW). The inclusion of this method is to facilitate the involvement of decision-makers and experts in the multi-criteria decision-making processes. Additionally, it should be noted that this method is also used in the two components of the GIS Module described in Chapter 10.

The most significant site related factors that impact the pipe cost function, besides soil conditions, is the topography. Topography dictates the burial depth of the gravity lines, influences the number lift stations in a gravity system and the pumping cost in a pressurized system because these depend on the variation of the elevation profile. Section 10.2 describes how the DSS gathers information obtained from the GIS Module to design pipe paths.

This research assumes that decision-makers might like to consider three criteria when determining the optimum route: (1) financial costs (capital investment cost of equipment, and annual operating cost), (2) energy requirements, and (3) Greenhouse gases (GHG) generated from pumping energy requirements in a pipeline. The aim of a multicriteria decision analysis is to reduce each option's performance into a single value (aggregation) to facilitate the ranking process.

The simplicity of this method makes it perhaps the best known and widely used method for multiple attribute decision making. The principle of the method is that a linear additive function that aggregates contributions from each criterion score multiplied by its weight can represent the preferences of decision-makers [214].

A *criterion* is a standard of judgement used to test the desirability of an alternative. Criteria can be tangible (measurable) or intangible (subjective scale). The term *criteria* also comprise attributes and objectives. An *attribute* (not to be confused with the terms introduced on Section 7.2.3) is a measurable qualitative or quantitative property (functionality is related to the attributes).

An *objective* is a statement about the desired state and indicates the directions of improvement (a policy can be an objective). The *weight* of each criterion provides the information about the relative importance of the considered criterion to the decision maker.

The scoring procedure in SAW requires that criteria values must be ordinal (numerical and comparable). Criteria can be in different scaling systems therefore, before aggregation, the method normalises the different measurement units into a common numerical scaling system with values in the interval [0,1]. The consolidated score for each alternative is computed by multiplying the normalised value of each criterion by its weight. Finally, these products are added. In the Additive Weighting Method, the optimization problem is formulated according to the following equation:

$$\Phi_{SAW}(a_i) = \sum_{j=1}^{n} \lambda_j \times r_{ij} \qquad (7\text{-}4)$$

$$\text{s.t. } \lambda \in \Lambda$$

$$\Lambda = \left\{ \lambda \in R \mid \lambda_j \geq 0, \sum_{j=1}^{n} \lambda_j = 1.0 \right\}$$

where

*$\Phi$ = utility or cost of the ith alternative*
*a = **alternative** or **option**. In this research an alternative represents different available choices of action*
*$\lambda$ = criterion weight*
*i = number of alternative*
*j = number of criteria.*
*$r_{ij}$ = normalized preferred ratings of the ith alternative with respect to the jth criterion*

The SAW cost function is the mathematical representation of the decision-makers' judgement values. For instance, the design of a sewerage system could consider how much equivalent carbon dioxide ($CO_2e$) emissions, which quantifies the GHG generated, is generated by the energy requirements of pumps during its operation and maintenance, and the financial construction cost. The best route, according to the decision-makers' requirements, is the alternative with the lowest SAW cost function value.

## 7.5 SUMMARY

The overview of the Decision Making (Layout Option Generator) is presented in Table 7-3.

Table 7-3 Decision Making (Layout Option Generator) overview.

| | |
|---|---|
| **Functionality** | Generate semi-centralised layout design alternatives and rank them in order to identify the recommended one. |
| **Solving approach** | Combination of Branch and Bound to generate information to be used to guide a GA search. |
| **Classes** | • Decision_Model<br>• Semi-centralised_Wastewater_Treatment_System_Designer<br>• Sewerage_System_Designer |
| **Design steps** | 1. The Decision_Model class is the master level class that orchestrates the decision-making process. This class generates alternatives varying the wastewater treatment plant technology in each feasible plant site.<br>2. For each alternative Decision_Model obtains functionality and information from the Semi-centralised_Wastewater_Treatment_System_Designer class, which designs a candidate semi-centralised layout design.<br>3. The Semi-centralised_Wastewater_Treatment_System_Designer class identifies the number of wastewater treatment plants that are worth building from the set of feasible wastewater treatment plant (WWTP) sites and the wastewater collection points to connect to each WWTPs.<br>4. To design the semi-centralised layout. Semi-centralised_Wastewater_Treatment_System_Designer obtains functionality and information from Sewerage_System_Designer, which builds a shortest path tree from a potential wastewater treatment plant facility location to all sewage collection points or reclaimed water demand points.<br>5. The Decision_Model class ranks the alternative layouts designed by the Semi-centralised_Wastewater_Treatment_System_Designer class and after a number of iterations presents the best layout alternative to decision-makers. |

# CHAPTER 8
# WASTEWATER TREATMENT TECHNOLOGIES LIBRARY

Figure 8-1 illustrates the inheritance relationships created in the OOP. A solid line and a hollow triangle connecting the Wastewater_Treatment_Plant_Technology and MBR or SBR classes indicate an inheritance relationship. With this taxonomy it is very easy to incorporate new technologies into the Library. The design of a WWTP with a particular technology is used in the Semi-centralised_Wastewater_Treatment_System_Designer class.

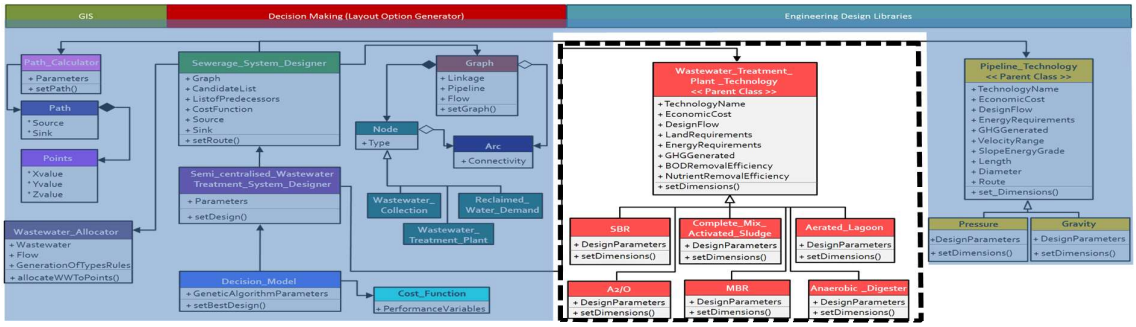



Figure 8-1 Class inheritance of the Wastewater_Treatment_Plant_Technology class.

## 8.1 COSTS EQUATIONS

Cost is a critical parameter that plays an important role in wastewater management strategies [215]. As discussed earlier (e.g. see Sections 5.2 or 2.4), these are rarely publicly available, thus in the absence of specific data and given that this work is intended as a design guide, it sometimes can be helpful to use surrogate cost equations. Cost equations are extremely contextual and accurate ones are rarely available given that engineering firms protected this information. Since the DSS is intended as a design guideline, freely available cost equations [216, 217, 218], although unreliable, were used to illustrate the logic of the approach. Undoubtedly, a release version of the DSS must require collaboration with an engineering firm to use reliable, site-based equations.

For the Lagoon, Complete Mix and A2/O technologies the costs equations were generated based on data extrapolated from different sites, thus probably not allowing the accurate reproduction of cost on a given locality under analysis. Given that the cost equations used were found in sources prepared in different years, all costs where either scaled up or down to 2010 US dollars using cost factors [219,220]. Ideally real site-specific cost equations should be used.

According to the American Association of Cost Engineers (AACE), there are three levels of cost estimate throughout the design process: order-of-magnitude, preliminary (early phase of the project) and definitive [221]. In this project the cost level is of the order-of-magnitude level. This has an accuracy between +50% to -30% with a recommended contingency between 20 to 30% [222].

Costs are subdivided into investment (capital) and operating costs. Operating costs can be fixed (costs related to the plant size or unit size e.g. fixed power requirements of an office building) or variable (power and chemical consumption depending on the wastewater inflow quality). Variable costs require the development of specific cost functions and thus are dependent on the simulation.

Capital and total operating cost equations for wastewater treatment plants are quantified as a function of global plant parameters (e.g. flow rate) and are expressed either by power laws of the form $y = a \cdot x^b$ (where a and b are calculated coefficients) or other polynomial functions. Table 8-1 shows the breakdown in the capital cost equations, whereas Table 8-2 shows the operation and management (O&M) cost breakdown. The annualised construction and O&M cost equations used in this research are shown on Table 8-3.

Costs are expressed as annualised cost values (AC):

$$AC = FRC_{PP} \sum_{k=1}^{N} IC_k + \sum_{k=1}^{N} OC_k \qquad (8\text{-}1)$$

$$FRC_{PP} = \frac{(1+int)^{npp}}{(1+int)^{npp} - 1} \quad (8\text{-}2)$$

where

$IC_k$ = investment cost of a unit k
$OC_k$ = operating cost
$FRC_{PP}(int, npp)$ = annual plant cost return coefficient
*int* (%) = annual interest = 5
*npp* (years) = life span of the wastewater treatment plant = 30

Table 8-1 Wastewater treatment plant capital cost breakdown [217].

| Factor | Capital Cost (2010 USD$) |
|---|---|
| Equipment cost | Technology-specific |
| Installation | 25 to 35 % of Equipment cost |
| Piping | 31 to 66 % of Equipment cost |
| Instrumentation and control | 6 to 30 % of Equipment cost |
| Subtotal | Equipment + Installation + Piping + Instrumentation and control |
| Contractor overhead and profit | 15 % of subtotal |
| *Total Construction Cost, $* | Subtotal + Contractor overhead and profit |
| Engineering/Legal/Administration | 15 % of Total Construction Cost |
| Contingency | 15 % of Total Construction Cost |
| Land | |
| Total Indirect Cost | Engineering + Contingency |
| *Total Capital Cost, $* | Total Construction Cost + Total Indirect Cost |
| Interest rate | (e.g. 5%) |
| Number of years | (usually 30 years) |
| P/A (per annum) Factor | |
| *Amortized Capital Cost, $/yr* | Total Capital Cost / PA |

Table 8-2 Wastewater treatment plant O&M cost breakdown [217].

| Factor | O&M (2010 USD$/year) |
|---|---|
| Maintenance | 4 % of Total Capital Cost |
| Taxes and Insurance | 2 % of Total Capital Cost |
| Labour | Region specific |
| Electricity | Technology specific and region specific |
| Chemicals | Technology specific |
| Residuals Management | Technology specific |
| *Yearly Total O&M Cost, $/yr* | Maintenance + Taxes and Insurance + Labour + Electricity + Chemicals + Residuals Management |
| Interest rate | (e.g. 5%) |
| Number of years | (usually 30 years) |
| P/A (per annum) Factor | |
| *Total O&M Cost, $* | Yearly Total O&M Cost * PA |

Table 8-3 Cost Functions per technology.

| WWTP Technology | Annual Operation (OM) and Management | | Annualised Construction Cost | |
|---|---|---|---|---|
| Lagoon (MM USD$) | $= 0.0607 + (0.00000331\ Flow_{ww})$ | ( 8-3 ) | $= FRC_{PP}\ 0.0143\ Flow_{ww}^{\ 0.681}$ | ( 8-4 ) |
| MBR [223] (MM USD$) | $= \frac{0.0114 + (0.00005\ Flow_{ww})}{CF}$<br>CF = 0.866, conversion factor from 2004$ to 2010 | ( 8-5 ) | $= \frac{FRC_{PP}\ 0.032614\ Flow_{ww}^{\ 0.7005}}{CF}$<br>CF = 0.866 conversion factor USD$2004 to USD$2010 | ( 8-6 ) |
| Complete Mix (MM USD$) | $= 0.05249 + (0.0000131\ Flow)$ | ( 8-7 ) | $= FRC_{PP}\ 0.0031\ Flow^{0.881}$ | ( 8-8 ) |
| SBR [217] (USD$) | $\ln(C) = \frac{1}{CF}(13.139 + 0.562\ln(flow_{ww}) + 0.02\ln(flow_{ww})^2)$<br>CF = 0. 569 conversion factor USD$1989 to USD$2010 | ( 8-9 ) | $\ln(C) = \frac{1}{CF}(15.707 + 0.512\ln(flow_{ww}) + 0.0022\ln(flow_{ww})^2)$<br>CF = 0. 569 conversion factor USD$1989 to USD$2010 | ( 8-10 ) |
| Anaerobic digester [224] (MM USD$) | $= 125.89\ Flow_{sludge}^{-0.208}\ XR$<br>XR = 1.37 exchange rate Euro to US Dollar | ( 8-11 ) | $= 865.43\ Flow_{sludge}^{-0.688}\ XR$<br>XR = 1.37 exchange rate Euro to US Dollar | ( 8-12 ) |

## 8.2 $CO_2E$ EQUATIONS

Tables 8-4 and 8-5 describe the methods used to compute the value of equivalent carbon dioxide ($CO_2e$) emissions, depending on the emission sources. Greenhouse gas generation (GHG) is included as a performance measure to assess the carbon footprint of a particular wastewater treatment plant. The quantified carbon sources include direct and indirect GHG emissions of the treatment process.

Table 8-4 $CO_2e$ emission calculation. Adapted from [225].

| Type | Emission sources | Method | Equation | | Reference |
|---|---|---|---|---|---|
| Direct | ***$CO_2$ emissions*** | | | | |
| | Aerobic treatment | Stoichiometric relationships from oxidation of substrate and endogenous decay of active biomass. The elemental composition of BOD and biomass is represented as $C_{10}H_{19}O_3N$ and $C_5H_7O_2N$. | Biomass yield: $2C_{10}H_{19}O_3N + 25O_2 \rightarrow 20CO_2 + 16H_2O + 2NH_3$ | ( 8-13 ) | [20,226] |
| | | | Decay of biomass: $C_5H_7O_2N + 5O_2 \rightarrow 5CO_2 + 2H_2O + NH_3$ | ( 8-14 ) | |
| | Post-combustion of biogas | Stoichiometric relationships from combustion of methane | $CH_4 + 2O_2 = CO_2 + 2H_2O$ | ( 8-15 ) | [20] |
| | ***$N_2O$ emissions : will be multiplied by a conversion factor to obtain $CO_2e$ = 310*** | | | | |
| | Biosolids applied to agricultural land | Emissions obtained by multiplying total N content of sludge applied to land by an emission factor.<br>**Sludge Origin** / **N content (g N/g Dissolved Solids)**<br>Raw sludge: 0.044<br>Sludge treated by Anaerobic Digester: 0.038 | $N_2O\ (land)\text{-}N = F_{ON}\ EF\ 44/28$<br>$N_2O$ (land) -N = direct $N_2O$-N emissions from organic soils (kg $N_2O$-N /year)<br>$F_{ON}$ = amount of N in biosolids applied to soils<br>EF = emission factor from N inputs, kg $N_2O$-N /kg N input, IPCC default value: 0.01 for sewage sludge<br>44/28 is the conversion factor of $N_2O$-N emissions to $N_2O$. | ( 8-16 ) | [227] |
| | Indirect emissions from volatilisation, leachate and runoff | Emissions obtained by multiplying total N content of sludge applied to land by an emission factor.<br>Emissions from volatilisation assume that 20% of the applied N is volatile and 0.01 kg of $N_2O$-N will be emitted for each kg of $NH_3$-N + $NO_x$-N volatilised. | $N_2O\ (leachate\ and\ runoff) = sludge\ EF\ 44/\ 28$<br>sludge = sludge production (kg/year)<br>EF = emission factor of 0.0043 kg $N_2O$-N/kg total N applied. It is assumed that 30% of the N applied is lost through this leachate and 0.0075 kg of $N_2O$-N will be emitted for each kg of N leaching and runoff from land. These two indirect emission sources together give the value. | ( 8-17 ) | |
| | Discharge of wastewater effluent to water body | Emissions obtained by multiplying total N content of effluent by an emission factor | $N_2O\ (ww) = N_{\ effluent}\ EF_{\ effluent}\ 44/28$<br>$N_2O$ (ww) = total $N_2O$ emissions from wastewater effluent (kg $N_2O$ /year)<br>$N_{\ effluent}$ = nitrogen in the effluent discharged to aquatic environment (kg N/year)<br>$EF_{\ effluent}$= emission factor for $N_2O$ emissions from discharged to wastewater, kg $N_2O$-N/kg N, IPCC default value: 0.005<br>44/28 is the conversion of kg $N_2O$-N into kg $N_2O$ | ( 8-18 ) | |

Table 8-5 $CO_2e$ emission calculation (Continuation). Adapted from [225].

| Type | Emission sources | Method | Equation | | Reference |
|---|---|---|---|---|---|
| Direct | *$CH_4$ emissions : will be multiplied by a conversion factor to obtain $CO_2e$ =21* | | | | |
| | Wastewater treatment | Emissions obtained by multiplying total biosolids by an emission factor | $CO_2$ (treatment process) = sludge EF<br>Sludge = sludge production (kg/year)<br>EF = Emission Factor = 2.7 kg CH4/t (raw) dissolved solids | ( 8-19 ) | [225] |
| | Biogas production | Emissions obtained by multiplying total biosolids processed in the anaerobic digestion by an emission factor | $CO_2$ (biogas generation) = sludge EF<br>Sludge = sludge production (kg/year)<br>EF = Emission Factor = 4.63 kg CH4/ton raw dissolved solids | ( 8-20 ) | |
| | Biosolids applied to agricultural land | Emissions obtained by multiplying total biosolids applied to land by an emission factor | $CO_2$ (biosolids applied to land) = ASL EF<br>ASL = sludge applied to land (kg/year)<br>EF = Emission Factor = 0.55 kg CH4/ton (raw) Dissolves solids | ( 8-21 ) | |
| Indirect | Grid electricity usage by aeration requirements | $CO_2e$ emission is obtained by multiplying the source of electricity grid by an emission factor. | $CO_2e$ (indirect) = Energy PEM EF<br>Energy = aeration energy requirements<br>PEM = percent in energy mix<br>EF = emission factor<br>**Electricity Source** / **Emission Factor g $CO_2e$/kWh**<br>Hydropower 4<br>Gas 506<br>Biomass 18<br>Nuclear 16<br>Oil 731<br>Coal 1001<br>Wind 12 | ( 8-22 ) | [228] |

## 8.3 LAND REQUIREMENT EQUATIONS

Land requirements equations were obtained from peer reviewed papers [216] and USA environmental agency reports [217]. The land requirements include equipment (e.g reactors), miscellaneous equipment (e.g. pumps, access areas, etc.), offices and buffer areas. Land requirement equations for wastewater treatment plant technologies are provided in Table 8-6.

Table 8-6 Land requirement equations.

| WWTP Technology | Land requirement ($m^2$) | |
|---|---|---|
| Lagoon | $= Complete\ Mix\ Area(\text{equation}) * 1.5$ | (8-23) |
| MBR | $= 0.25 \cdot 1.467 \cdot Flow^{0.985}$ | (8-24) |
| | On average MBR plant size is 25% of that of Complete Activated Mix | |
| SBR [217] | $= CF \cdot e^{-0.531+(0.906\log(flow))+(0.072\log(flow)^2)}$ | (8-25) |
| | CF = 4046.86 conversion factor from acre to $m^2$ | |
| Complete Mix | $= 1.467 \cdot Flow^{0.985}$ | (8-26) |

## 8.4 SUMMARY

The design of a WWTP is highly site-specific. Average performance of WWTPs often suffers uncertainties. Unless very similar plant configurations are considered or simulation data to estimate operating cost are obtained (which is not within the scope of this work) the values reported in this Thesis only provides estimations.

# CHAPTER 9
# PIPELINE TECHNOLOGY LIBRARY

The class diagram in Figure 9-1 shows the incorporation of new technologies into the library. A solid line and a hollow triangle connecting the Pipeline_Technology and Pressure or Gravity classes indicate an inheritance relationship. With this taxonomy it is very easy to incorporate new technologies into the Library. A specification of the DSS is the design of separate sanitary sewerage and water supply system**.** The pipes designed are used by the class Semi-centralised_Wastewater_Treatment_System_Designer.

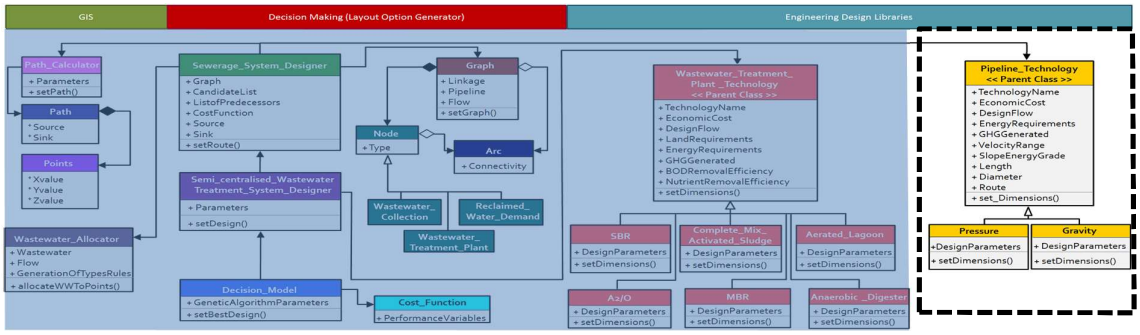



Figure 9-1 Simplified class diagram of Pipeline_Technology class.

## 9.1 SEWER DESIGN CONSIDERATIONS

The pipeline technology library designs a main separate sanitary sewerage system. That is, a collection of underground pipes that transmit exclusively municipal wastewater to a treatment or disposal system. This type of sewerage system was selected because it is assumed that the SCUWWTS would be implemented in a planned urban area built from scratch in which harvesting rainwater run-off would be another strategy set in place for collection and recycling water. Table 9-1 presents some of the advantages and disadvantages of the separate collection system.

Table 9-1 Advantages and disadvantages of separate sewerage systems. Adapted from [20].

| Advantages | Disadvantages |
|---|---|
| • The capacity of the water treatment plant will be smaller since only domestic sewage is to be treated<br>• Operational problems are reduced<br>• Higher potential for resource recovery | Storm water may always find its way into the domestic sewerage system and overload the sewage treatment plant either through wrong house sewer connections or through manholes. |

There is a variety of collection system design methodologies, so the selection of the appropriate sewerage depends on the characteristics of the area to be served. The design of sewerage requires an integrated study of the area to be served. To begin with it is important to evaluate the characteristics of the site: topography, climate, type of soil, depth of freezing zone, groundwater conditions and information on existing structures and utilities. Once these data are available the flow rate is calculated.

The design and construction of the collection system must comply with highly site-specific design standards and legislations. Standards and legislations dictate issues and criteria applicable to: Right-Of-Way (ROW), type of pipeline material, available pipeline diameters, corrosion protection, maintenance requirements, maximum and minimum flow velocities, discharge pressures, lift stations, pump selection, and manhole spacing, among other factors.

Construction standards for collection systems can be broadly classified into “conventional” and “alternative” (or “simplified”). The former refers to those widely used in developed countries, whereas the latter is particularly important as a sanitation option in peri-urban or low-income areas of developing countries because conventional collection systems are generally too expensive [229,230]. The construction standards can be applied to either separate or combined sewerage systems.

Alternative types of collection systems include: (a) conventional gravity flow systems, (b) STEG (septic tank effluent gravity) collection systems (c) STEP (septic tank effluent pump) pressure collection systems, (d) grinder pump pressure collection systems, and (e) vacuum collection systems [20].

The following sections describe the "conventional" collection designs that are widely used in developed countries: gravity and pressure systems. These are the standard systems to which "alternative" systems are generally compared.

### 9.1.1 Design Flow Rate

The first consideration in the design of a collection system is the peak flow rates for the area to be served. Wastewater flow rate is influenced by land use (residential, commercial, institutional or industrial), population growth, economic growth, cultural values, infrastructure integrity and climate. The flow and concentration of wastewater varies with time and at different scales (hourly, daily, seasonally, and yearly). For example, the flow rate reflects daily household activities; it shows peaks in the morning and afternoon, whereas it has a minimum at night. Such factors must be considered in the design, operation, and control of a wastewater treatment plant.

Collection system projects are normally designed to meet the requirements of the twenty to thirty-year period following the project completion. A wide variety of methods have been developed to estimate the peak flow rate. The selection of the method to be adopted for the service area depends largely on the factors considered and the experience of the design team.

In the design of a pipeline, it is important to consider infiltration which is expressed in terms of an infiltration coefficient, which is a function of the pipe diameter: 0.01 to 1.0 $m^3$ $day^{-1}$ $km^{-1}$ per mm [20]. In this research project it was assumed that the utilisation of good materials and construction procedures would be applied; therefore, the infiltration value will not significantly change the peak flow value.

### 9.1.2 Hydraulic Design Equation

After determining the design peak flow rate, it is necessary to determine the diameter of the pipe that will convey the wastewater. The adequate pipe size is selected by using hydraulic principles. Two important parameters that govern the selection of pipe size are velocity and

headloss or pressure drop. There are various equations to calculate such parameters. The formulas used in the Pipeline Technology Library are for the relatively less energy intense systems, at least in comparison to that required by Vacuum Sewer:

- **Gravity Sewer**. The principle is that wastewater is conveyed by gravity, although pumping lift stations might be required to reduce pipe's depth (construction costs rise with depth of pipe).
- **Pressure Sewer**. Wastewater transmission under pressure by pumps, thus this system is an energy intensive one.

Topography is a critical factor in the sewerage design: thus, a gravity system, wherever possible, is the standard design option. Nevertheless, a combination of gravity and pressure systems are regularly used when the natural slopes are not sufficient to promote flow. Vacuum sewers are required on flat terrains [231]. The empirical Manning's equation is commonly used to determine the adequate pipe diameter. The average cross-section velocity equation $Vg$ (m $s^{-1}$) is:

$$V_g = \frac{1}{n} R_h^{0.667} J^{0.5} \qquad (9\text{-}1)$$

Where

*$Vg$ (m $s^{-1}$) = velocity of flow*
*$n$ = Mannings's coefficient*
*$R_h$ (cm) = hydraulic radius*
*$J$ = pipeline slope*

$$J = h_f / L$$

$$R_h = A/P$$

Where

*$h_f$ = fall*
*$L$ (m) = length of pipeline*
*$P$ = wetted perimeter. For gravitational pipelines it is considered as a standard that flow is in a non-full cross-section of 80% of the pipeline's diameter. For pipes flowing full:*

$$R_h = D/4$$

Where

*$D$ (cm) = pipeline diameter*

The pipe design involves the selection of the material that will provide the adequate performance required for a particular goal. For instance, if the pipe must support high loads, ductile iron pipe is often used, yet this material is susceptible to corrosion both from acid attack and hydrogen sulphide build- up.

It should be noted that the head loss along a pipe is influenced by the friction losses due to the pipe's material. Typically used pipe materials include reinforced concrete, pre-stressed concrete, polyvinyl chloride (PVC) or metal reinforced polyethylene (MRP). A Mannings's headloss coefficient (n) of 0.010 for PVC and 0.013 for Concrete are usually recommended for new sewers. The minimum pipe size ranges could be from 150 to 375 mm in diameter and the maximum for the Metal Reinforced Polyethylene (MRP) can be up to 3000mm.

For the design of a conventional gravity flow pipeline, the value of the pipeline slope is used to determine the suitability of the pipe diameter. In general, the slope should fall between 0.5 and 0.15 percent (m $m^{-1}$) [232]. The design should consider that there is a maximum excavation depth because it is expensive and perhaps impractical to excavate below a given depth value.

Standards specify minimum and maximum velocity requirements to avoid particle accumulation, to protect the pipeline and to avoid excessive friction loss. In general, the values for such velocities are 0.6 m $s^{-1}$ and 2.5 m $s^{-1}$, respectively.

Sewerage failure is a costly consequence of sewer corrosion: besides the obvious loss of structural integrity and a system prone to infiltration/inflow, the sewerage is susceptible to back-up during storm season. This is because corrosion increases pipe roughness and as a result the pipe's design flow rate is reduced.

## 9.2 COST EQUATIONS

Tables 9-2 to 9-5 illustrate the pipe cost equations implemented in the DSS. The cost functions were taken from Brand and Ostfeld [128] who based the selection of model coefficients on an Israeli price list database specialized in civil engineering and construction. It was planned to evaluate the impact of cost equations in the layout of a SUWWTS, so the selection of this equation was somewhat arbitrary. However, it is sufficient for exemplar purposes. Sewerage costs are highly site-specific, to begin with, the pipe path is determined by the topography and soil. As mentioned in Section 4.4.3 the path is computed in the GIS module.

Table 9-2 Pressure Pipeline cost equations [128].

$$C_{PP} = FRC_{PP}(int, npp)\ 382.5\ D_P^{1.455}\ L \quad (9\text{-}2)$$

where

$C_{PP}$ ($/year) = annual pumping pipeline construction cost
$FRC_{PP}$(int, npp) = annual pipe cost return coefficient
*int* (%) = annual interest = 7
*npp* (years) = life span of the pipeline = 40
$D_P$ (cm) = pipeline (steel) diameter for pumping line
L (km) = pipeline length

$$FRC_{PP} = \frac{(1+int)^{npp}}{(1+int)^{npp} - 1} \quad (9\text{-}3)$$

$$C_{PC} = FRC_{pu}(int, npu)\ 64920\ P^{0.33} \quad (9\text{-}4)$$

where

$C_{PC}$ ($/year) = annual pump construction cost
$FRC_{pu}$*(int, npu)* = annual pump cost return coefficient
*npu* (years) = pump life span = 15
P (W) = pump power

$$P = 3.454\ \Delta h\ Q + 6409\ (Q^{2.852}\ D_P^{-4.87}\ L) \quad (9\text{-}5)$$

where

$\Delta h$ (m) = total head difference along the line (elevation difference between two points)
$Q$ ($m^3/h$) = flow through pipeline

$$C_{EP} = \frac{EC\ HR}{1000}\ [3.454\ \Delta h\ Q + 6409\ (Q^{2.852}\ D_P^{-4.87}\ L)] \quad (9\text{-}6)$$

where

$C_{EP}$ ($/year) = annual pump energy cost
*EC* ($/kWh) = energy cost
*HR* (h/year) = number of annual pumping operational hours = 8760

Table 9-3 Gravitational pipeline shallow excavation cost equations [128].

The gravitational pipeline construction cost equations' variables are shown in Figure 9-2:

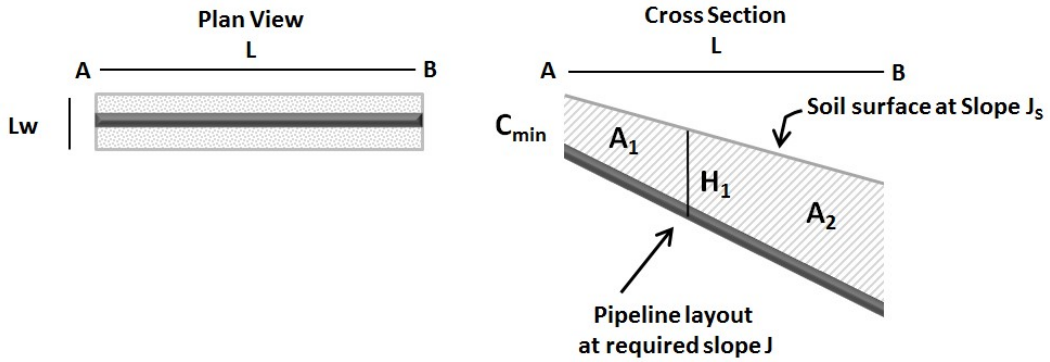



Figure 9-2 Pipe construction variables.

where ( 9-7 )

L = pipeline length

$L_w$ = pipe excavation width (pipe diameter + space between the pipeline and the excavation on both of its sides)

$C_{min}$ = minimum pipeline depth

$H_1$ = least excavation cost to a depth of H1

$A_1$, $A_2$ = excavation areas to and above a depth of H1.

Construction cost Shallow excavation (for $H_l \leq 4$ m)

$$C_{PG} = FRC_{pg}(int, npg)\left[21.6\, D_g^{2.26}\, L + 7\frac{Hl^2 - C_{min}^2}{2\,(J - J_S)}\, L_W\right]$$

Table 9-4 Gravitational pipeline deep excavation cost equations [128]

$$C_{PG} = FRC_{pg}(int, npg)\left[21.6\, D_g^{2.26}\, L + 7\frac{Hl^2 - C_{min}^2}{2\,(J - J_S)}\, L_W + 10\left[L\, C_{min} + \frac{L^2}{2}(J - J_S) - \frac{Hl^2 - C_{min}^2}{2\,(J - J_S)}\right] L_W\right] \quad (9\text{-}8)$$

where

$C_{PG}$ ($/year) = annual gravitational pipeline construction cost

$FRC_{pg}(int/npg)$ = annual pipe cost return coefficient

*npg* (years) = life span of the pipeline = 40

$D_g$ (cm) = pipeline diameter for gravitational pipelines

$H_l$ (m) = least excavation cost depth (above which the cost of excavation increases) = 4

$C_{min}$(m) = minimum pipeline depth = assumed very close to surface (approximately zero)

$L_W$ (m) = pipe excavation width = pipe diameter + 0.6 (m)

$J_S$ = soil slope

*J* = gravitational pipeline slope required

$$FRC_{Pg} = \frac{(1 + int)^{npg}}{(1 + int)^{npg} - 1} \quad (9\text{-}9)$$

where

*int* (%) = annual interest = 7

*npg* (years) = life span of the pipeline = 40

Table 9-5 Pressure and gravitational energy equations [128].

$$E = P\,O \quad (9\text{-}10)$$

where

*E* (kWh) = annual energy requirement
*P* (kW) = annual pumping power requirement
*O* (h) = annual operating hours = 8760

$$P = \frac{g\,Q\,C\,\rho}{1000\,\varepsilon} \quad (9\text{-}11)$$

where

*P* (kW) = annual pumping power requirement [233]
*g* (m/s$^2$) = gravity = 9.81
*Q* (m$^3$/s) = flow rate
*C* (m) = pressure head
ρ (kg/m$^3$) = density wastewater = 1000
$\varepsilon$ = pump efficiency = 0.77 (for radial pump) [24]

$$C = C_{min} + (S\,L) - \Delta h \quad (9\text{-}12)$$

where

*C* (m) = pressure head
$C_{min}$(m) = minimum pipeline depth
$\Delta h$ (m) = total head difference along the line (elevation difference between two points)
*L* (m) = pipeline length
S = hydraulic slope (slope pipeline layout, minimum slope of 0.08%)

## 9.3 $CO_2E$ EQUATIONS

Indirect GHG are included using local data on electricity supply mix (see Table 8-5).

## 9.4 SUMMARY

The values stored as default in the DSS are intended to provide estimations. The design and cost of sewerage is highly site-specific, hence the limitations of the equations used are acknowledged.

# CHAPTER 10
# GEOGRAPHIC INFORMATION SYSTEMS

This module is integrated by two classes:

- **Path_Calculator**. This class integrates urban socio-economic factors and topography. Its functionality is to calculate the pipe path from a destination point to a source, its specifications are (x,y,z) point coordinates and length.
- **Wastewater_Allocator**. This class integrates changes in wastewater generation driven by socio-economic factors through an "organic" process of cultural values or the enactment of public policies, such as incentives in urban development (e.g. raising household income, population density targets) or environmental conservation. Its functionality is to calculate the generation of wastewater in each "collection point."

The information obtained in this module is used by the Sewerage_System_Designer class.

## 10.1 TECHNICAL BACKGROUND

Spatial data is stored in two data types: (1) *raster* and (2) *vector*. A raster is like a digital image represented by a pixel grid; it is a matrix of equally sized cells arranged in rows and columns, and composed of single or multiple bands. Each cell contains an attribute value and location coordinates [234].

A raster data set that contains elevation information is called a *digital elevation model* (DEM). NASA's DEM from the Shuttle Radar Topographic Mission (SRTM) is a breakthrough in digital mapping by providing accessibility of high-quality elevation data for large portions of the world [235]. Sometimes the SRTM raw DEM has a land surface pixel value with "no data", in the jargon this is referred to be *void*, and this makes it necessary to apply pre-processing before using the DEM.

A vector data type stores geographical features as geometrical shapes: points, lines (e.g. roads) and polygons (e.g. urban areas, water bodies), which are linked to an entry in a database that describes their attributes. The ArcMap vector file format is called *shapefile* [236].

Common to both data types are the basic steps to any spatial analysis:

1. To flatten the Earth's spatial data via a mathematical process called *projection* onto a planar surface. There are many types of map projection that are used in one particular part of the world e.g. Universal Transverse Mercator Projection in which the coordinates of a point are given as Easting (meters), Northing (meters). A projection aims to represent the shapes of the map accurately, to ensure that the distances measured on the map are accurate, to represent the areas on the map proportionally to their true area on the Earth and to represent the directions between points on the map accurately.
2. To set the *datum* to provide a frame for defining local coordinate systems: latitude and longitude [237]. The datum is a mathematical model that consists of a series of numbers that define the shape and size of the Earth's spheroid and its orientation in space. There are several datums to give the best possible fit to the true shape of the Earth for one particular part of the world, e.g. WGS-84 (the most recent one). The Latitude and Longitude geographic coordinates of a point are expressed in the format Degrees, Minutes, Seconds: ( ° , ' , " ).

## 10.2 PATH CALCULATOR

Figure 10-1 presents how the Path_Calculator class is related to Path class, which stores the destination (or sink) and source points. Path class is an aggregation of Point, which stores the height profile (x,y,z) specification. The Path_Calculator class implements a method that produces a dataset of the cost of building a path through a landscape, in terms of the influence of two parameters: slope and elevation. Table 10-1 describes the data required, its sources and its pre-processing steps.

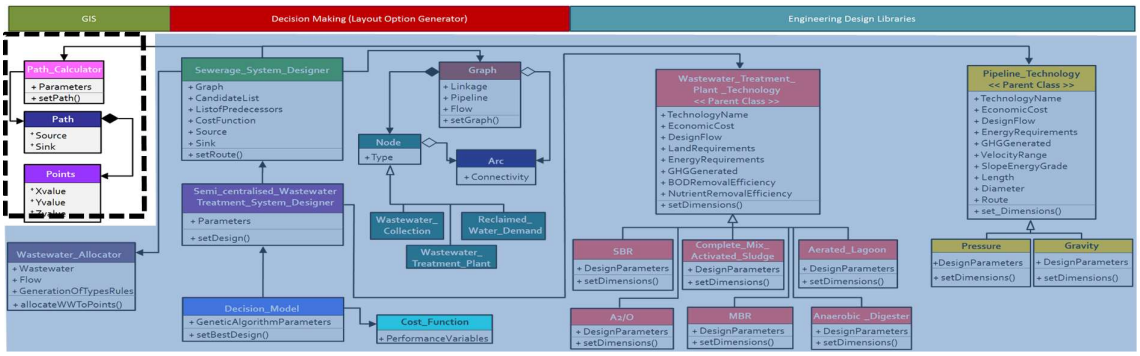



Figure 10-1 Relationship between the Path_Calculator class and Path classes.

Table 10-1 Data required and their pre-processing steps.

| Data | Source | Pre-processing steps |
|---|---|---|
| Elevation (DEM) | Provided by the user. | Merge and fill void raster values. |
| Slope | Calculated from the DEM. | |
| Exclusions (e.g. national parks, water bodies) | Provided by the user. | Data resampled to DEM's resolution. |

The Slope and Elevation rasters were *reclassified* (a method to standardise values) into a common scale to account for the differences in data units. The output is a raster with pixels classified into categories. By default, the program classifies using different methods, such as the "Manual Method" or "Equal Intervals", to capture the preferred values. In this research the "Manual Method" is used because the user can manually reclassify in a scale from 1 to 10, with an increase of 1 unit, the values of the scale to represent perceived adequateness, 1 represents the best value.

The commonly scaled or reclassified data sets are further combined, indicating their relative weights or percentage of influence; this is a multi-attribute decision technique [238]. Percentage values of the influence of each data set can express subjectivity. As such, the user could define the weight of the parameters; subsection 10.2.1 provides an example of the weight influence. By default, this research assumes that all data sets have equal influence.

The resultant weighted map is called a "cost raster" in which locations with low values indicate areas where it would be least costly to build a path since it would be costlier to traverse

steep slopes or construct a path on certain land-use types. With the cost raster, or cost surface, and the source site a raster is produced to show the accumulated cost of traveling from any cell, or pixel, to the source cell. An additional raster is generated to show the path from any cell to the source cell following the least costly path.

An analogy of the algorithm would be that of a hiker that decides his/her next step on the least costly option: the cost raster is interpreted as a labelled graph. The algorithm uses a node/arc representation, each centre of a raster is considered a node and each node is connected to its adjacent nodes by arcs [239]. That is, cells ($i$,$j$) and ($i$',$j$') are connected by a bidirectional arc only when they are adjacent to each other. The cost of that arc is the average of the costs in the two cells multiplied by the distance between their centres; $i$, $i$', $j$, and $j$' are integer row and column indexes in the raster. A cost-based priority queue is generated.

The standard method to find the solution to the single-source shortest path problem in graph theory is *Dijkstra's algorithm* [240,241]. The algorithm begins by putting all origins into the priority queue with a cost of zero to reach them. The iteration step extracts the least-cost cell $C$ in the queue, marks it, and then inserts all unmarked cells directly reachable from arcs emanating from $C$. To these it assigns costs equal to the cost of reaching $C$ plus the cost of each arc. It also associates a pointer back to $C$ ("back-link") with each of those nodes.

When the destination cell is encountered, its cost is immediately known. A least-cost path back to some origin is obtained by following the chain of back-links. If no destination is specified, the algorithm continues until all nodes are exhausted, thereby creating a "least cost" grid (and, optionally, an associated grid of back-links) for the set of source locations.

Figure 10-2 illustrates the procedure to calculate the path between two points.

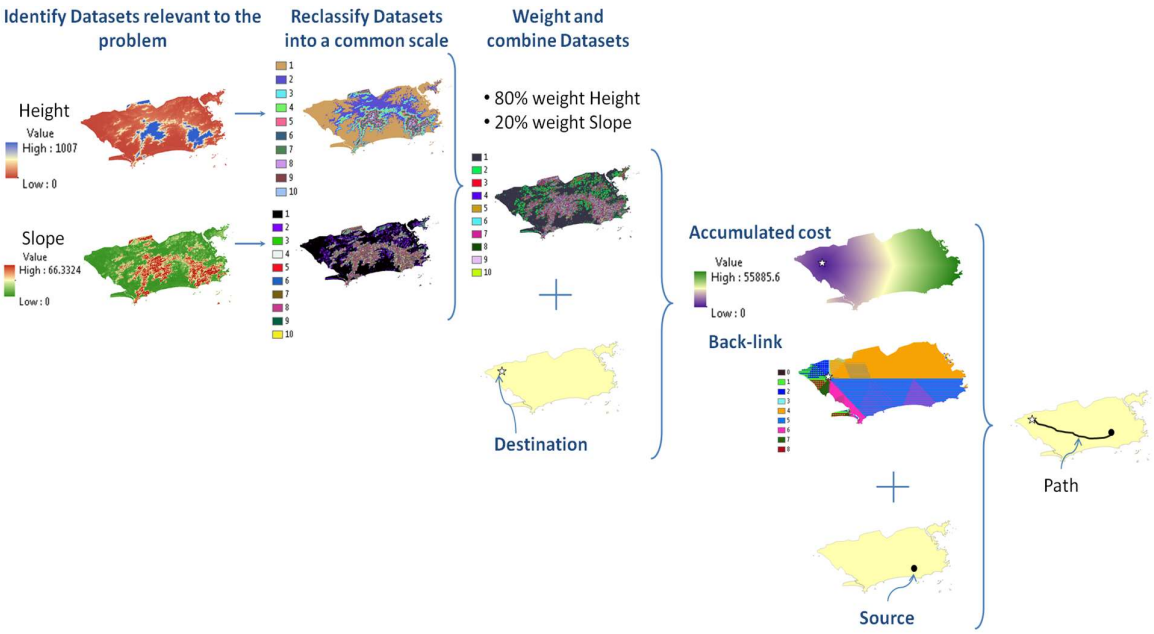



Figure 10-2 Simplified procedure to calculate the Path between two points.

## 10.3 WASTEWATER ALLOCATOR

The class diagram is shown in Figure 10-3. The output of Wastewater_Allocator is the value of wastewater collected at each collection point. The data input is shown in Table 10-3.

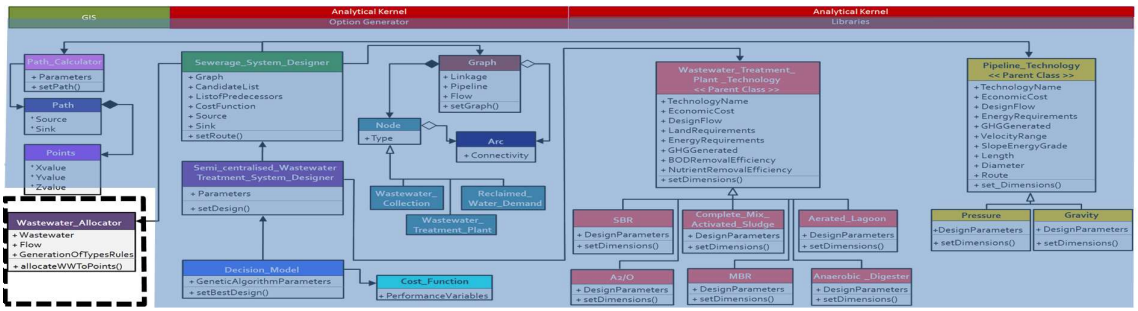



Figure 10-3 Identification of the Wastewater_Allocator class in the DSS.

Table 10-2 Data requirements for Wastewater Allocator.

| Data provided by the user | Description |
|---|---|
| Household income map | |
| Classification values | The definition of the household income tiers in each residence area or city district. |
| Minimum monthly wage | |
| Population map | |
| Location wastewater collection point map | |
| Per capita wastewater generation rate or water demand rate | The influence of household income in the generation of wastewater. |

The wastewater generation model developed has the following steps. A simplified visualisation of the wastewater generation model is shown in Figure 10-4.

1. Reclassification of the income map according to the tiers of classification values. Reclassification means to standardise values in the income map. Average household income is a social attribute that is correlated to the water consumption rate per capita. Water consumption rate is defined as the monthly water volume per inhabitant ($m^3person^{-1}month^{-1}$).

   It is assumed that the value of the wastewater generated per capita will be equal to that of water consumption (given that all water used will be collected) and that there is no pipe leakage. The wastewater generation model uses the average income obtained from the census and the value will be the total for those responsible for a family, either by receiving a salary or state benefits.
2. With the reclassified map and the per capita water demand rate as a function of income, the water demand per capita per reclassification category is calculated. The per capita water demand rate as a function of income is obtained from peer reviewed papers either for the city itself or for a city with similar features.
3. To calculate the total water demand per residence area, the map with the water demand per capita per reclassification category is multiplied by the population per residence area map.

4. Finally, to obtain the wastewater collected at each collection point, it is necessary to assume that the collection points only collect wastewater from their corresponding residence areas and in an equal fashion. Thus, if there are two collection points per residence area, each collects half of the wastewater generated. This assumption can be changed in future work.

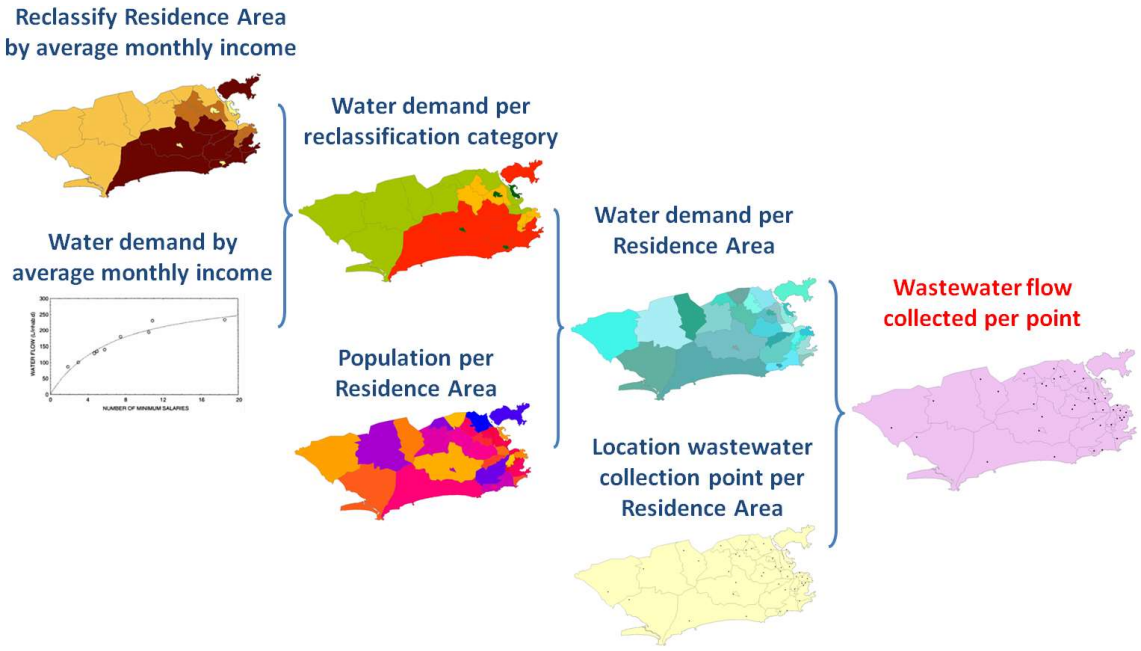



Figure 10-4 Visualisation of the wastewater generation model to calculate the wastewater flow collected in each point.

## 10.4 SUMMARY

The data calculated by the GIS module are used by Sewerage_System_Designer class. To differentiate the influence of the factors it was necessary to make experiments with the DSS (see Chapter 12).

# PART V
# DEMONSTRATION CASE

# CHAPTER 11
# SPATIAL DATA INPUT FOR THE CITY OF RIO DE JANEIRO

## 11.1 SPATIAL DATA

Rio de Janeiro City is the *demonstration case* [242], capital of the State of Rio de Janeiro, it occupies approximately 1,200 $km^2$ and is characterised by being nested in a rugged topography in Southeast Brazil, as shown in Figure 11-1.

Rio de Janeiro is the capital of the State of Rio de Janeiro, Brazil. The ocean and mountains determine the city's configuration, it has hundreds of rivers, canals, lagoons, marshes, and the largest urban forest in the world: *Floresta de Tijuca*. The rivers of the *Guandú* watershed provide about 80% of the fresh water and generate 25% of the electricity used by residents of the Rio de Janeiro metropolitan area [243].

According to the Census 2010 the city of Rio de Janeiro has a population density of 5,265.81 hab $km^{-2}$ [244]. This value is less than those reached in other Brazilian cities, like Belo Horizonte city 7,167.02 hab $km^{-2}$ [245] or Sao Paulo city 7,387.69 hab $km^{-2}$ [246]. The average rate annual geometric population growth of the city has been declining (2.54% in the 1960s, 1.82% in the 70s, 0.67% in the 80s and 0.74% in the 90s) and it is projected a value for 2020 between 0.35% and 0.45% [247], yet population projections must be treated with caution [248].

Urban human development varies greatly by locality, the city is characterised by being one with spatial segregation and socioeconomic inequalities [249]: the metropolitan Gini Index is 0.576 [250]. Upper class has access to a better education, better jobs and to a prominent, vibrant cultural life. Rio de Janeiro faces a scarcity of highly qualified workers whilst wages for low

skilled workers are very low [251]. Youth between 15 to 24 years that are neither working nor studying reach 26% (called "*nem-nem*"); up to 45% of these youth live in the poorest areas [252]. The need for them to develop job skills, so that they can avoid chronic unemployment, has been identified as a major priority [251]. In June 2013 there were massive demonstrations spurred by the demand for better public services, such as security, health, education, and transport conditions[h], and against corruption [253]. Besides the growing population and level of urban poverty, Rio de Janeiro city might be vulnerable also to climate change since it is a coastal city and to its inherent water-energy nexus. The electricity-mix is highly hydro-energetic dependent, and the city has a considerable industrial activity.

For administrative purposes the city is divided into five zones called Planning Areas (PA), as illustrated in Figure 11-2. Figure 11-3 shows with pins the 30 potential wastewater treatment plant (WWTP) sites. The areas were chosen based upon criteria which effectively constrained the number and size of locations in the densely populated areas, but the areas chosen may well not be acceptable because of socio-political constraints. In turn, Figure 11-4 shows with pins the proposed 40 wastewater collection points. Figure 11-5 displays the proposed 10 reclaimed water demand points.

Figure 11-6 provides a visualisation of the feasible network. That is, connectivity options between wastewater collections points, reclaimed water points and available wastewater treatment plant sites. The connectivity options reflect political feasibility. Finally, Figure 11-7 shows the identification number (ID) and key of the input data. Reclaimed water demand points are shown as stars, and their corresponding node numbers are in blue font. Potential wastewater treatment plants are shown as triangles, and their corresponding node numbers are in red font. Wastewater collection points are shown as circles, and their corresponding node numbers are in **black font**.

[h] The City of Rio de Janeiro port is Brazil's third busiest, it is also the centre for cruises. The city has 6 airports. Although having a considerable transport infrastructure, Rio has two subway lines and ferry services, it is inefficient: going from one part of Rio to another can take hours.

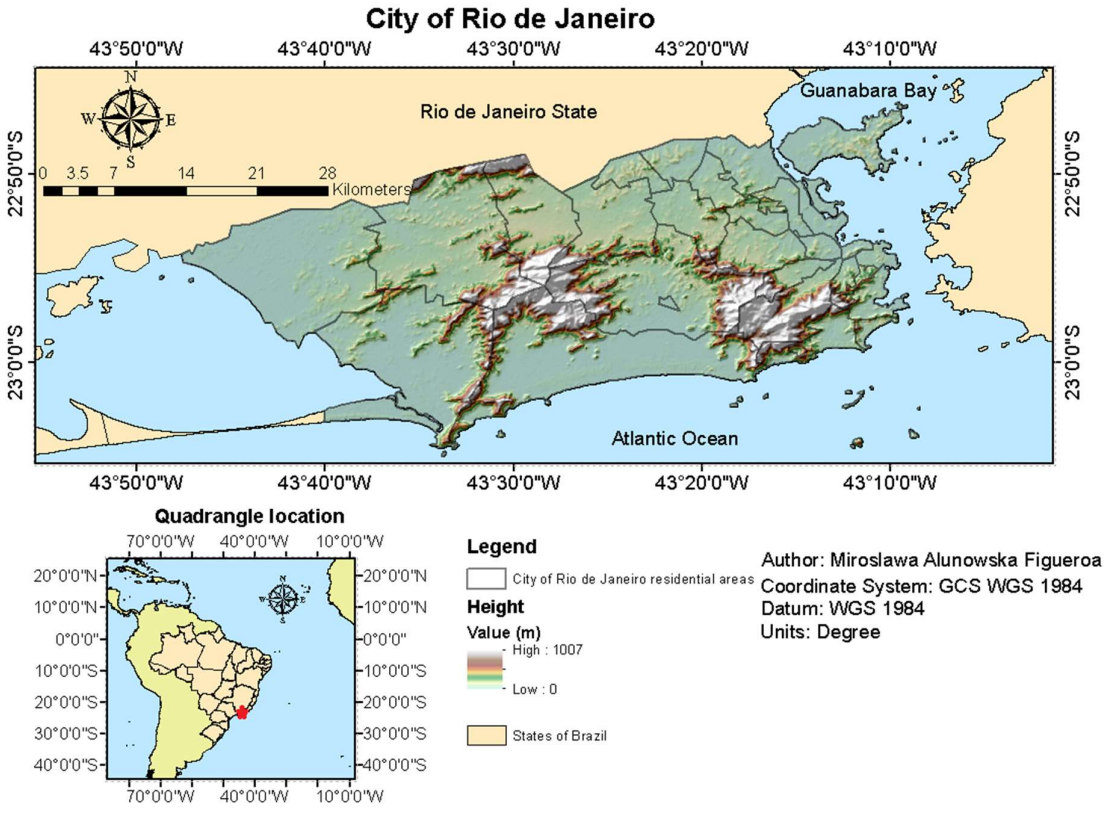



Figure 11-1 Location of the city of Rio de Janeiro, Brazil.

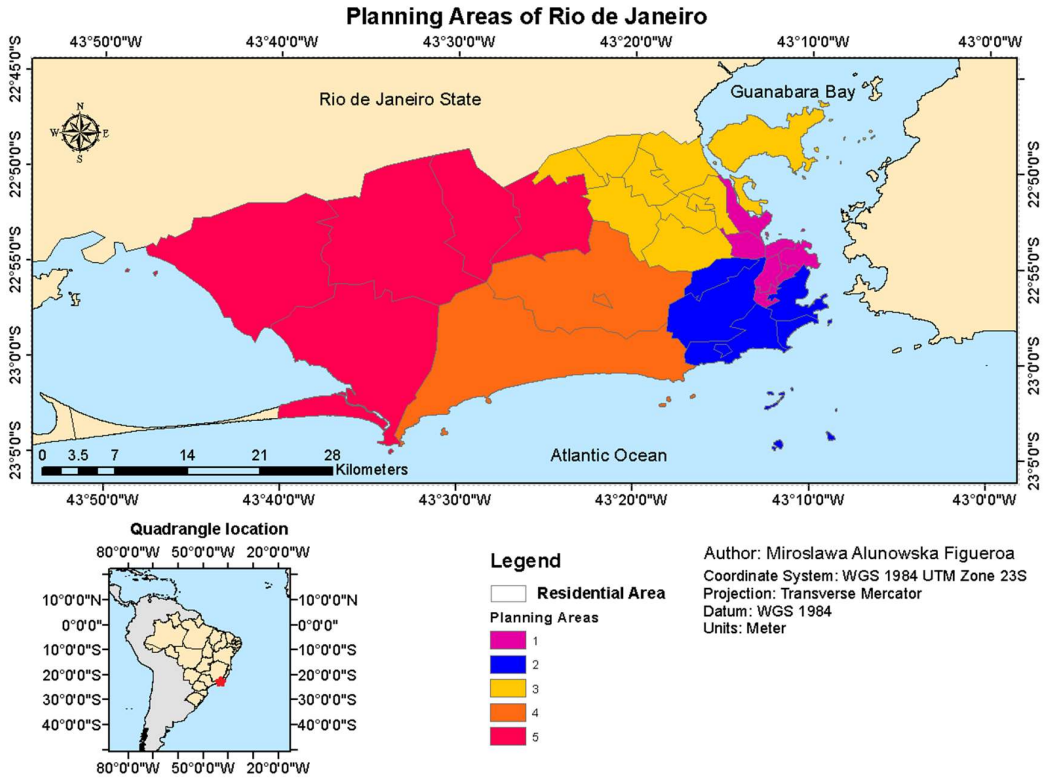



Figure 11-2 Map of Planning Areas of Rio de Janeiro city.

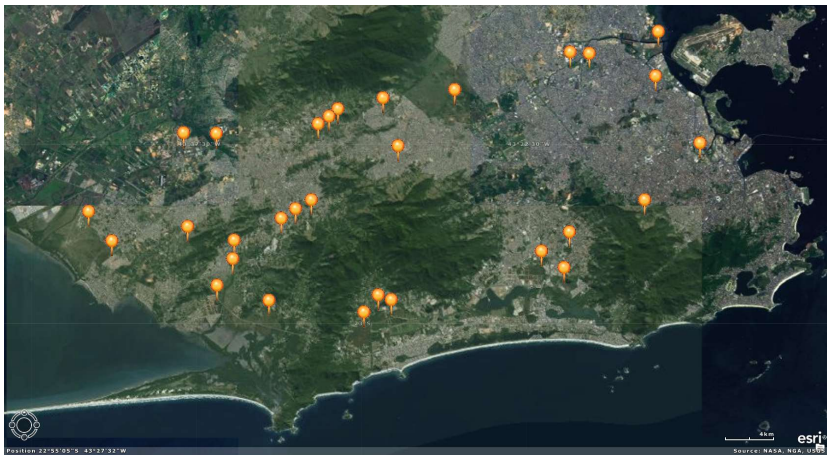


Figure 11-3 Map of the city of Rio de Janeiro with pins marking WWTP available areas.

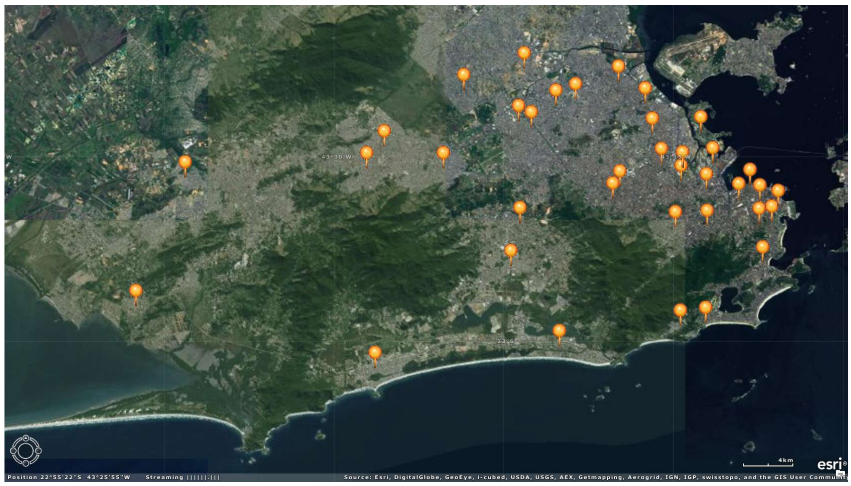


Figure 11-4 Map of the city of Rio de Janeiro with pins marking wastewater collection points.

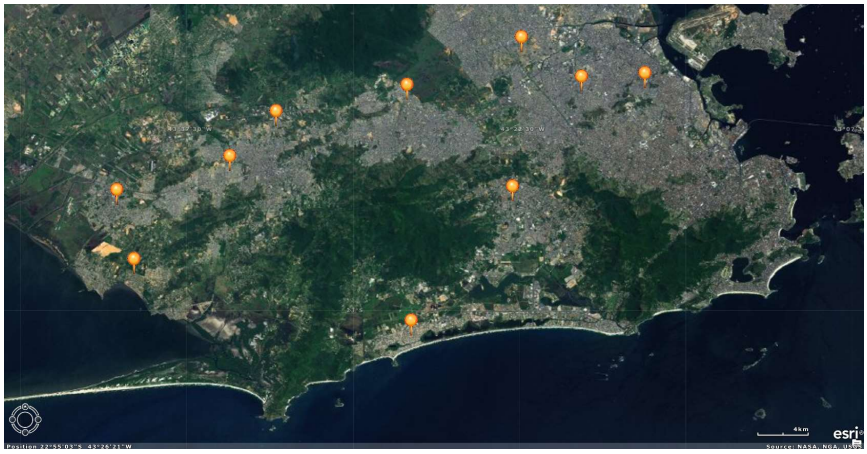


Figure 11-5 Map of the city of Rio de Janeiro with pins marking reclaimed water demand points.

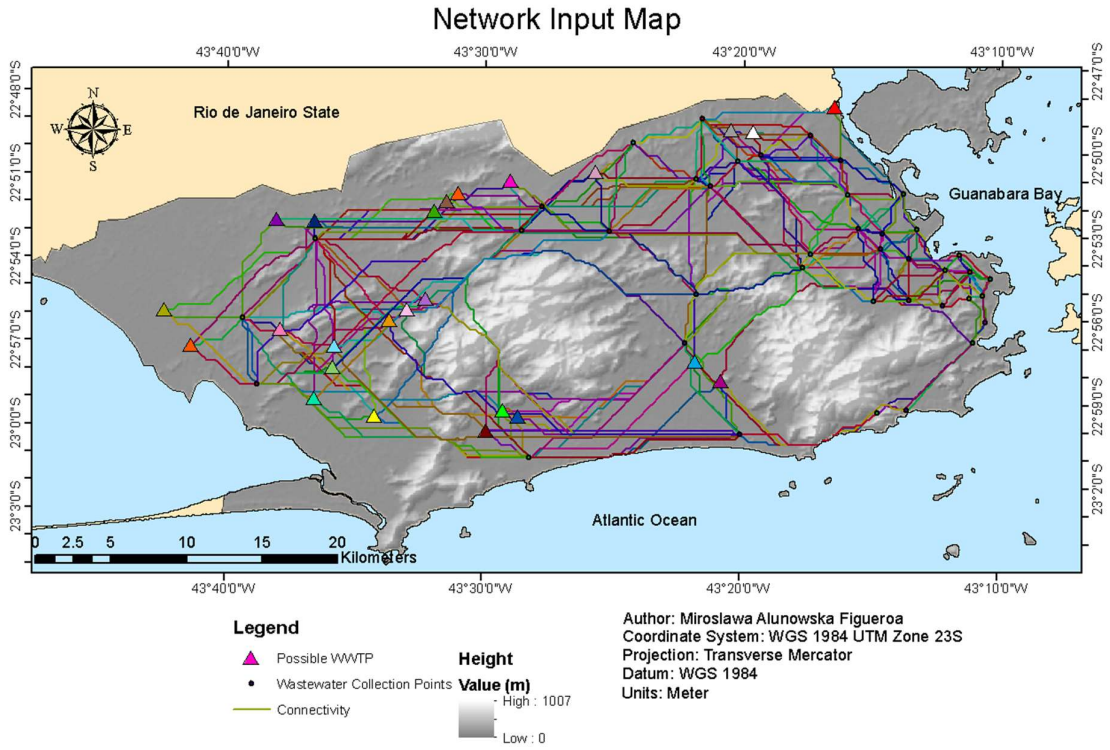



Figure 11-6 Visualisation of node connectivity.

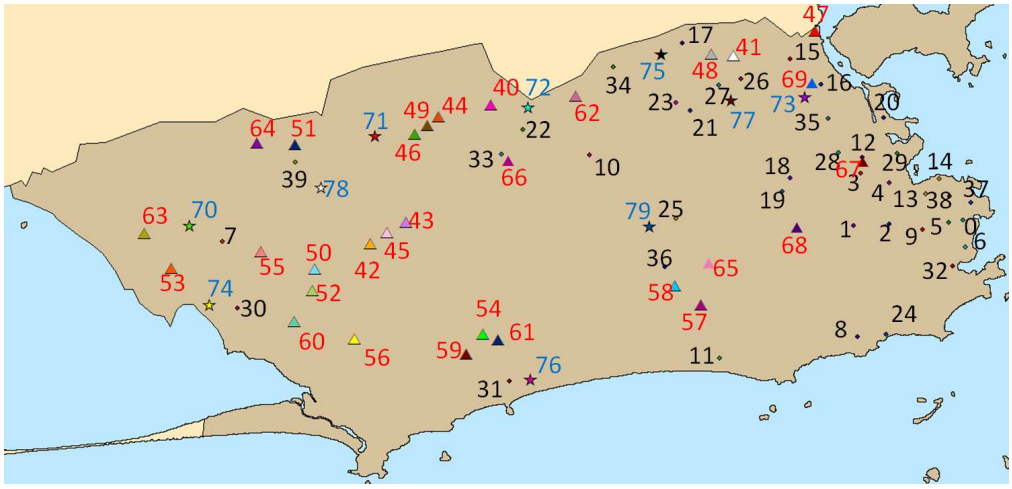


Figure 11-7 ID and key of input data. Reclaimed water demand points are shown (stars, blue font). Potential wastewater treatment plants (triangles, red font). Wastewater collection points (circles, black font).

## 11.2 SOCIO-ECONOMIC DATA

The following socio-economic data were used:

- The standard was the Brazilian electricity tariff for industrial use (317.2 BRL R$ $MWh^{-1}$ or 0.14 USD$ $kWh^{-1}$) as reported for 22 July 2014 [254].

- The energy mix was the standard national energy mixture from 2010 [255]: Hydropower (80.6%), Gas (7.2%), Biomass (5.1 %), Nuclear (2.7%), Oil (2.7%), Coal (1.3%) and Wind (0.4%).
- The wastewater composition is an average reported in literature [256], see Table 11-1.

Table 11-1 Wastewater average municipal composition [256].

| Parameter | Unit | Value | Parameter | Unit | Value |
|---|---|---|---|---|---|
| Biological Oxygen Demand (BOD) | g $m^{-3}$ | 357 | Phosphorous (P) total | g $m^{-3}$ | 10 |
| Chemical Oxygen Demand (COD) | g $m^{-3}$ | 627 | Total Suspended Solids (TSS) | g $m^{-3}$ | 210 |
| COD soluble | g $m^{-3}$ | 151 | Volatile Suspended Solids (VSS) | g $m^{-3}$ | 160 |
| Ammonia-N ($NH_3$) | g $m^{-3}$ | 30 | pH | - | 7.6 |
| Total Kjendahl N | g $m^{-3}$ | 54 | T | $^oC$ | 20 |

- A minimum wage of Brazilian real R$151 or USD$ 66.24 (exchange rate July 2014: R$ 1 = USD$ 0.45 [257]) was reported in the census for the month of July of 2000 [258]. The average income is for all responsible for a family either by salary or state benefits.

## 11.3 DATA SOURCES

The DEM was obtained from the Ministry of Agriculture, Livestock and Supply [259]. The raster file has a resolution level of 3 arc sec, which has 90 m by 90 m squares, and is void-filled from data obtained from the SRTM. Geographical data and socio-economic data, such as political divisions, were obtained from the Brazilian Institute of Geography and Statistics (IBGE) [260,261,262]. The IBGE code for Rio de Janeiro city is 3304557. Information of the city's Administrative Areas, such as population density and average household income, were obtained from the Rio de Janeiro Aggregates Database of the Institute *Pereira Passos* [263,264].

## 11.4 SPATIAL REFERENCE

The WGS 84 UTM Projection was used as a projection coordinate system. The Datum was WGS 1984 UTM Zone 23S [265].

# CHAPTER 12
# EXPERIMENTS WITH THE DSS

The purpose of this chapter is to assess whether the model is generating reasonable results by evaluating *uncertainty* associated with key parameters within the model. This is essential because the usefulness to decision-makers of the model depends on the accuracy, *reliability,* and clarity of its outputs [266]. There are many definitions of uncertainty; the one used in this research is as stated in Section 2.2.5. Reliability is defined as "*the likelihood that a component (or a system) will perform its intended function without failure for a specified period of time under stated operating conditions*" [89]. The most used engineering approach to identify the impact of uncertainty in parameters is known as a *sensitivity analysis*.

Sensitivity analysis is an integral part of model development since it aids in model validation by determining the most influential parameters on the model results and can calibrate some model inputs using real output observations. Additionally, a sensitivity analysis guides future research [267]. Having a range of outputs increases our understanding of the SUWWTS and helps us to understand the implications of our modelling assumptions.

From the several sensitivity analysis methods available (local or global), the approach adopted in this Thesis is the most engineering-used screening method, the so-called *One-At-a-Time* (OAT). The screening methods are based on a discretization of the inputs allowing a fast exploration of the code behaviour [268]. In OAT the values of a key variable are changed, while keeping other variables constant, to analyse that variable's effect on the model's outputs [267]. The sensitivity measure was determined by calculating the model results while varying the input parameter by ±%.

Key parameters were chosen as those that were expected to have the most influence on the SUWWTS layout (e.g. WWTP site opened, sewer network) and on the sustainability management indicators (see Section 4.5).

Several technologies were considered to illustrate that the DSS is useful for several technology types. A range of technologies commonly used in wastewater treatment were considered. Assuming cost as the only selection criterion, the treatment technologies spectrum ranges from the most expensive represented by a semi-centralised system of "All Membrane BioReactors (MBRs)" (high energy requirements, low land footprint, includes Nitrogen removal, highest reclaimed water quality) to the cheapest represented by a semi-centralised system of "All Lagoons" (low energy requirements, high land footprint, lowest reclaimed water quality). An intermediate cost is represented by a "Mixed-technologies" approach, which herein arbitrarily assigned technologies for each available WWTP potential site.

This demonstration case shows the effects of the three technology types considered under a Standard case and using variations. As such, seven set-ups were prepared to look at selected parameters. These parameters are as follows:

- Quantity of wastewater. The standard quantity is 3.75 $m^3$ $month^{-1}$ $person^{-1}$, a value reported as the average water consumption in The Netherlands in 2007 [269]. In addition, set-ups A and B were formed to consider the effects from a +50% (set-up A) and -50% (set-up B) of the average water consumption.
- Distribution of population. The standard is a homogeneous population increase from 2010 (with population on the East part of the city). The analysis range will explore development (greater Average Annual Population Growth) on other zones of the city. Set-up C considers the West part of the city for comparison.

  The standard population is assumed to have a homogeneous Average Annual Population Growth increase of 0.65% throughout the city as of the 2010 census (time horizon 20 years).
- Terrain height. This refers to the geographical elevation. The standard height is the actual elevation of the city. The analysis range considered here includes a terrain height of only 5% of the city's original, which is set-up D. In addition, a terrain height that is

50% of the original was considered as set-up E. These height changes were used as a means to explore the influence of new topography (see Section 10.2.1). Such changes will showcase the applicability of the DSS to alternative terrain by changing the height input dataset (that is, the DEM, see Chapter 10) while keeping the other parameters equal. These are the (x,y) coordinates of the nodes: wastewater collection points, reclaimed water demand points, feasible WWTP sites (see Section 4.4.2).

- Number and distribution of WWTP site options. The standard number of potential WWTP points is 25. The variations considered are ±20%, which relate to set-ups F and G respectively. The potential site areas were chosen based upon criteria which effectively constrained the location size and number in the densely populated areas, but the areas chosen may well not be acceptable because of socio-political constraints. The assigned technologies for the standard number of potential sites for the "Mixed technologies" are shown in Table 12-1.

Table 12-1 Technologies assigned for each WWTP potential site.

| WWTP ID | Technology | WWTP ID | Technology | WWTP ID | Technology |
|---|---|---|---|---|---|
| 40 | Activated Sludge | 50 | Lagoon | 60 | MBR |
| 41 | Sequencing Batch Reactor (SBR) | 51 | Lagoon | 61 | SBR |
| 42 | Lagoon | 52 | MBR | 62 | Lagoon |
| 43 | SBR | 53 | Lagoon | 63 | SBR |
| 44 | Activated Sludge | 54 | Lagoon | 64 | Lagoon |
| 45 | MBR | 55 | MBR | | |
| 46 | Lagoon | 56 | Activated Sludge | | |
| 47 | MBR | 57 | Lagoon | | |
| 48 | Activated Sludge | 58 | SBR | | |
| 49 | Lagoon | 59 | Lagoon | | |

As mentioned above, the demonstration case shows the likely outputs for a standard case and several set-ups containing variations in one parameter. These model runs are summarised in Table 12-2.

Table 12-2 Summary of the models run.

| Set-up | Parameters | | | |
|---|---|---|---|---|
| | Potential WWTP | Population distribution | WW Flow | Height |
| Standard | Standard | Standard | Standard | Standard |
| A | Standard | Standard | -50% | Standard |
| B | Standard | Standard | +50% | Standard |
| C | Standard | West part of the city | Standard | Standard |
| D | Standard | Standard | Standard | 50% |
| E | Standard | Standard | Standard | 5% |
| F | 20 | Standard | Standard | Standard |
| G | 30 | Standard | Standard | Standard |

## 12.1 EVALUATION OF ALTERNATIVE TECHNOLOGIES

### 12.1.1 Impact on the Layout

The parameter values in this section correspond to those of the Standard set-up of Table 12-1. Figure 12-1 gives the number of WWTPs opened and their respective IDs. Each technology type is colour coded to distinguish them from one another, thus whenever referring to them the word font will change to: **All Lagoons**, **Mixed Technologies** and **All MBRs (**nitrogen removal process).

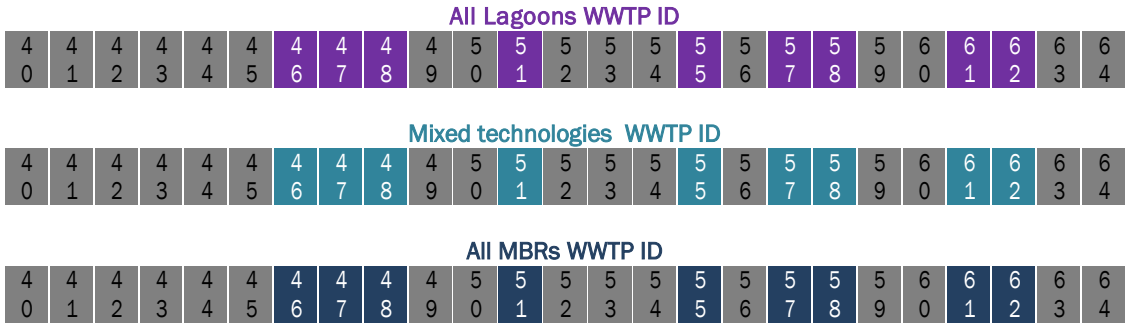


Figure 12-1 WWTP opened for each technology type in the Standard set-up. Opened sites are: purple squares for "All Lagoons", aqua squares for "Mixed technologies", and blue squares for "All MBRs". Grey squares refer to sites not opened.

Figure 12-2 illustrates the sites opened and the percentage of collection points that are connected to a particular WWTP site. WWTP IDs 58 and 48 are the two with the highest percent of connected nodes. Both sites are close to the highly densely populated East area of the city (see Figure 11-2).

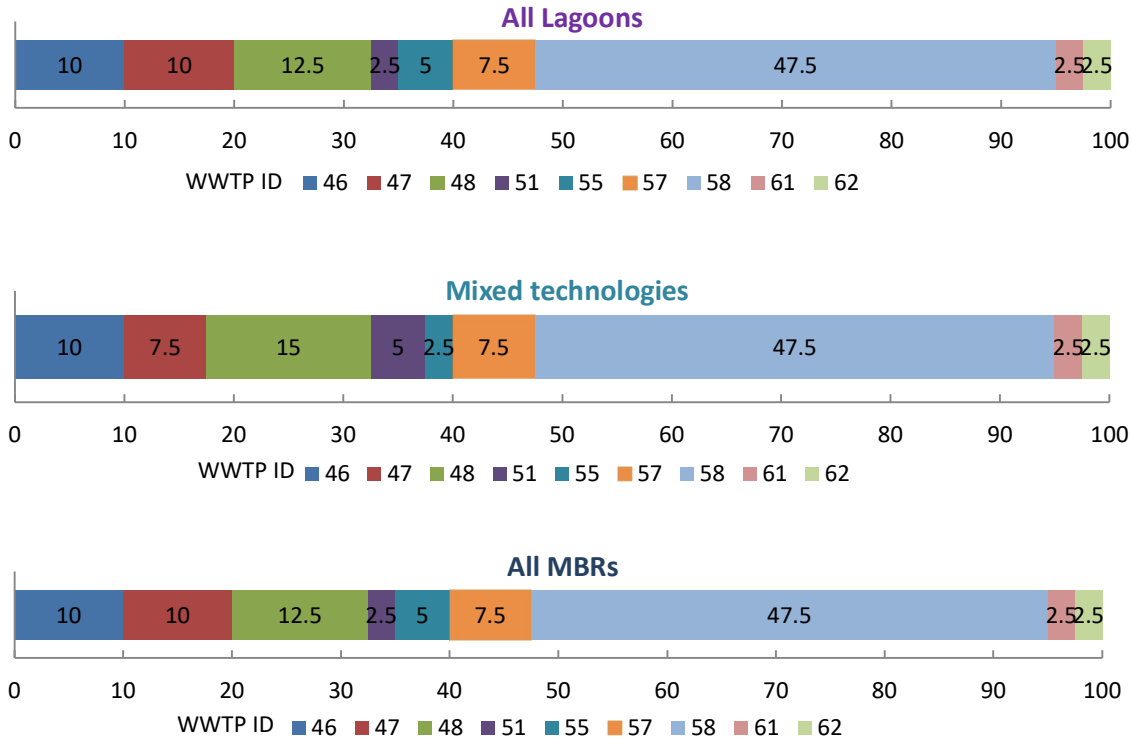



Figure 12-2 Percentage of collection points that connect to each WWTP opened for each technology type in the Standard set-up.

### 12.1.2 Impact on Sustainability Management Indicators

As observed in Figure 12-1, the number and location of the sites opened does not change when considering the alternative technologies. The greatest influence of the treatment technology is, as expected, in the semi-centralised system's sustainability management indicators. The following subsections describe these impacts.

#### *12.1.2.1 Economy*

The Annual Cost criterion ($ year$^{-1}$) includes capital, operation and management costs. Figure 12-3 illustrates the cost difference with reference to the cheapest system comprised of "All Lagoons". The bars pertaining to each technology type is colour coded to distinguish them from one another: The "All Lagoons" is the **purple bar**, "Mixed technologies" is the **aqua bar with white dots**, and "All MBRs" is the **blue bar**. Figure 12-4 illustrates the cost breakdown in terms of the sewer network (grey bars) and the 9 potential WWTP sites that were opened. For

the entire treatment technology spectrum, it is the sewerage system that accounts for the highest percentage in overall system costs.

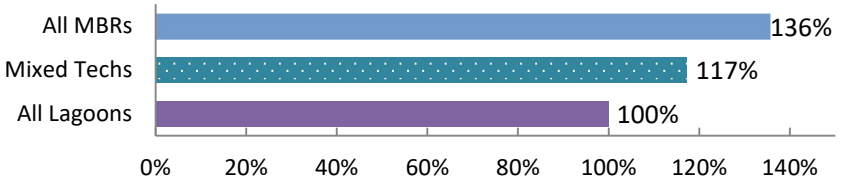



Figure 12-3 Cost difference with referenced to "All Lagoons" system (the cheapest) for the Standard set-up. "All Lagoons" is the purple bar, "Mixed technologies" is the aqua bar with white dots, and "All MBRs" is the blue bar.

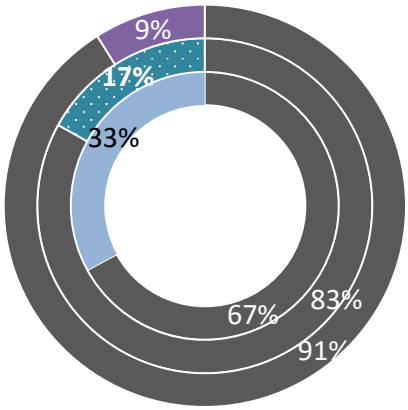



Figure 12-4 Cost breakdown in terms of the sewer network and the 9 potential WWTP sites that were opened for the Standard set-up. "All Lagoons" is the purple bar, "Mixed technologies" is the aqua bar with white dots, and "All MBRs" is the blue bar. Grey bar refers to the sewer network.

#### *12.1.2.2 Socio-cultural*

The criterion is Ability to Pay in terms of the percent of the average consumption costs with respect to the average salary. Figure 12-5 illustrates the percent (%) of the average minimum monthly salary for treating an average water consumption of 3.75 $m^3 month^{-1}$ $person^{-1}$.

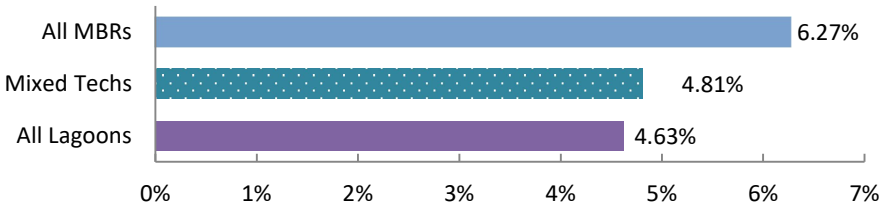



Figure 12-5 Percent (%) of the average minimum monthly salary that it costs to treat the average water consumption of 3.75 $m^3 month^{-1}$ $person^{-1}$ for the Standard set-up. "All Lagoons" is the purple bar, "Mixed technologies" is the aqua bar with white dots, and "All MBRs" is the blue bar.

#### *12.1.2.3 Environment: use of natural resources*

There are two indicators. The first criterion is Land Use; calculated as $m^2$ $person^{-1}$. Figure 12-6 illustrates the land requirements from the potential WWTP sites that were opened with reference to the smallest footprint system comprising of "All MBRs".

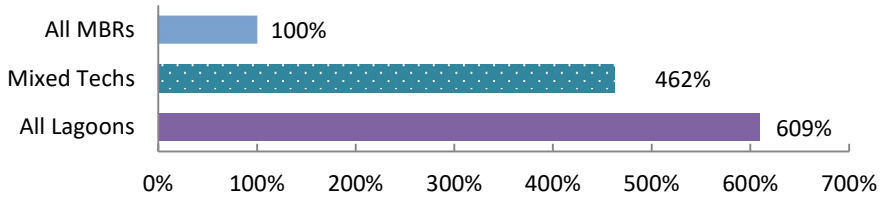



Figure 12-6 Percent (%) of land requirements, referenced to "All MBRs" system (smallest footprint) for the Standard set-up. "All Lagoons" is the purple bar, "Mixed technologies" is the aqua bar with white dots, and "All MBRs" is the blue bar.

The second criterion is Energy Requirements; the indicator is kWh $year^{-1}$ $person^{-1}$ (operation and management). Figure 12-7 illustrates the energy requirement breakdown in terms of the sewer network and the 9 potential WWTP sites that were opened. As expected, the system of "All MBRs" has the highest percentage. This occurs because of the aeration requirements for biological processes and scouring of the membrane filtration system to abate fouling (see Section 9.2).

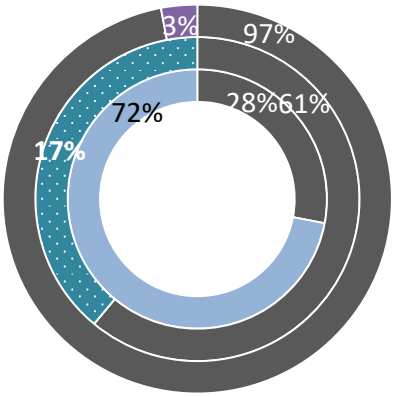



Figure 12-7 Energy breakdown in terms of the sewer network and the 9 potential WWTP sites that were opened for the Standard set-up. “All Lagoons” is the purple bar, “Mixed technologies” is the aqua bar with white dots, and “All MBRs” is the blue bar. Grey bar refers to the sewerage system in each technology type.

#### *12.1.2.4 Environment: Discharges*

The first of two criteria is Greenhouse Gas Generation in tons of $CO_2$equivalent ($CO_2e$) year$^{-1}$. Figure 12-8 illustrates the breakdown of the indirect $CO_2e$ released by pumping energy requirements in the sewer network and by aeration requirements of the 9 potential WWTP sites that were opened. The $CO_2$ generated depends on the electricity energy mix used, and higher $CO_2e$ emissions result in relation to mixes depending more on oil. The system comprised solely of Lagoons released the minimum $CO_2e$.

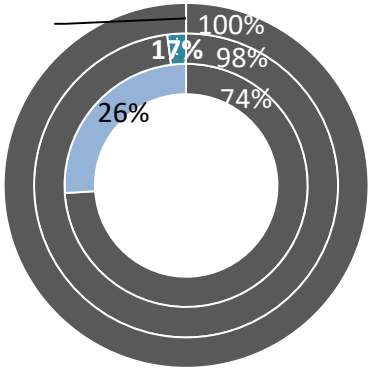



Figure 12-8 Indirect $CO_2e$ from energy requirements breakdown in terms of the sewer network and the group of WWTPs for the Standard set-up. “All Lagoons” is the purple bar, “Mixed technologies” is the aqua bar with white dots, and “All MBRs” is the blue bar. Grey bar refers to the sewerage system in each technology type.

Figure 12-9 compares the indirect $CO_2e$ generated from the effluent and sludge. That is, $CO_2e$ from $CH_4$ emissions by biosolids applied to land, $CO_2e$ from $N_2O$ emissions from biosolids applied to land, $CO_2e$ from $N_2O$ emissions from emissions by discharging effluent into receiving water body and $CO_2e$ from $N_2O$ emissions from volatilisation leachate and runoff.

These results potential consistent with the fact that the system comprised of all MBRs is the one with the highest BOD removal as illustrated in Figure 12-10 and has nitrogen removal. Thus, there are less emissions there is less nitrogen content in the sludge and reclaimed water. Whereas the "All Lagoons" system is the one with the lowest BOD removal and, as expected, its resultant sludge has more nitrogen and carbonaceous content.

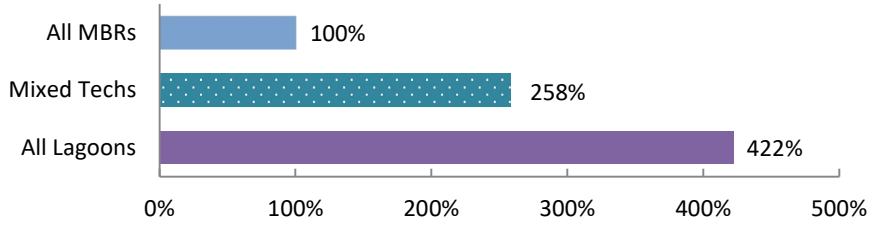



Figure 12-9 Comparison of indirect $CO_2e$ generation from $CH_4$ and $N_2O$ emissions for each treatment technology type for the Standard set-up. "All Lagoons" is the purple bar, "Mixed technologies" is the aqua bar with white dots, and "All MBRs" is the blue bar.

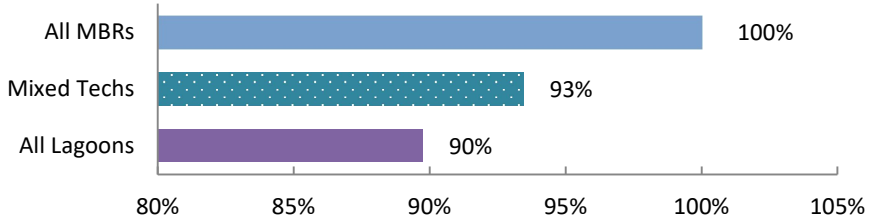



Figure 12-10 Average BOD efficiency removal (%) of the 9 potential WWTP sites that were opened for the Standard set-up. "All Lagoons" is the purple bar, "Mixed technologies" is the aqua bar with white dots, and "All MBRs" is the blue bar.

## 12.2 QUANTITY OF WASTEWATER

In this section, each parameter's values correspond to those of the Standard, A and B set-ups of Table 12-1. Figure 12-11 presents the number of WWTP sites opened after changing the quantity of wastewater. In general, it can be concluded that 88% of the opened sites in the standard flow are robust to any given flow range regardless of the technology. It is interesting to note that the "Mixed technologies" system is more sensitive to flow than the two systems composed of the same technologies; an additional site (ID 63 technology SBR) is opened when conveying less flow.

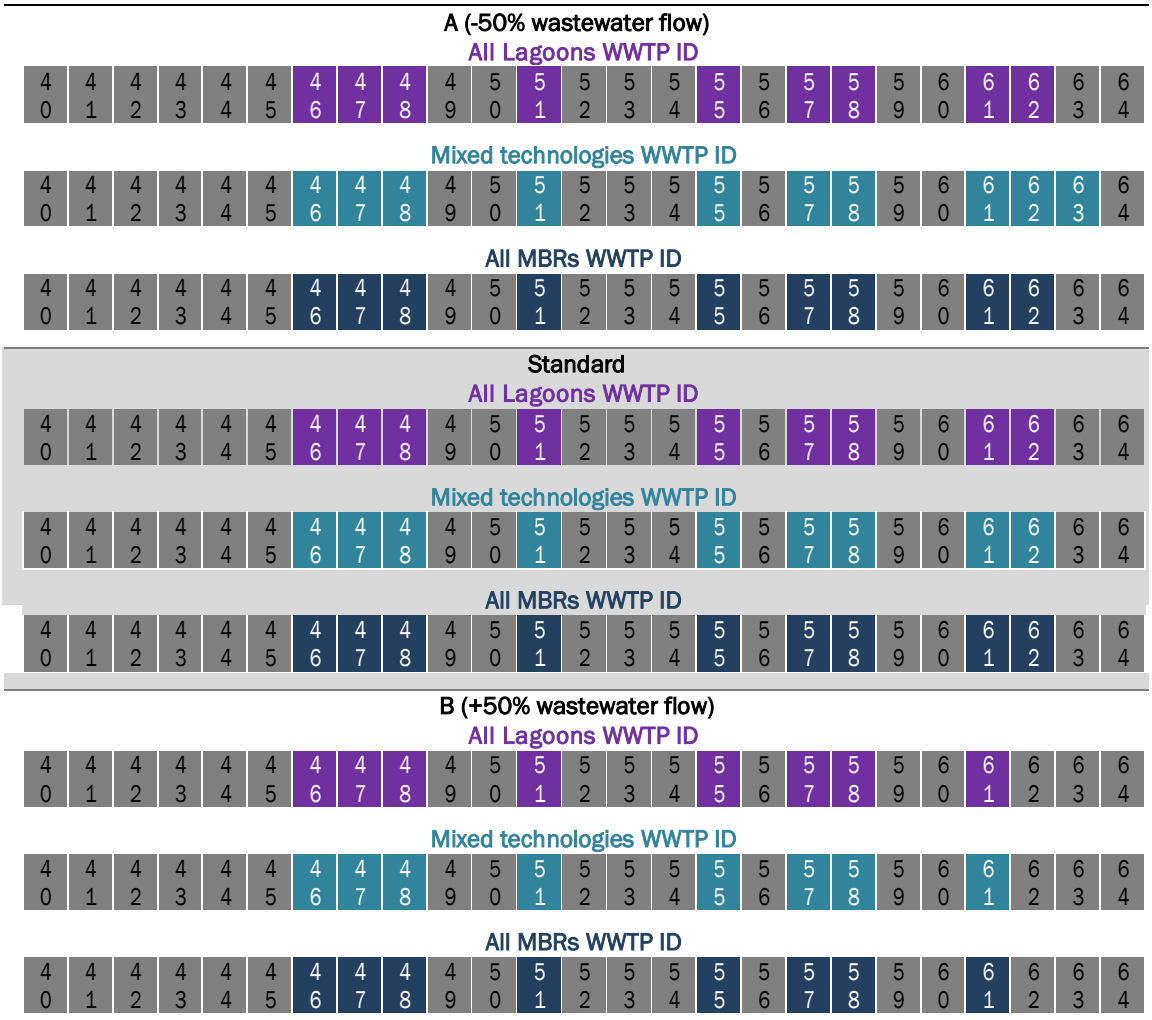



Figure 12-11 Variation of the number of WWTPs opened between the Standard, A (-50% wastewater flow) and B (+50% wastewater flow) set-ups. Opened sites are purple squares for "All Lagoons", aqua squares for "Mixed technologies", and blue squares for "All MBRs". Grey squares refer to sites not opened.

Figure 12-12 illustrates the WWTP sites opened and the percentage of collection points that are connected to a particular WWTP site. WWTP ID 58 and 48 still have the highest percent of nodes connected. As expected, the values of the sustainability management indicators increase with increasing flow.

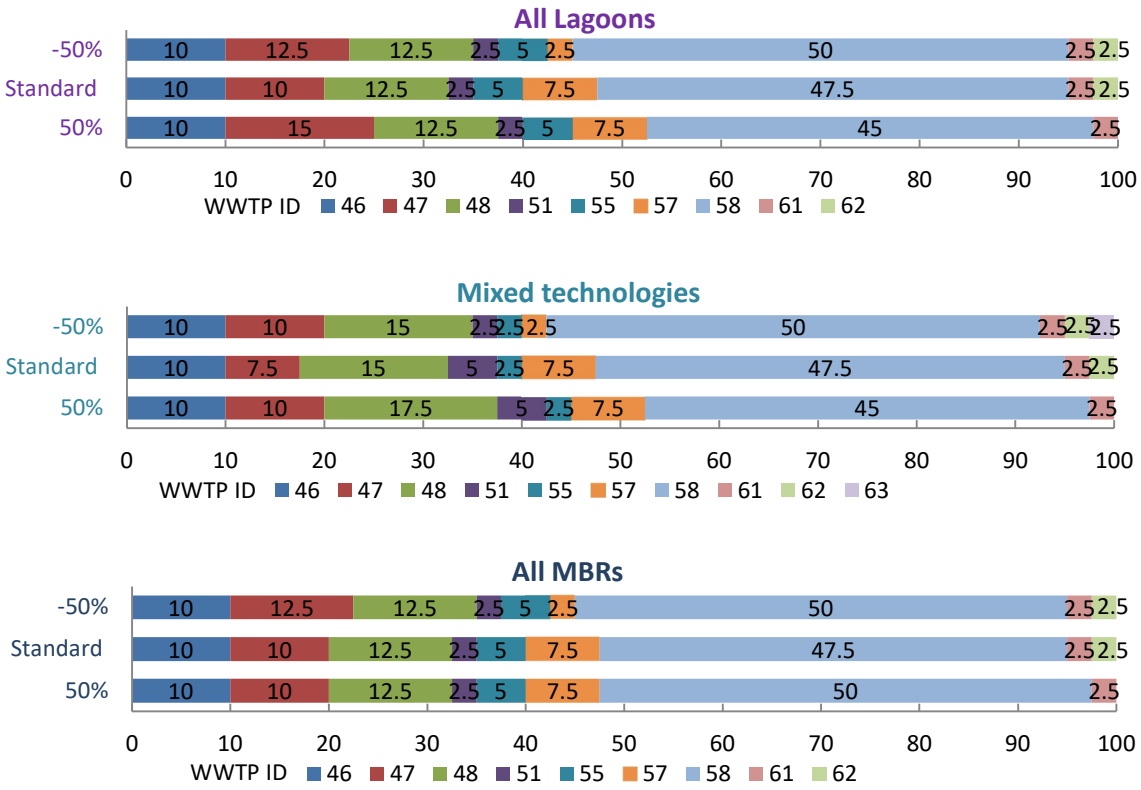



Figure 12-12 Percentage that each collection point conveys to each WWTP under standard and ±50% wastewater volumes.

## 12.3 POPULATION DISTRIBUTION

The parameters' values in this section correspond to those of the Standard and C set-ups of Table 12-1. The influence of the population distribution was accomplished by proposing a greater development (more Average Annual Population Growth) in the West Zone of the city (Planning Areas: 4 and 5) in comparison to the Standard set-up.

For the Standard set-up, the city of Rio de Janeiro was divided into four areas depending on the average household income based on the classification of Olivier (2006) [270]. According to

family income Oliver classifies Manaus, the capital of the Brazilian state of Amazonas, into four residence types and associated per capita water consumption rates. Although water consumption rates are site specific [271], the use of the tiers as defined by Oliver are valid given that Manaus has features, such as an income inequality, a Human Development Index (HDI) 1995/1999 of 0.705, rainfall and temperature, which are analogous with the city of Rio de Janeiro e.g. the average HDI of the city of Rio de Janeiro is 0.766.

Table 12-3 shows the residence types according to the average monthly average income and its related wastewater generated. In 2007, Rio de Janeiro had an average per capita consumption of 224 l $day^{-1}$ [272] or 7 $m^3$ $month^{-1}$.

Table 12-3 Wastewater generated per person depending on average family income

| Residence Type | Family income per Neighbourhood (minimum salaries per family per month) | Wastewater ($m^3$ $month^{-1}$ per person) | Wastewater ($m^3$ $sec^{-1}$ per person) |
|---|---|---|---|
| 1 | Less than or equal to three | 6.10 | 2.35E-06 |
| 2 | Between 3 and 5 times | 6.18 | 2.38E-06 |
| 3 | More than 5 and 7 times | 7.12 | 2.75E-06 |
| 4 | More than 7 times | 8.57 | 3.31E-06 |

The city of Rio de Janeiro 2010 census data [273] of monthly income per Residence Area and the Standard Population Distribution map are illustrated in Figures 12-13 and Figure 12-14, respectively. After implementing the method described in 10.3 given the available information, the developed water allocation model is suitable, the results expect a requirement to convey and treat 1.4 $Mm^3$ $day^{-1}$ or 500 $Mm^3$ $year^{-1}$ of water. The value agrees with the average consumed water volume (*Volume de Água Consumido*) in Rio de Janeiro between 1996-2008 period: 523 $Mm^3$ $year^{-1}$ [274].

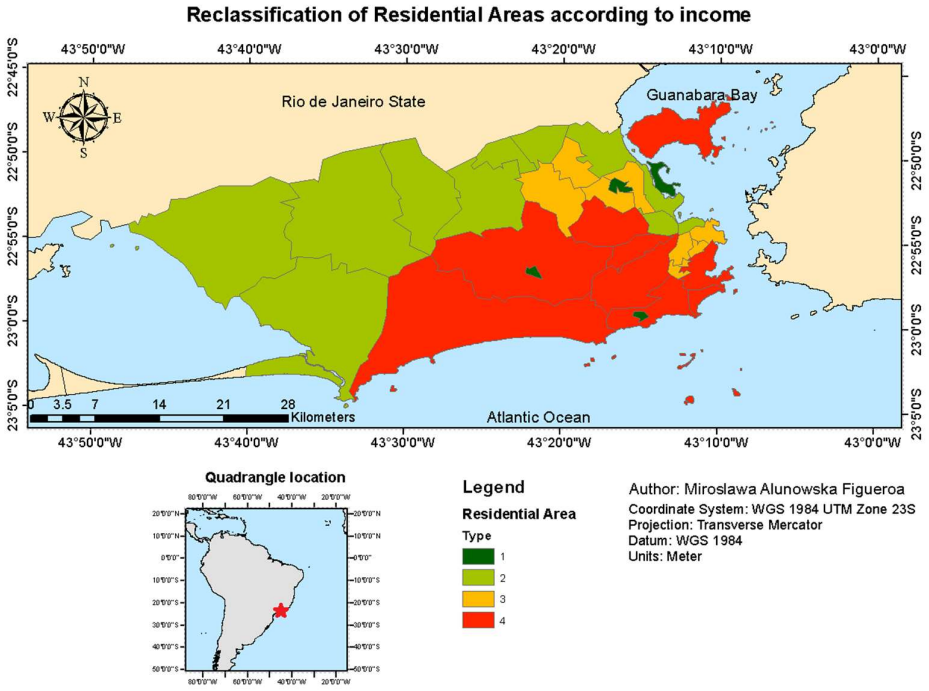



Figure 12-13 Reclassification of Residential Areas according to income.

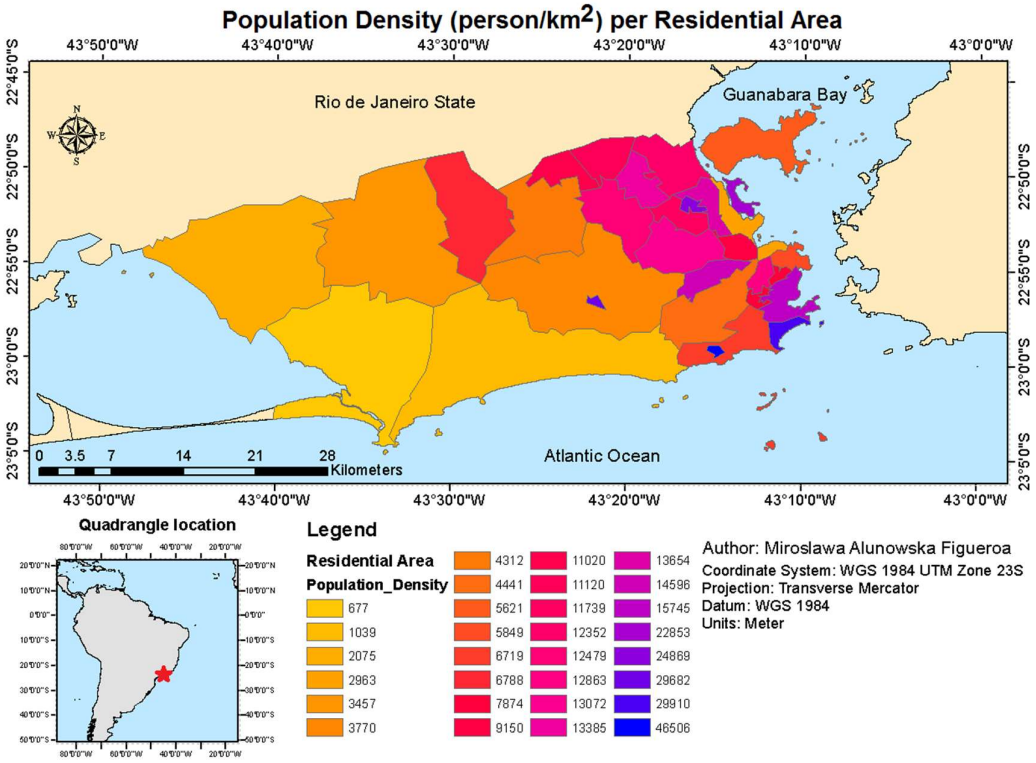



Figure 12-14 Standard population distribution map per Residential Areas.

Table 12-4 presents the difference of population distribution for each Planning Area (PA) assuming greater development in the West part of the city as compared to the Standard set-up.

Figure 12-15 presents the number of WWTP sites opened after changing the population distribution.

Table 12-4 Variation of population distribution in each Planning Area between the Standard and the C (West zone development) set-ups.

| | Planning Area | | | | |
|---|---|---|---|---|---|
| | 1 (Centre) | 2 (South) | 3 (North) | 4 (Barra-Jacarepaguá) | 5 (West Zone) |
| Variation of population density distribution (%) | -7 | -7 | -7 | +9 | +12 |

When looking at the impact on the number of WWTPs opened, case C results are the same as those from the Standard set-up, as shown in Figure 12-15. WWTP IDs 58 and 48 continue to have the highest percent of nodes connected. Figures 12-16 and 12-17 illustrate the influence of different population distributions on the size of each WWTP with reference to the Standard set-up. The WWTPs which showed size increases (WWTP IDs 46, 51, 55 and 61) are in the West Zone of the city. Meanwhile, the WWTPs that showed size reductions in case C (WWTP IDs 47, 48, 58 and 62) are located closer to the East part of the city.

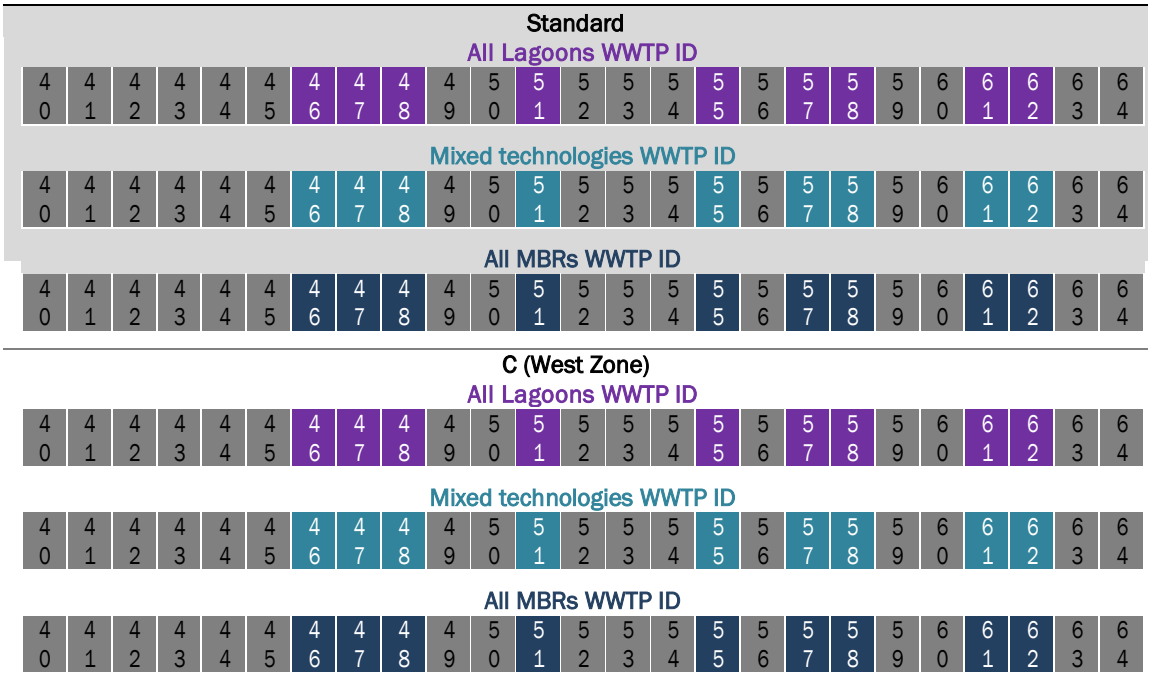



Figure 12-15 Variation of the number of WWTPs opened between the Standard and C (West zone development) set-ups

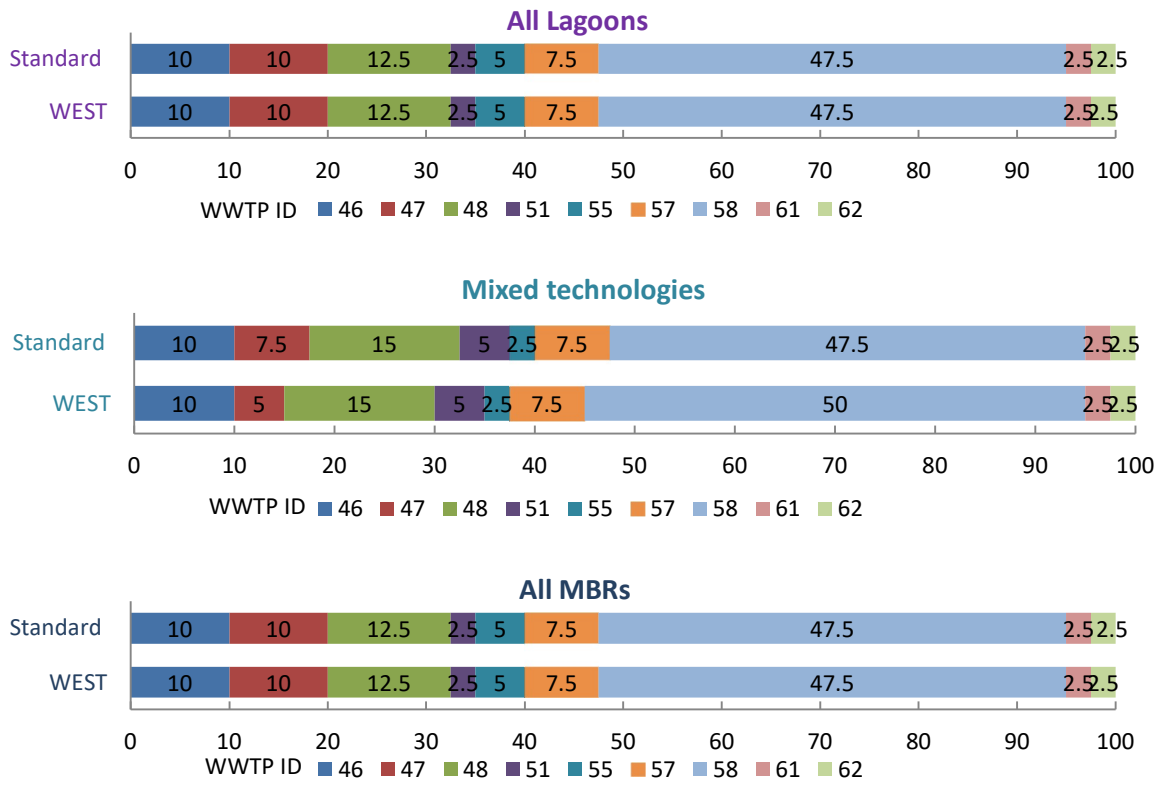



Figure 12-16 Percentage of collection points that connect to each WWTP opened when considering changes in population distribution.

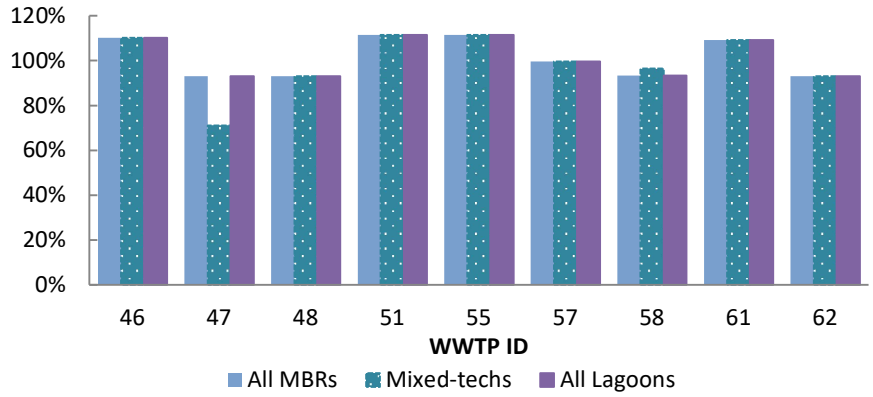



Figure 12-17 Influence of population growth in the West Zone (case C) on the size of each WWTP in comparison with the Standard case.

From these figures, the impacts on the WWTPs opened is on (1) the node connectivity for Mixed Technologies, and (2) the size of each WWTP; which is reasonable given the change in population distribution. WWTP ID 47 (MBR) has a decrease in incoming flow because wastewater collection point ID 35 changes connection to a cheaper technology WWTP ID 58

(SBR) in comparison with the standard population distribution. This resulted in a 33% decrease in node connectivity to WWTP ID 47 and a 5% increase in node connectivity to WWTP ID 58.

The spatial changes in wastewater conveyance cause variations in pipe construction, that is, diameters and angles. Figure 12-18 illustrates the influence of population growth in the West Zone (case C) on the semi-centralised WWTP system cost in comparison with the Standard set-up.

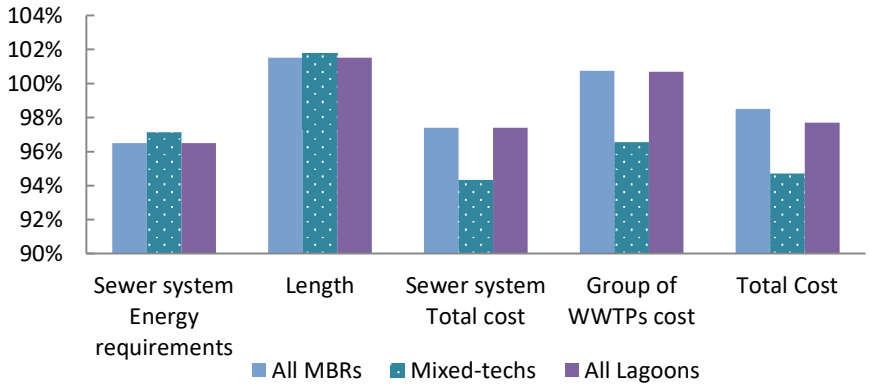



Figure 12-18 Influence of population growth in the West Zone (case C) on the semi-centralised WWTP system cost in comparison with the Standard case.

## 12.4 TERRAIN HEIGHT

The values of the parameters in this section correspond to those of the Standard, D and E set-ups of Table 12-1. Figure 12-19 illustrates the influence of terrain height on the number of WWTPs opened. Figure 12-20 illustrates the influence of terrain height on the number of plants opened within set-ups D and E relative to the Standard set-up. It is interesting that the differences in the number of plants are not greater, there are certain locations that are consistent in all three set-ups (WWTP ID 46, 47, 48, 58, 61 and 62) that are closer to the urban area.

Figure 12-21 illustrates the influence of terrain height on the percent of collection points that are connected to a particular WWTP site. WWTP Node ID 58 has the highest percent of nodes connected for any height option.

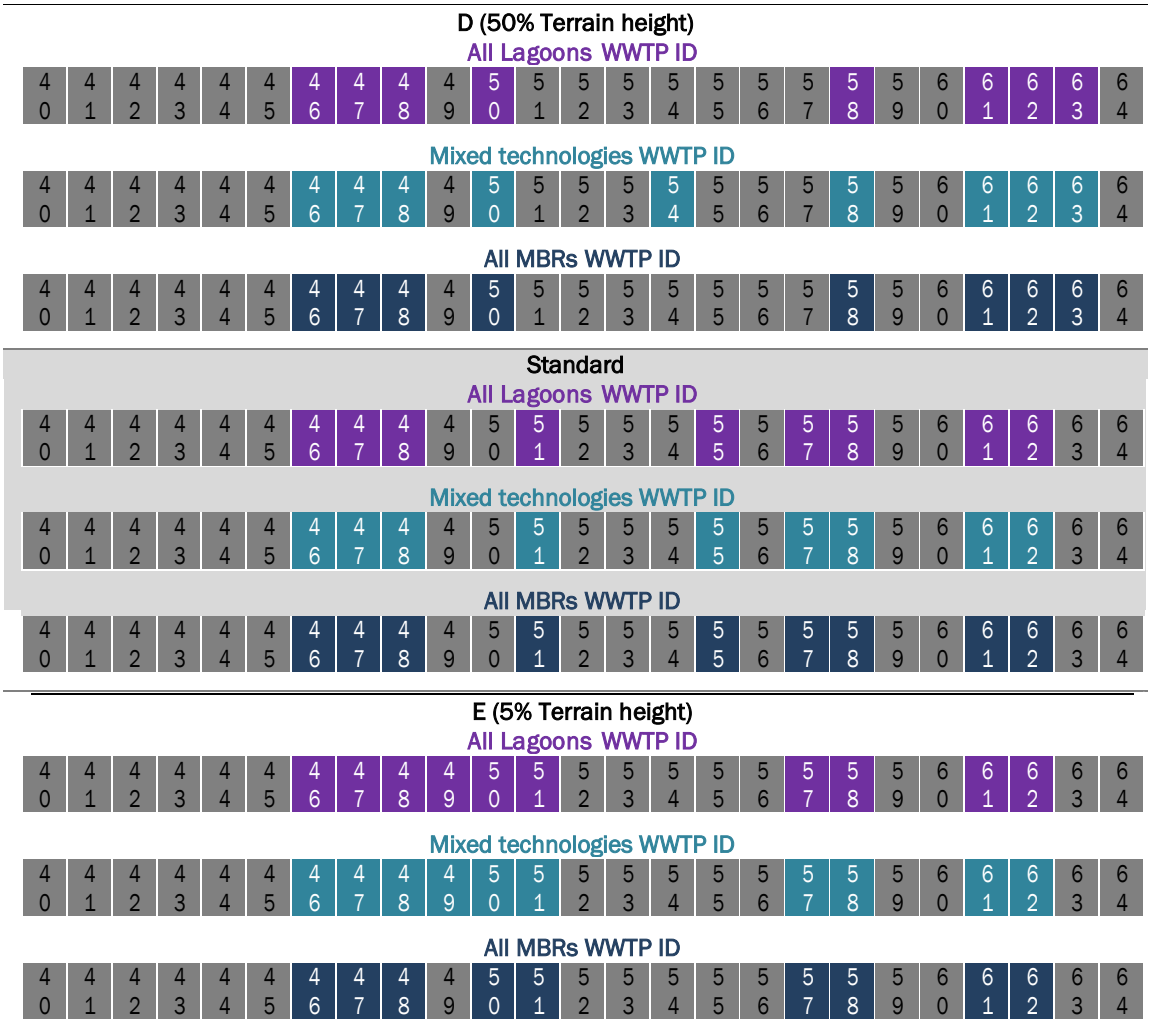



Figure 12-19 Number of WWTPs opened between the Standard, D (50% Terrain height) and E (5% Terrain height) set-ups.

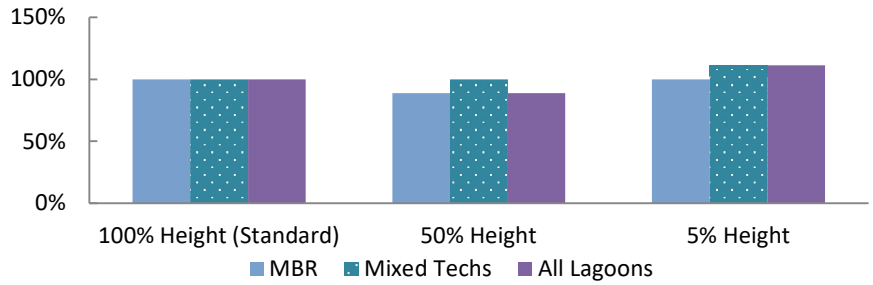



Figure 12-20 Influence of terrain height on the number of plants opened in comparison with the Standard.

The influence of height outweighs the influence of treatment technology because, for a given terrain height, nearly the same sites were opened across the technology type spectrum. On a

flatter surface, a cheaper technology (lagoons) has more plants opened in comparison with the most expensive technology (MBRs) because wastewater transmission is cheaper than to open a more expensive treatment plant. As discussed in Section 7.2, the decision to build a plant is based on whether it was cheaper to build a plant than wastewater transmission.

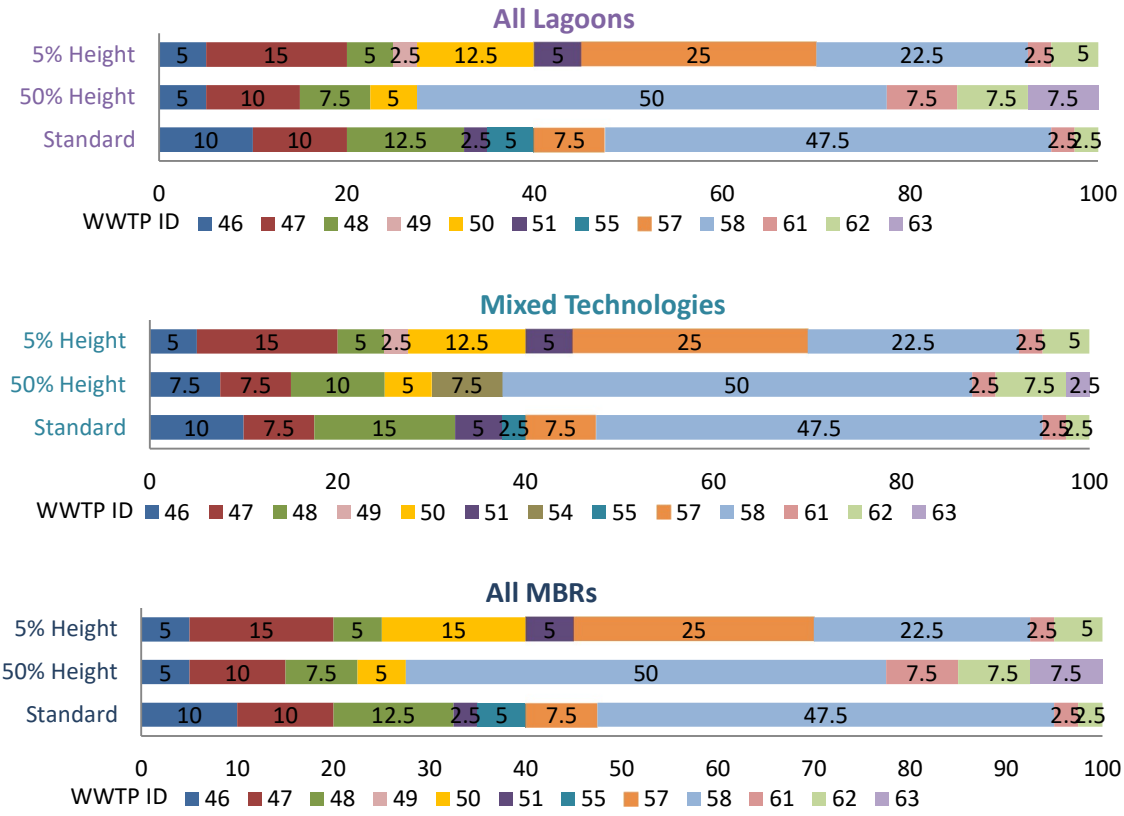



Figure 12-21 Height influence on the WWTPs opened and the % from the set of collection points that are connected to a particular WWTP site.

The reason that different WWTP sites are opened, assuming only cost as the selection criterion, is that the most significant impact of height is on the sewerage system (see Subsection 10.2.2). *The wastewater transmission cost is largely determined by the distance it must be conveyed (as determined by the network) and the height it has to be pumped*.

Figure 12-22 illustrates the influence of terrain height on the sewerage systems in comparison with the Standard set-up. Darker colours refer to the 50% terrain height. Lighter colours refer to the 5% terrain height. For the D set-up (50% terrain height) the "Mixed technologies" sewer cost is reduced because an additional plant is opened. For the E set-up (5%

terrain height) the sewerage system costs are raised substantially in comparison to the costs of the 50% flattened case given that the surface is essentially flat. As mentioned in Chapter 9, it is necessary to provide a minimum slope of 1 m per km to provide a velocity of 0.5 m $s^{-1}$ to avoid solid sedimentation, so the cost equation used is that of deep excavation (see equation 9-8).

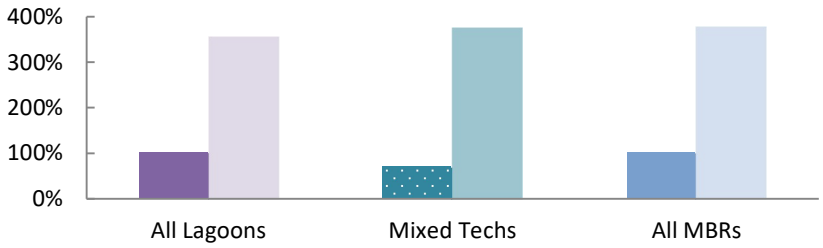



Figure 12-22 Influence of terrain height on the sewerage system costs for each technology type. Darker colours refer to the 50% terrain height. Lighter colours refer to the 5% terrain height.

### 12.4.1 Influence of weight of parameters on the pipe path

Given that the area suitability to build a pipe change depending on the weight of the parameters described in Section 10.2, the influence of parameters weights on the route of the pipe was explored.

Figure 12-23 illustrates the comparison of the influence that the weights of two parameters, slope, and height, have in the classification of area in a mountainous area. In the left-hand side of the figure, the weight of both parameters has equal importance, it can be appreciated that the area ranked with the value 1 (in purple) is larger than that of the right-hand side, in which the height has a weight importance of 80% and slope 20%.

Figure 12-24 illustrates the pipe path obtained for both weight scenarios. The coordinates of the points: Point A (22°52’23”S, 43°25’11”W) and Point B (22°54’37”S, 43°21’48”W), are the same for both cases. Since in this research the pipe is set to be built in areas ranked with the best suitability value, the path is shorter in the equal weight scenarios in comparison with that obtained in the scenario in which the DEM has an importance of 80%.

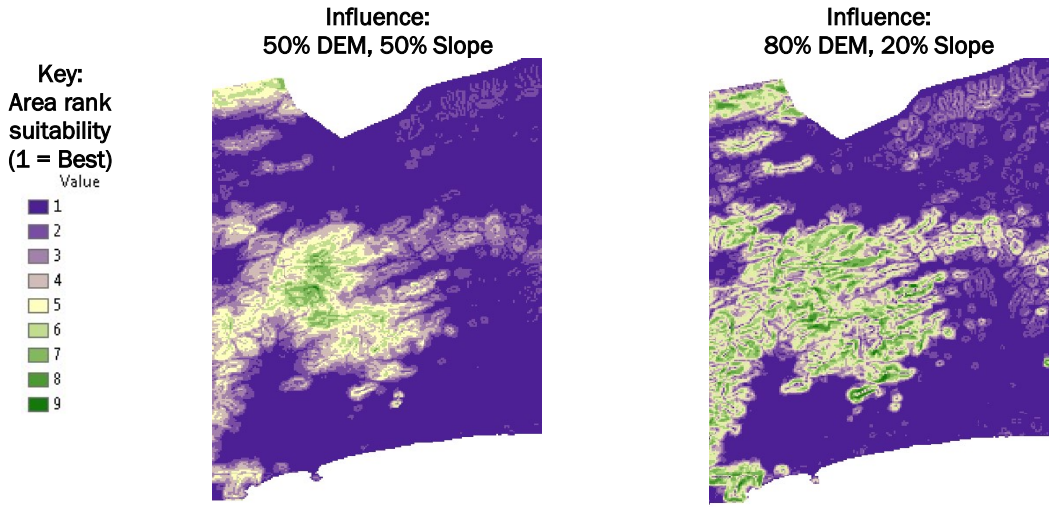



Figure 12-23 Influence of parameters' weights on area suitability.

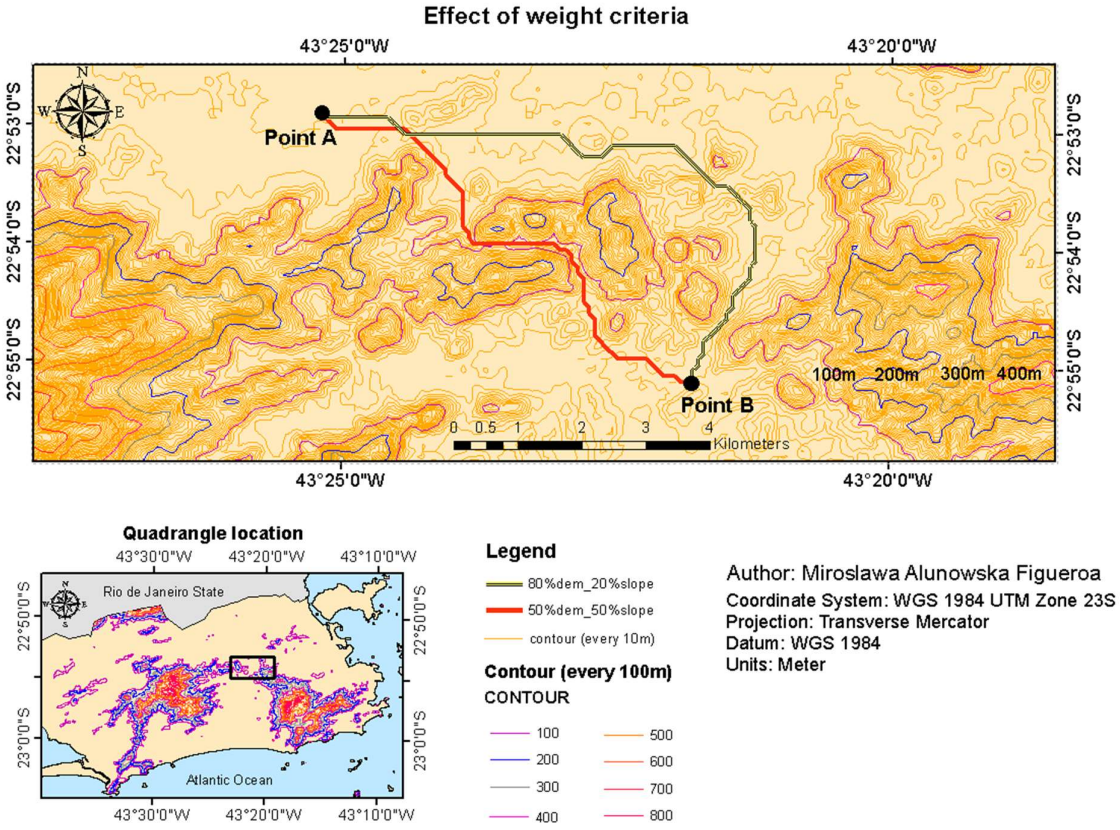



Figure 12-24 Influence of the parameters' weight on the path. The coordinates of the points are: Point A (22°55'30"S, 43°12'24"W) Point B (22°55'37"S, 43°13'53"W).

### 12.4.2 Influence of terrain height on the pipe path

An original DEM was compared with another for the same geographical area but using 50% flattening. To appreciate the effect, it was necessary to standardise values between the two DEMs, the method is called reclassification. The same approach was applied to the comparison of slopes. The respective DEM's height and slope proposed reclassification values are shown in Table 12-5.

Table 12-5 Reclassification values for Elevation and Slope.

| Value | Elevation | Slope |
|---|---|---|
| 1 | 0.0 – 100.7 | 0.0 – 6.6 |
| 2 | 100.7 – 201.4 | 6.6 – 13.3 |
| 3 | 201.4 – 302.1 | 13.3 – 19.9 |
| 4 | 302.1 – 402.8 | 19.9 – 26.5 |
| 5 | 402.8 – 503.5 | 26.5 – 33.2 |
| 6 | 503.5 – 604.2 | 33.2 – 39.8 |
| 7 | 604.2 – 704.9 | 39.8 – 46.4 |
| 8 | 704.9 – 805.6 | 46.4 – 53.1 |
| 9 | 805.6 – 906.3 | 53.1 – 59.7 |
| 10 | 906.3 – 1007 | 59.7 – 66.3 |

Figure 12-25 illustrates the comparison of the reclassification of a mountainous area of Rio de Janeiro city. On the left-hand side is the original DEM and its homogeneous 50% flattening is on the right-hand side. Each value in the reclassification scale is associated with a colour, e.g. black corresponds to value 1, and light green corresponds to value 2, etc. It can be clearly seen that the mountainous area with the flattened DEM has considerably more black and green areas in comparison with the original DEM.

The consequence of flattening the surface is, assuming no other changes, a shorter pipe path between point A and B, as illustrated in Figure 12-26. The coordinates of the example points are: Point A (683906, 7462642) or (22°55'30"S, 43°12'24"W) Point B (681342, 7462452) or (22°55'37"S, 43°13'53"W). The average slope for both scenarios is -0.00056, yet there is a contribution towards the reduction in the accumulated pumping cost from the decrease in the pipe's elevation in the flattened DEM.

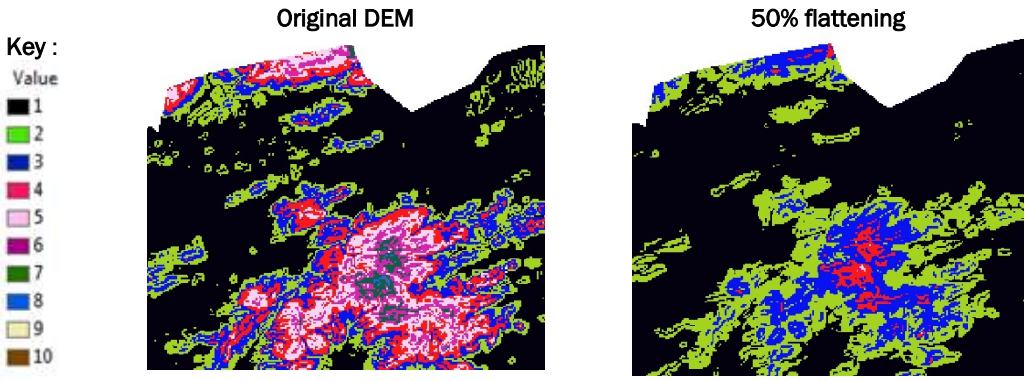



Figure 12-25 Effect of flattening a DEM using standardised values in a mountainous area. In the flattened DEM the area ranked with the value 1 (in black) and 2 (in green) is larger than in the original DEM.

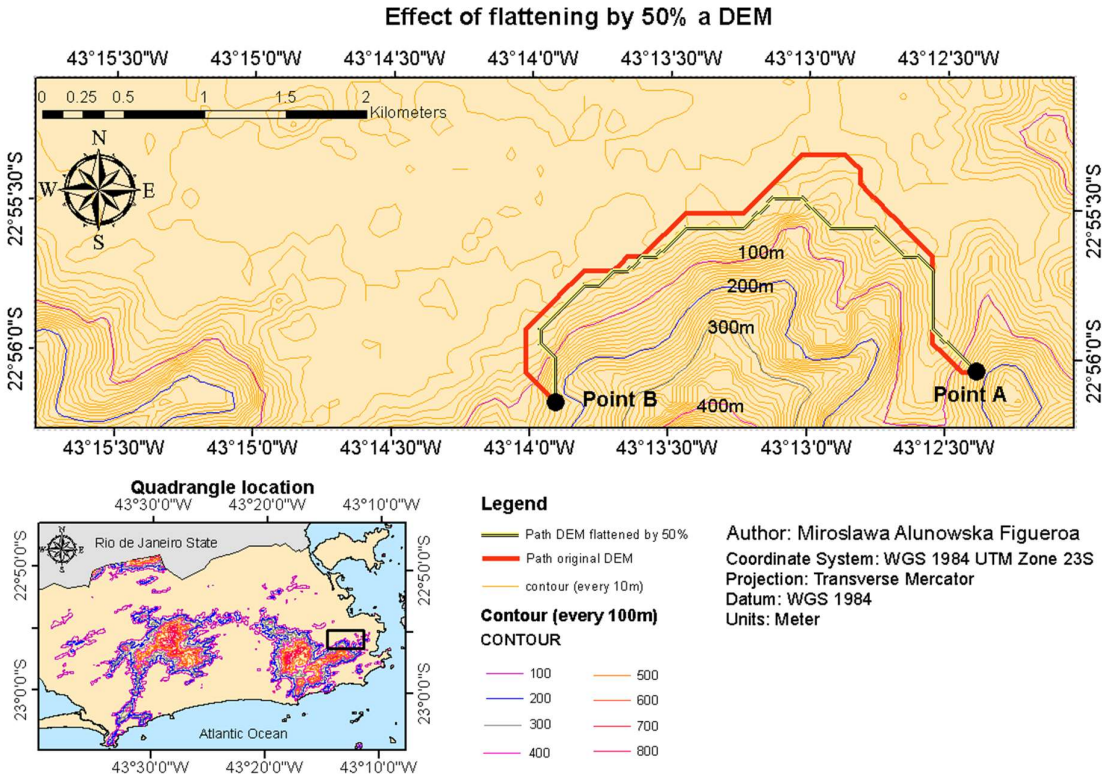



Figure 12-26 Effect of flattening a DEM on a pipe path. The coordinates of the points are: Point A (22°55'30"S, 43°12'24"W), Point B (22°55'37"S, 43°13'53"W).

## 12.5 Number and Distribution of WWTPs Potential Site Options

The parameter values in this section correspond to those of the Standard, F and G set-ups of Table 12-1. Figure 12-27 illustrates the sites opened and the percentage of collection points

that are connected to a particular WWTP site. Figure 12-28 illustrates the influence of the number and distribution of WWTP site options on the number of WWTPs opened. The assigned technologies for the "Mixed technologies" system for each corresponding potential site from WWTP ID 65 to 69 were respectively as follows: Lagoon, SBR, Lagoon, SBR, Lagoon.

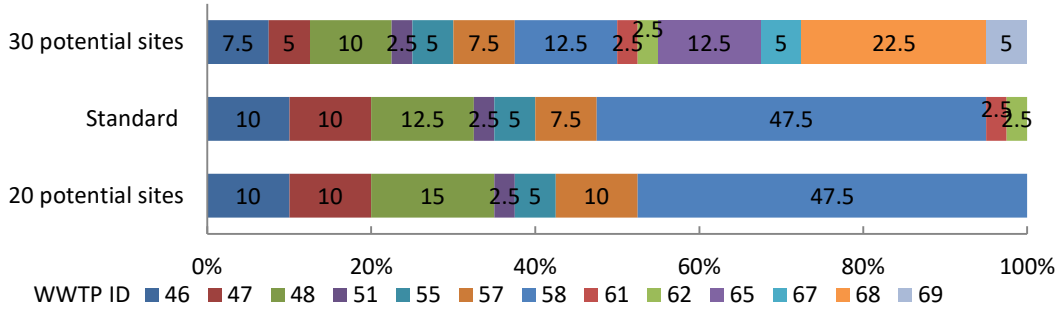



Figure 12-27 Plants opened and percentage of collection points that convey to each WWTP from changes in availability of potential WWTP sites.

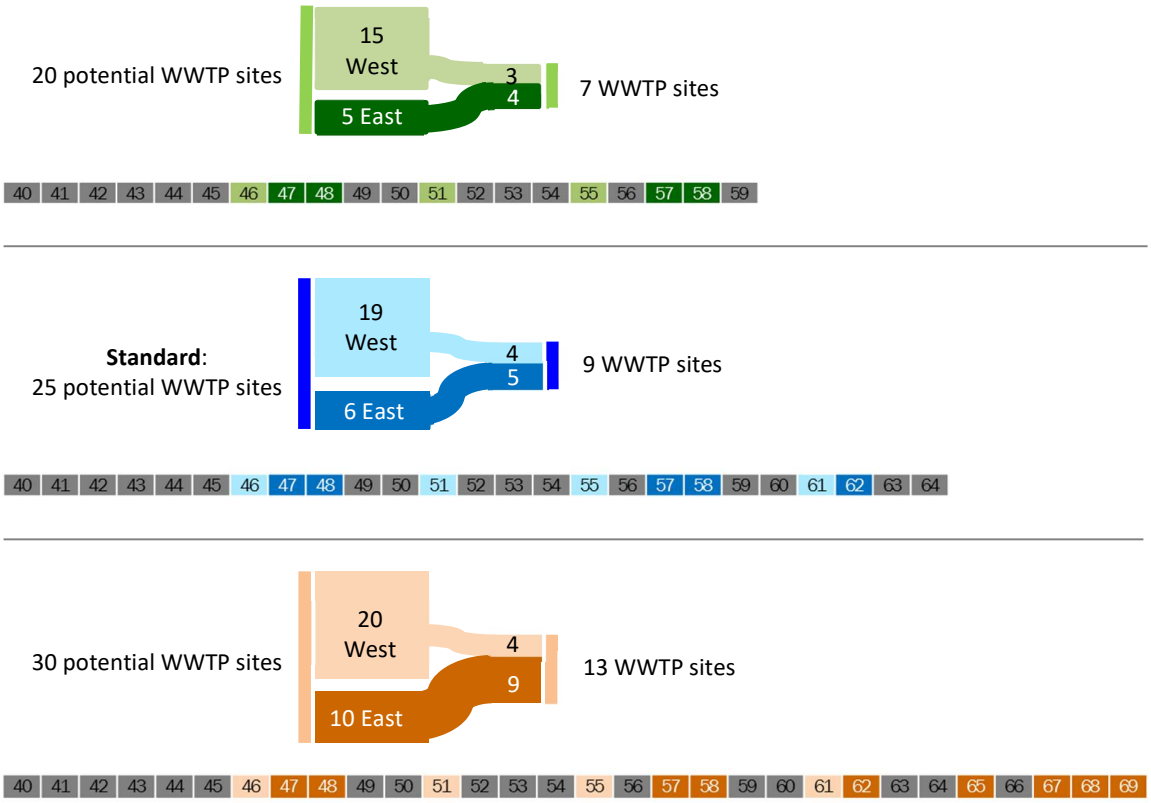



Figure 12-28 Number and distribution of potential WWTP sites and WWTP sites opened considering changes in availability of potential WWTP sites.

Not only is the number of potential WWTPs important, but their distribution is as well, as shown in Figure 12-29. The new sites chosen to be added by the system each time have more viable attributes. For example, they are mostly located in the East part of the city, so their locations are closer to the more densely populated area. Between 80 and 90% of the East zone's potential nodes, e.g. WWTP IDs 47, 48, 58, and 57, (see Figure 12.6) are opened in comparison to the near constant 20% of those located in the West zone e.g. WWTP IDs 46, 51 and 55 (see Figure 11.7).

Each set-up is colour coded to distinguish them from one another, thus whenever referring to them the colour will be set-up F (20 potential sites) will be **green bars**, set-up Standard will be **royal blue bars** and set-up G (30 potential sites) will be **peach bars**. The amount of wastewater to treat is constant, so some of the individual WWTP sizes decrease as the number of opened WWTPs increases. Figure 12-23 illustrates the influence of the number and distribution of potential WWTP in comparison with the plants opened in the Standard set-up.

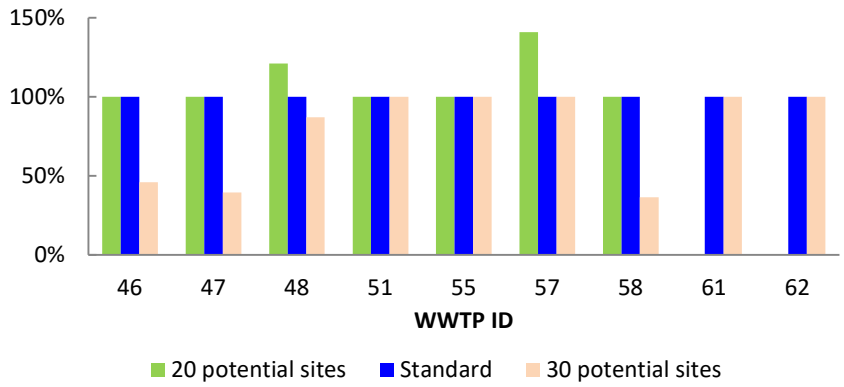



Figure 12-29 Influence of the availability of WWTP sites on the amount of wastewater treated per plant in set-ups F and G compared with the Standard set-up.

Figures 12-30 and 12-31 illustrate the influence of availability of potential WWTP sites on the sewerage system and on the total semi-centralised system in comparison with the Standard set-up. It is important to mention that economies of scale on the group of WWTPs are not implemented in the model. As more plants are opened the average cost per unit of water would increase as well as the overall. Thus, the 131% value in Figure 12-30 will be an overestimate.

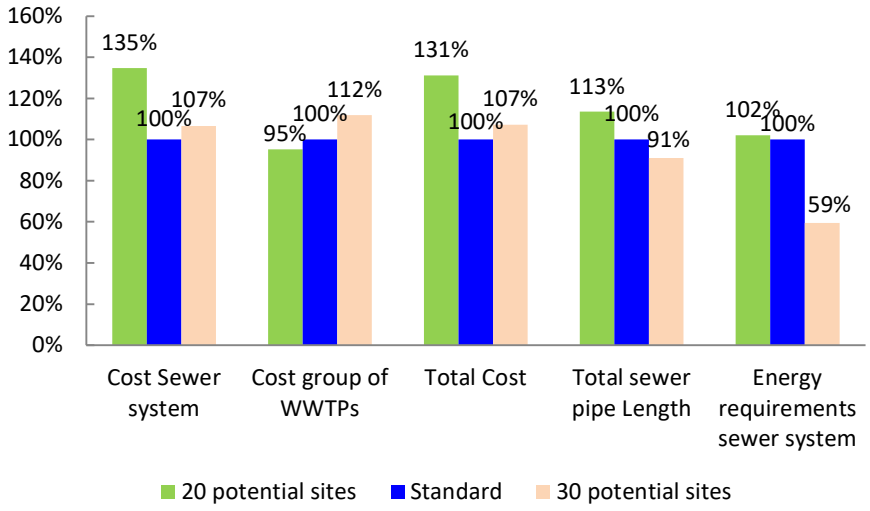



Figure 12-30 Cost comparison of set-ups F and G with the Standard set-up considering changes in the availability of potential WWTP sites.

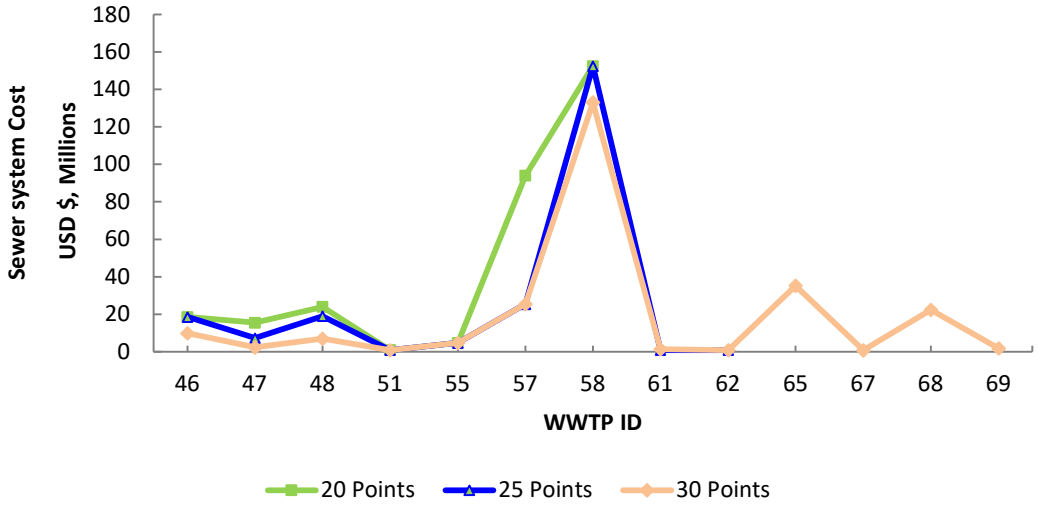



Figure 12-31 Comparison of set-ups F and G sewerage system costs in relation to the WWTPs in the Standard set-up.

In terms of the sewerage system, the Standard set-up is the cheapest of the three options, although it might have been expected that set-up G would have had the lowest cost because its total sewer pipe length is the shortest one. To gain a better insight, Figure 12-31 takes a closer look at the three cases.

The locations of the potential WWTP sites are important because the entire layout of the semi-centralised system changes; this is evident when comparing the Standard and G set-ups.

In the G set-up, there was a major reallocation of wastewater collection points as illustrated in Figure 12-31 from WWTP 58 to either WWTP ID 65 or 68. The cost reduction associated with set of plants consisting of WWTP 46, 47, 48 and 58 is 74% of the cost associated with the sewerage systems of the four additional sites (WWTP ID: 65,67,68,69) needed to fulfil set-up G.

Finally, a comparison between a semi-centralised system and a centralised system depends on the placement of the centralised system. For instance, if WWTP ID 63 were proposed, the total wastewater transmission cost would be greater in comparison with the Standard case, but its location could be contested.

## 12.6 GAZA STRIP APPLICATION

The DSS was applied in a completely different urban area: the Gaza Strip. The Palestinian region occupies approximately 360 $km^2$ and is located on the eastern cost of the Mediterranean Sea and borders Egypt on the southwest and Israel on the east and north. The input data is as shown in Figure 12-32.

The methodological framework was implemented as described in Figure 3-1. The activities undertaken to contextualize the DSS were: (1) Provided the data input as described in Figure 1-4. That is: regional cost equations, electricity tariff, influent wastewater quality, DEM, etc. (2) Created completely new WWTP technologies classes to capture the decision maker's regional preferences, the OOP approach facilitated this task. The results of the implementation of the methodological framework and DSS are illustrated in Figure 12-33.

The results obtained showed that the model is robust, and the automation steps saved time. Although the details of the project are outside the scope of this document, a paper will be published; it helps to validate the methodological framework and DSS.

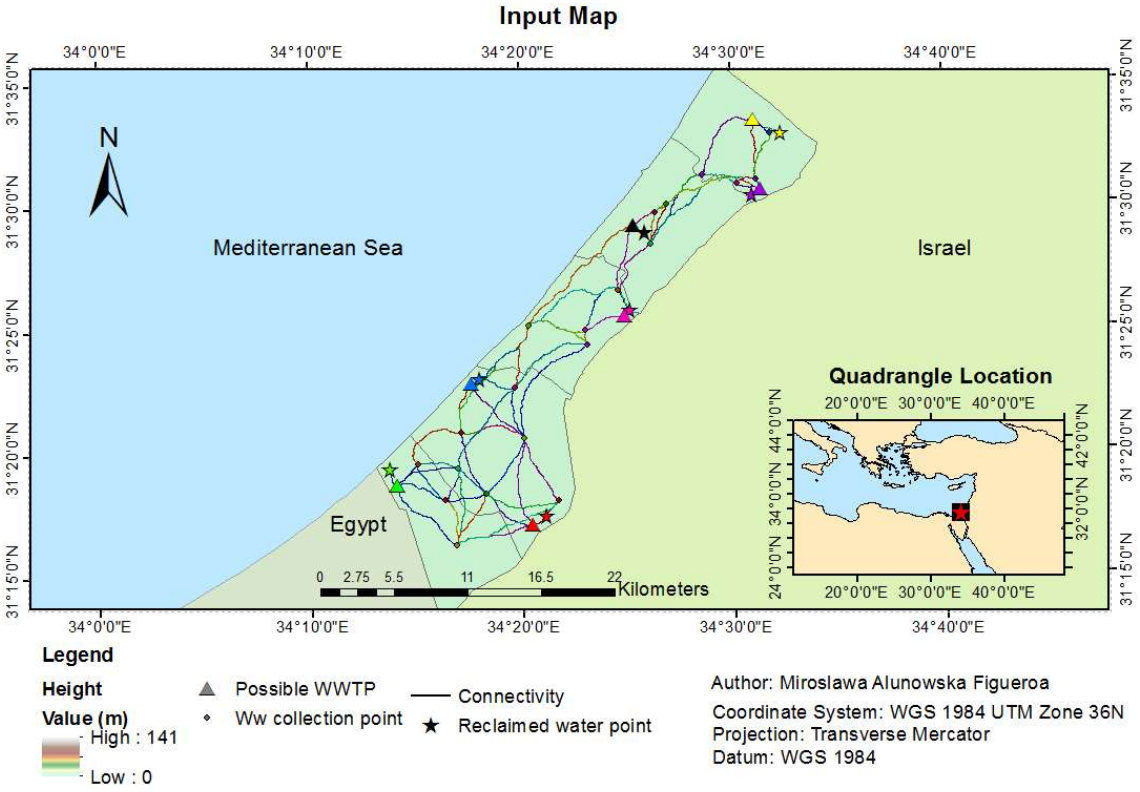



Figure 12-32 Visualisation of node connectivity.

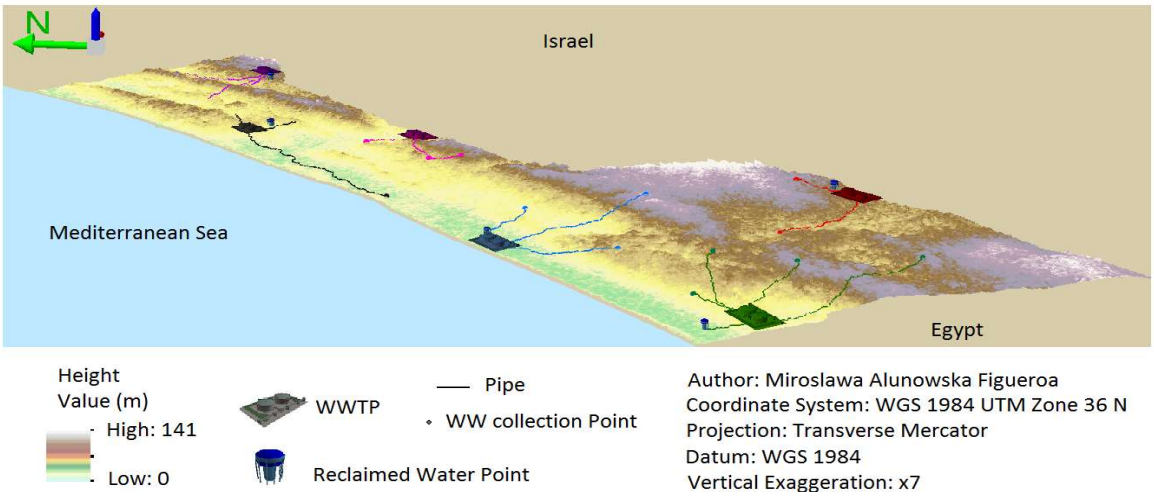



Figure 12-33 Visualization in 3D of the SUWWTS layout for the Gaza Strip.

## 12.7 SUMMARY AND CONCLUDING REMARKS

Table 12-6 presents the effects of the parameters. The colour code on the cells were normalised according to the relative impact of each model input, increasing shades of blue represent a larger impact [275]: white represents zero impact and dark blue represents maximum impact.

Table 12-6 Effect of the parameters on the semi-centralised system layout. The colour code on the cells were normalised according to the relative impact of each model input, meaning that increasing shades of blue represent a larger impact: white represents zero impact and dark blue represents maximum impact.

| Model Input | Impact on | | | Comments |
|---|---|---|---|---|
| | Number of WWTPs opened | Sewerage system | Cost | |
| Terrain Height | | | | A. The more expensive technologies are more sensitive to height. Fewer sites are opened in comparison to the cheapest technology as the surface is flattened.<br>B. As the surface is flattened, less energy is required for wastewater transmission, but in an essentially flat situation the construction costs rise. |
| Number and distribution of WWTP site options | | | | Potential sites closer to the urban area are opened |
| Wastewater quantity | | | | The system of "Mixed-technologies" is more sensitive to wastewater quantity |
| Population distribution | | | | It influences the flow conveyed, so there are changes in the sewerage system |
| Wastewater Treatment Technology | | | | Influences occur on land requirements, $CO_2e$ and energy requirements |

Following analysis of the outputs from the sensitivity analysis, the main findings are as follows:

1. The semi-centralised system layout and the wastewater treatment cost are largely defined by the wastewater transmission cost. The variables that influence this cost include the following:
    1.1. Wastewater quantity. The wastewater quantity is a function of population growth, population distribution, average water demand values and earnings (the poorest tend to consume less water).
    1.2. The number and distribution of WWTP site options. These parameters, together with connectivity, determine the distance wastewater must be conveyed.
    1.3. Network connectivity. This parameter also influences the distance wastewater must be conveyed (node from - node to).

1.4. Terrain height. This parameter determines the height that wastewater must be lifted.

2. Although some parameters, such as height and number of available WWTP sites, have a more significant impact on the layout than others (e.g. electricity cost).

Finally, although it is difficult to demonstrate applicability of alternative design approaches because the analysis of urban water systems relies on case studies [276], the sensitivity analysis demonstrated the capabilities and usefulness of the DSS:

- The semi-centralised wastewater treatment system model is robust
- The results obtained with the DSS are mostly realistic
- The DSS can be applied to any region, as proven by implementation in the Gaza Strip.

# CHAPTER 13
# SCENARIO ANALYSIS

A feasibility study on implementing a SUWWTS in the city of Rio de Janeiro in 2030 was undertaken to illustrate how to tailor the DSS and to showcase its functionality. In doing so, we transition the framework's concept from the general goal to a specific case.

In the absence of existing case-studies in an urban area with comparable characteristics to those of Rio de Janeiro city and given that research into semi-centralisation is in its infancy, a rigorous validation of the DSS is not possible. Hence, the proposed DSS should be used as a first estimate of the preferred solution. Until the reality of semi-centralisation grows, it is not possible to have facts and evidence that characterize the emerging reality. Consequently, the outcome is **not** a proposed solution for the city of Rio de Janeiro but is illustrative of the benefits that can be gained from semi-centralisation which will be of value to those planning new cities.

## 13.1 OVERVIEW

Future Studies examine key trends and their outcomes with the hope of successfully influencing such outcomes [277]. The results provide information of what mid- or long-term time frame future may be and are useful for the planning stage for preparation of decisions.

The foresight method implemented in this research is the "intuitive logics" school to develop *scenarios*, which is the generation of stories that describe *plausible* futures [278,279]. The author of this Thesis agrees with the notion that there are limitations to knowing and instead appreciates intrinsic uncertainty [75].

A scenario development project entails considerable time and resources [280,281,282] and it is not the aim of this Thesis to develop a comprehensive one given time and financial constraints. The analysis is simplified (could be considered exploratory) given that it is an exercise to illustrate the DSS' usefulness.

## 13.2 FRAMING

This step defines the scope: the issue for which foresight is needed. There is uncertainty surrounding the future of the city of Rio de Janeiro, future is by no means a linear extrapolation of the past. Project planning should have a forward-looking, long-term point of view: how do its inhabitants envision their city?

The importance of smart solutions and appropriate infrastructure within limited space becomes very relevant considering the uncertainty of future drivers. A feasibility study of the semi-centralisation of wastewater treatment plants may be part of a resource management practices portfolio to ensure the robustness of a 2030 Rio de Janeiro city.

The objective (problem statement) is to design of more integrated wastewater networks across a city as a means of promoting sustainability. The research question is: How does socio-economic and geographical urban context relate to the number of semi-centralised wastewater treatment plants in the City of Rio de Janeiro? The ultimate end of the semi-centralised wastewater treatment system is to achieve water security, to create a robust city that copes with urbanisation challenges whilst exerting less pressure on ecosystem services.

The expected audience are design engineers who are exploring the implementation of SUWWTS. The goal is to support decision making and it can arguably indirectly engage a political dialogue when decision makers are configuring the DSS with the required data

The rationale of this project is that Brazil, along with its fellow BRICS countries (Russia, India, China, and South Africa) might become a significant player in the multipolar international system because of its economic size, stable democratic government and material resource capabilities [283]. Consequently, Brazil should manage its urban water resources efficiently to keep economic growth and social development whilst limiting environmental impacts.

Brazil is a continent-sized country: it is the world's fifth largest country, both by geographical area and by population with its 190 million people, as of 2010 [284]. The Brazilian economy is

the world's sixth largest by nominal GDP [285] and, as of 2011, it was the seventh largest by purchasing power parity (PPP)[i] [286]. Brazil's share of urban population growth over the last 50 years has been impressive: from a population of 52 million residents in 1970 (56% of the country's population) to 138 million residents in 2000 (81% of the population). It has been predicted that all net population growth over the next 30 years will be in cities [287].

Rio de Janeiro is the second largest city with the second GDP in the country. The city is a major national hub, it is the second financial and service centre, as well as having significant industrial production. It is the headquarters for the Stock Exchange of Rio de Janeiro (BVRJ), for state-owned and for transnational companies. Also, major entertainment, fashion and media organisations are based in the city. It would be wise for the city to meet the challenges created by the pace of global change, otherwise through resisting the impulse for transformation, it would stagnate [288].

The city is still attracting industry: in the West Zone the largest steel complex (*Complexo Siderúrgico da Zona Oeste*) has been built and perhaps its northern zone might attract more investment with the recently discovered oil reserves. Petrobras, the Brazilian State Oil Company, announced in 2006 a discovery of Brazil's pre-salt region that can mean reserves of over 50 billion barrels of oil, a volume four times greater than the current national reserves (approx. 14 billion barrels) [289]. The pre-salt region is located under salt layers, is up to 200 km wide and extends for 800 km along the Brazilian coast: from the state of Santa *Catarina* to *Espirito Santo* state, passing through Rio de Janeiro State. The oil and natural gas lie 6000 m below sea level.

[i] A nation's GDP at purchasing power parity (PPP) exchange rates is the sum value of all goods and services produced in the country valued at prices prevailing in the United States. This is the measure most economists prefer when looking at per-capita welfare and when comparing living conditions or use of resources across countries. The measure is difficult to compute, as a US dollar value has to be assigned to all goods and services in the country regardless of whether these goods and services have a direct equivalent in the United States.

## 13.3 DATA GATHERING

A collection of information on Rio de Janeiro city was made to identify the driving forces behind the internal and external issues that may impact on the issue framed in the first step (framing). In general change may occur in the following areas: societal, technological, economic, environmental, or political. This step is important because it will eventually set out the terms and conditions for the computation of results.

Despite the efforts made by the government, such as the expansion of wastewater treatment and collection systems to contribute to clean up the *Sepetiba* basin, *Jacarepaguá* Lagoon and *Guanabara* Bay [290,291,292], there is an opportunity for improvement in sanitation and water management e.g. there are obsolete wastewater collection systems in the North East and a need for services in the West Zone of the city [293]. According to the latest information on wastewater treatment the city treats approximately 47% of the wastewater per consumed water [293,294]. In 2007, Rio de Janeiro had an average per capita water consumption of 224 l $day^{-1}$ [272] or 7 $m^3$ $month^{-1}$. The average drinking water and wastewater treatment tariff in Rio de Janeiro is 2.4 R$ per $m^3$ $month^{-1}$ [295] or 1.05 USD $ per $m^3$ $month^{-1}$.

### 13.3.1 Values and Priorities in Brazilian Society

The author of this Thesis believes that perhaps one of the reasons for the lack of sanitation infrastructure in comparison to that of water supply in Brazil could be, besides the endemic corruption, the population's values, and priorities [296]. It might be valid to mention that Brazilians have suffered considerably since the time they were a Portuguese colony, so it might have played a role in how they think.

From the perspective of a person who is financially struggling, which is quite a large sector of the Brazilian population, a wastewater treatment plant or *Estação de tratamento de águas residuais* (ETE), benefits the community, not the individual, as such it comes last to the person's priorities. The person might consider a sewerage system important because sanitation issues affect the neighbourhood yet paying for the wastewater collection system is not at the top of

the priorities; consequently, the person will prefer to remain without it. Whilst in the case of water supply the rationale is that having running water benefits the individual immediately, consequently having a water supply system has high priority. Therefore, water supply has been a significant lever of political power in Brazil. Thus, for a successful implementation of a wastewater treatment service the project is to be funded by the Brazilian taxpayer.

### 13.3.2 Water and Sanitation Legislation and Institutional Organisation

Brazil is one of the world's fastest-growing markets for industrial water and wastewater treatment, as of 2008 the market was worth about USD$ 126m. It is a country in which there is a great professional capacity in the water and wastewater sector as well as interest from its stakeholders (federal institutions, state governments, universities, and the private sector).

Brazil's water supply and sanitation reached its present form when it was reorganized during the 1970's implementation of the *Plano Nacional de Saneamento* (PLANASA) or National Sanitation Plan. With the aim of improving water supply and sanitation services a new structural regime was established for the sector in which the responsibility for the provision of services was transferred to each state. Thus, although the municipalities owned the services under the then federal constitution, in effect they had to authorize the transfer of services to the state level.

As a result, concessions to state companies were granted for 25 to 30 years. In every state of the federation companies were created e.g. *Companhia Estadual de Águas e Esgotos do Rio de Janeiro* (CEDAE), to provide either only water services, only sewer services or both. Each of these companies is responsible for financing, for introducing (or expanding) systems, for their operation and maintenance, and has the right to collect tariffs.

Most state water and sewer companies are mixed public-private companies with most shares owned by the state government [297]. The performance of these type of concession varies considerably, some are successful whereas others do not comply with their obligations. Perhaps the most successful state water company is *Sabesp*, in Sao Paulo state, which has floated shares in the Brazilian Stock Market and in the New York Stock Exchange.

After the PLANASA period, the Brazilian government, under President Luiz Inácio 'Lula' da Silva administration, signed a new federal water and sanitation law (*Lei 11.445/2007 para o saneamento básico*) to outline federal policies in the sector to provide universal access to water and sanitation, and launched the *Programa de Aceleração de Crescimento* (PAC) or Growth Acceleration Program with the objective of accelerating economic growth in Brazil by enhancing investments in construction, sanitation, energy, transport and logistics sectors.

The technologies most used for wastewater treatment in Brazil, as of 2011, are: stabilisation ponds (32%), biological filter (28%), up flow anaerobic sludge blanket (27%), activated sludge (11%) and sedimentation tanks (2%) [298]. Activated sludge is a more expensive technology, so it is more commonly used in richer states (like *São Paulo*, *Distrito Federal* and *Minas Gerais*).

The Brazilian government has set ambitious environmental targets that will bring Brazil's wastewater treatment regulations closer to those of developed countries. The implementation of such high goals will require the analysis of strategies to establish a step-change process in order to meet such an ambitious regulatory regime [299]. With the new regulations it is expected that there will be investment growth in biological secondary treatment, nutrient removal, sludge treatment systems and water reuse and recycling technologies, such as MBRs, to provide high-purity process water for the growing industrial demand. In addition, the National Water Supply and Sanitation Policy identified six steps to improve service coverage and efficiency, one of which is the promotion of different decentralized alternatives for service provision.

Some of the laws, programs and institutions put in place to manage water and sewage treatment are the Municipal Climate Change and Sustainable Development Policy, Law no. 5248/2011 [300], the National Water Resources Policy approved by Federal Law No. 9433/97 [301], the *Agência Nacional de Águas* (ANA) or National Water Agency and the *Programa Despoluição de Bacias Hidrográficas* (PRODES) or Basin Restoration Program.

Funding sources are from federal government, local governments, and international institutions. One of the federal sources would be that of the ANA's revolutionary program based on "*output-based aid*," which pays for results given that it is more effective to pay for an actual result than for a promise. For PRODES the result is the treated sewage quantity and quality. The committed funds are set aside in a development bank, thus from the service provider perspective non-payment risk is reduced in case there are government budgets cuts. If the service provision does not meet the standards, the allocated funds return to Brazil's National Treasury [302].

According to the World Bank's Private Participation in Infrastructure database, investment commitments by the private sector in Brazil's water and sanitation sector reached USD$ 3 bn in 1994-2004 through 52 projects. The country's water and wastewater treatment market is expected to continue growing in the following years in order to meet the demand from population growth as well as to meet the growing demand from oil and gas, petrochemicals, mining, pulp and paper, and the metal industries.

Recent sanitation projects of a total of USD$ 842m (BRL R$ 2,4bn) are intended to be invested in concessions for sanitation projects, infrastructure investment spurred on by the sporting events of the World Cup 2014 and the Olympics in 2016 [303,304,305]. This amount is the largest sanitation concession project in Brazil which, besides improving the social impact, also sets up environmental rehabilitation plans to clean up the city's *Guanabara* Bay, *Rodrigo de Freitas* and *Barra de Tijuca* lakes; a number of 2016 Olympics events will take place in the last one.

Despite the obvious investment opportunities in the water and sanitation sector, there are some political challenges. Throughout Brazil's history the water and sanitation sector has been seen as a significant lever of power, thus it is characterised by tensions between interest groups that struggle for social, economic, and political power. To begin with, there are tensions between the federal, state, and municipal governments regarding their role in the sector. In

addition, there are disputes between representatives of the public and private sectors and federal authorities. Furthermore, within the sector the main antagonistic groups are the state governments, and the state sanitation companies on one side and the federal government, municipal authorities, and civil society on the other [306]. Some comprehensive reports in English of the legislation and organisational structure in Brazil are [298, 307,308].

## 13.4 SCENARIO DRIVERS

Five different sets of scenario *drivers*, or driving forces, were identified. A driver is defined as an uncertain issue that shapes a particular plot or plausible future context; if there is certainty, then it is not a scenario driver [309]. Table 13-1 summarizes the main drivers identified and their code, each set is colour coded to make them easier to distinguish from one another. The codification criteria are described in Table 13-2. The fifteen scenario drivers identified can readily be linked to the DSS data input as shown in Table 13-3.

Table 13-1 Scenario drivers

| Social | Technological | Environmental | Economic | Political |
|---|---|---|---|---|
| **Demographic Change (S1)**<br>Uncertainties:<br>- The degree of social integration, particularly of Favelas (shanty towns)<br>- Education.<br>- Percentage of working population<br>- Distribution of wealth<br>- Population growth<br>- Inmigration/emigration<br>Direction: Equality or inequality | **Embracing New Technology (T1)**<br>Uncertainties:<br>- Investors willingness to adapt innovative technologies<br>- Global competition<br>- Institutional incentives to adapt new technologies<br>- General public perspective of a technological implementation<br>Direction: Hi-tech or Old-fashioned | **Water Availability (E1)**<br>Uncertainties:<br>- Economic/population growth<br>- Consumption habits/sustainability values<br>- Climate change<br>- Water management policies and their succesful implementaiton<br>- Water availability: human and environmental needs<br>- Rainfall concentration<br>Direction: Availability or Exploitation | **Economic Model (F1)**<br>Uncertainties:<br>- Values and paradigms<br>- Climate change impact<br>- Power struggle<br>- International financial stability<br>Direction: Corporate social responsibility or Pure pursuit of profits | **Government Vision of Regional Competitiveness (P1)**<br>Uncertainties:<br>- Ability of federal and regional government to develop policies<br>- Nationalism<br>- Values and priotities for investment<br>- International geopolitics trends<br>Direction: Competence or Incompetence |
| **Consumption (S2)**<br>Uncertainties:<br>- Use of resources.<br>Direction: Sustainable or Unsustainable | **Innovation and Research & Development (T2)**<br>Uncertainties:<br>- Economic environment<br>- Investment in R&D<br>- Education<br>- Attraction of highly skilled personnel<br>Direction: Pioneer or Follower | **Sustainability (E2)**<br>Uncertainties:<br>- Consumption habits/sustainability values<br>- Climate change<br>Direction: Preservation or Exploitation | **Investment (F2)**<br>Uncertainties:<br>- Incentives: political/economic/social stability<br>- Infrastructure<br>- Paradigms e.g. crowdsourcing<br>Direction: Inflow or Contracted | **Governance (P2)**<br>Uncertainties:<br>- Effective leaders<br>- Paradigms for public governance<br>- Quality of governance institutions<br>Direction: Effective or Corruption |
| **Urbanization (S3)**<br>Uncertainties:<br>- Urban planning policies and their successful implementation<br>- Economic, social and political atmosphere<br>- Security: Implementation of security policies or Pacification of Favelas (e.g. against drug gangs)<br>- Health services: Quality and quantity of practitioners and resources; universality<br>Direction: Smart city or slum | | **Resource availability (E3)**<br>Uncertainties:<br>- Availability, accessibility and viability to exploit finite resources e.g. biofuel, phosphorus (used in food production)<br>- Recycling resources<br>Direction: Abundance or Scarcity | **Economic Growth (F3)**<br>Uncertainties:<br>- Tax rate<br>- Income<br>Direction: Strong or Weak | |
| **Values (S4)**<br>Uncertainties:<br>- Corruption<br>Direction: Corrupt or Honest | | **Climate Change Impact (E4)**<br>Uncertainties:<br>- The impact of the change<br>Direction: Mild or Harsh | | |
| | | **GHG Emissions (E5)**<br>Uncertainties:<br>- Rate<br>Direction: Increase or Reduction | | |

Table 13-2 Scenario driver's codification criteria.

| Criteria | Description |
|---|---|
| Document Inclusion | • Official documents<br>  ○ Brazilian Institute of Geography and Statistics<br>  ○ Institute Pereira Passos of the Municipality of Rio de Janeiro<br>  ○ Ministry of Agriculture (Ministério da Agricultura, Pecuária e Abastecimento)<br>  ○ National System of Sanitary Information (Sistema Nacional de Informações sobre Saneamento)<br>  ○ National Water Agency (Agência Nacional de Águas)<br>  ○ National Agency of Electricity (Agência Nacional de Energia Elétrica)<br>  ○ Rio Federation of Industries (Federação das Indústrias do Rio)<br>  ○ Petrobras<br>  ○ Presidence (Presidência da República)<br>• Newspapers: national e.g. Folha de S. Paulo, and international ones e.g. the Guardian<br>• International organisations:<br>  ○ World Bank<br>  ○ Intergovernmental Panel on Climate Change (IPCC)<br>  ○ Organisation for Economic Co-operation and Development (OECD)<br>  ○ International Council for Science<br>• Peer reviewed journals.<br>• Documents were dated 2000 onwards. |
| Search Keywords | Strategic plan, scenarios, economic development [310], energy, wastewater, urban management, population growth, urban slums, water management, Rio de Janeiro |
| Concepts | Scenario development approaches by consulting companies, governmental offices or universities e.g. Roland Berger Consultants [311], World Bank [312,313], Environmental Change Institute at University of Oxford [314]. |
| Cross checked efforts | • With other scenarios documents, such as companies e.g. Severn Trent Water, Natural England Commissioned Report NECR031 Scenarios Compendium -a very comprehensive report [61]- or international organisations e.g. Deutsche Bank [315].<br>• Meeting with experts in scenarios. |
| Rounds | Three. Originally 19 drivers were proposed, yet some social drivers were merged, and the list was reduced to 16 drivers. |

Table 13-3 Identification of scenario drivers in the DSS data input.

| Strategies | Scenario Drivers | Scenarios<br>Define urban area attributes:<br>(Data required to compute performance variables) | Scenario Drivers |
|---|---|---|---|
| Design variables | T1, E1 | Average Annual Population Growth | S1 |
| Performance variables | F1, E2, F2 | Average Water consumption | E2 |
| | | Energy Mix (%) | E3 |
| | | Average Annual Energy Tariff Increase | P2, E5 |
| | | WWTP available area | S2 |
| | | Network of node connectivity | S2 |
| | | Reclaimed water demand | E1, S3 |
| | | Wastewater collection points | S2 |

The interview participants were selected by purposive sampling and snowball sampling (the participants were asked to recommend other persons to invite to be interviewed) [316]. The criteria to identify participants included their specialist knowledge and willingness to participate. The interviews were conducted in person and notes were taken. The interviews were

semi-structured and personalised, some general open-ended questions were prepared to obtain their opinions, insights, and feelings, see Appendix VIII.

### 13.4.1 Ranking Driving Forces

The identified driving forces were ranked according to their importance and uncertainty. The exercise was subjective and is depicted in Figure 13-1. The most uncertain and important driving forces were Government vision of regional competitiveness (P1) and Climate change impact (E4), these are highlighted with a dashed line.

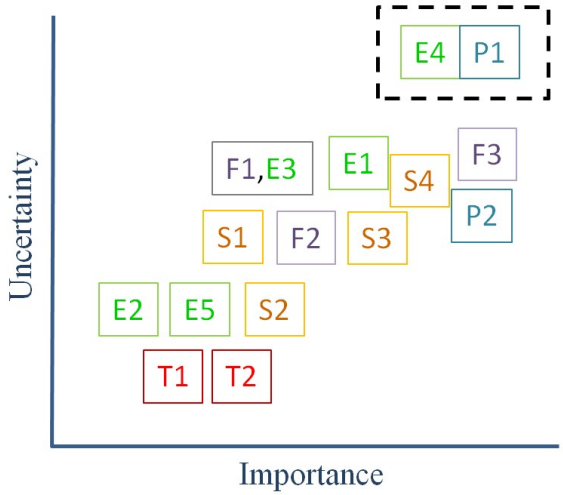



Figure 13-1 Ranking of driving forces in terms of their relative importance and uncertainty.

## 13.5 SCENARIOS

The third step is the creation of plausible futures using the deductive method [280]. The scenarios were based on two axes of uncertainty, the two drivers of change being on the y-axis Climate Change Impact Awareness (E4) and on the x-axis Government Vision of Regional Competitiveness (P1). The criteria used to select these two drivers were: (1) they are independent from each other, and (2) they appear to be the most uncertain and important driving forces. The axes produce a structure that determines the main scenario story lines [317].

The interpretation of the 2x2 matrix is that it represents *incommensurate possibilities.* The axes have an either/or calibration, each of the quadrants contains one scenario that represents a

different ‘frame’ or worldview. The present day is represented at the axes’ intersection point [317]. The four scenarios coexist only as plausible futures in the present. Once a quadrant is metaphorically ‘entered’ into from an unfolding future the other three scenarios cease to exist unless there is a return to the exact same state as the present [317].

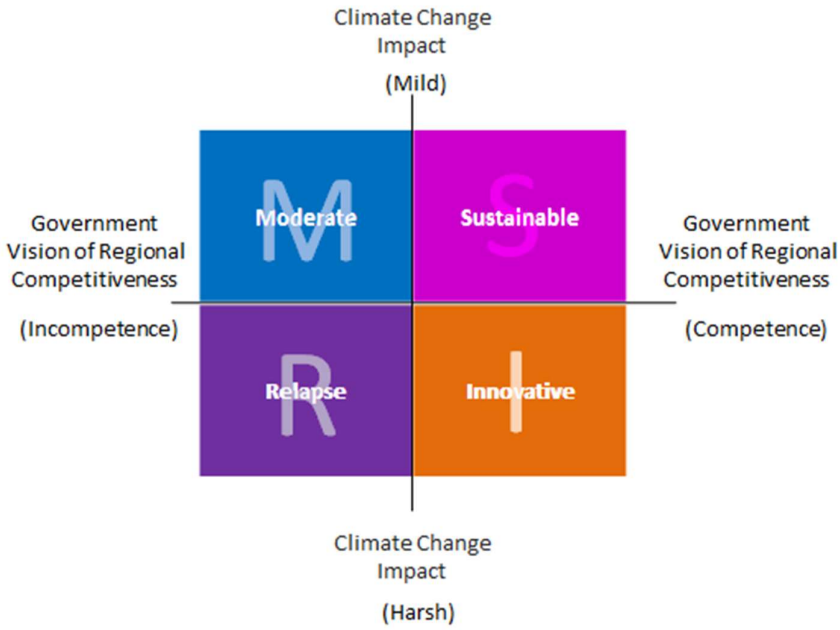



Figure 13-2 2x2 matrix. The scenarios were based on the two axes of uncertainty, on the y-axis Climate Change Impact (E4) and on the x-axis Government Vision of Regional Competitiveness (P1).

Thus, the futures are characterised as being *non-probabilistic, mutually exclusive*, and *equi-plausible*. Equi-plausible means there is no “best” or “worst” future [75, 317]. Mutually exclusive means that movement across an axis involves a discontinuity rather than an incremental change. Therefore, the plausible futures do not overlap; to be precise, do not affect different market segments or locations [317].

It should be noted that in the creation of the scenario storylines major shocks or extreme events that might fundamentally redraw the world (e.g. a meteorite hitting the city of Rio de Janeiro) have been excluded, which are known in the scenario’s jargon as *wild cards*. The scenarios were created through desk research and by seeking advice from experts in scenario creation. The criteria to evaluate a scenario are coherence, plausibility, challenge, novelty, and

internal consistent assumptions. The scenario stories are the following, each scenario is colour coded to distinguish one from another and whenever referring to them the word font will change, e.g. Scenario Name in their corresponding colour.

## Sustainable

In this scenario story Brazil is a powerful nation in which the geopolitics are characterised as multipolar centres of power. The decision-makers thinking will be focused on a good quality educational system and smart management of natural resources. The vision of the city is to be a sustainability leader whose great potential and success is due to the high quality of its human resources. There are regulatory and policy frameworks that incentivise the population to adopt sustainable consuming practices. Thus, investment is flowing towards encouraging companies to minimise negative impact on the environment. This is the scenario like the one proposed for Brazil by President Dilma Rousseff [318]. Immigration and population growth have kept the demographic growth at a reasonably low level. Water policies have achieved the average water demand per person to be the same as the value for Germany in 2007.

## Innovative

This scenario story describes a future in which Brazil is a key power player in international politics. The decision-makers thinking will be focused on high-tech to consolidate Rio de Janeiro's position as a financial, industrial, and cultural hub. This is a future like the one envisioned by the Municipal Government [292]. Decision-makers understand the importance of creating an attractive environment for investment, so to increase Rio de Janeiro's competitiveness and long-term prosperity, they foster incentives and tax benefits for innovative technology companies and create policies to minimise environment impact. The investment environment is one characterised as being an efficient collaboration between public-private sectors, especially in infrastructure and energy, and there is an efficient use of the region's bountiful resources. Immigration and population growth have kept the

demographic growth in a reasonable level. Water policies have achieved the average water demand per person to be the same as the value of The Netherlands in 2007. This is 6% higher than that of Germany in 2007.

## Mixed

The main characteristic of this scenario story is that international politics are driven by power struggles between USA and the five major emerging national economies: Brazil, Russia, India, China, and South Africa (BRICS). The decision-makers thinking will be focused on the pursuit of profits based on the exploitation of the city's bountiful natural resources; there is an excessive reliance on primary products, from the pre-salt oil fields. There are policies to mitigate climate change impact and improve the economy, but it is not clear how to implement them. Investment is particularly in old technologies given that regulation does not allow flexible and innovative approaches. Rio de Janeiro is still a very popular city given its resources, so it attracts qualified and unqualified, national, and international immigration. Thus, there is a considerable annual population growth. Water policies have achieved the average water demand per person to reduce by nearly 60% from the value reported in 2007, making it like the value that Denmark had in 2007 (13% higher than that of Germany in 2007).

## Relapse

A scenario that articulates a story characterised by a severe tension in the international politics, many nations are at war. The decision-makers thinking will be focused on achieving regional competitiveness based on financial profit, so the regulatory regime incentivises solutions with a high return on capital rather than sustainable solutions. There are policies to mitigate climate change impact and improve the economy, but these are not implemented. There is corruption, economic inequality, power greed and bad governance. The failure of regional governance results in contraction of investment in the city. There is an uncontrolled

population growth. Water policies have been unsuccessful and the average water demand per person remains like that of the national average in 2007.

### 13.5.1 Implications and Application

The scenarios provide visions of how decision-makers would think. The future of the city would be shaped by cultural values which would have a profound effect on behavioural choices people make. For instance, a culture that acknowledges the value of ecosystem services can implement actions that reflect their behavioural choices.

Each scenario story is represented as data sets that specify the relevant urban area attributes. The specific values are fed in the DSS, based on each of the scenarios, are shown in section 13.7.

## 13.6 INFRASTRUCTURE MANAGEMENT STRATEGIES

To enhance local water security, three infrastructure strategies are proposed for establishing a SUWWTS in the city of Rio de Janeiro, these are: Best Available Technology, Combined Technologies, and Technological Lock-in. These strategies were defined after discussions between the author of this Thesis and experts on the field.

According to the Oxford Dictionary a strategy is a plan of action designed to achieve a long-term or overall aim. Each strategy explores two organizing principles which are considered fundamental for assessing potential payoffs: investment trends (low to high) and diversification of resource recovery from wastewater (low-value to high-value).

Figure 13-3 illustrates the strategies in terms of these two criteria, each is colour coded to distinguish them from one another and whenever referring to them the word font will change, e.g. **Strategy_Name_in_corresponding_Colour**.

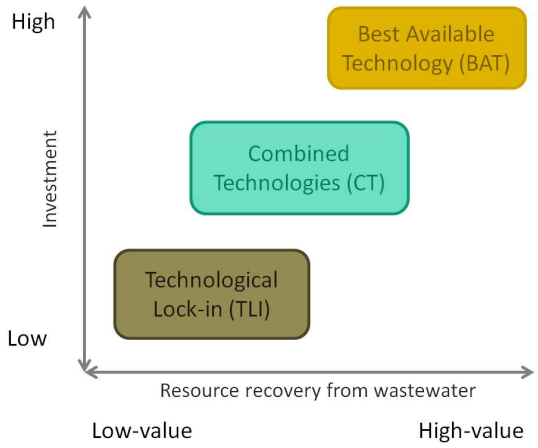



Figure 13-3 Visualisation of the three strategies for establishing a semi-centralised system.

The strategies are defined as follows:

- **Best Available Technology (BAT).** This strategy is characterized by high investment and high-value applications of resource recovery from wastewater. The strategy provides insight on the maximum achievable level of reclaimed resources obtained using wastewater treatment plant technologies with historically high investment requirements and which the highest-value applications of resource recovery from wastewater are obtained. This option can be regarded in the Brazilian context as the "leap-frog" given that currently the wastewater treatment capacity is insufficient and low-tech.
- **Combined technologies (CT).** This strategy is characterised by having a wide spectrum use of resource recovery from wastewater applications. It is characterized by a mix of wastewater treatment plant technologies and an average investment. This option can be regarded as the "step-by-step" one that could lead a gradual implementation of best technologies, assuming future upgrading towards BAT.
- **Technological Lock-in (TLI).** This strategy is characterized by low investment and low-value resource recovery from wastewater applications. The strategy represents the traditional mind set in infrastructure planning decisions of using wastewater treatment technologies which are cheap (and consequently achieve the lowest reclaimed resources quality). This option can be regarded as the "elementary" one: the semi-centralisation

concept is implemented, but not gaining all the benefits because low-tech technologies are still adopted.

Each strategy is analysed against the context of each of the four scenarios to provide insights on a SUWWTS layout performance across a wide range of conditions [160]. Each strategy defines the design and performance variables.

As discussed earlier, this Thesis depends on publicly available data, so it is acknowledged that other relevant technical options in the Brazilian context should have been considered (e.g. biofilters). It is highly recommended to include such technologies should access to cost and technical data be feasible.

## 13.7 SCENARIO REFINING (DSS DATA INPUT)

The quantification of each scenario was made. The approach was the one proposed by van der Heijden (2005) [281] in which the key variables were identified from the sensitivity analysis (see Chapter 12). The numbers used are illustrative of how the scenario could come about (history has passed), are consistent with the scenarios' story lines and, thus, their order of magnitude roughly fit their logic.

The average annual population growth variation is referenced to the 2010 census. The water consumption values for the **Mixed**, **Innovative** and **Sustainable** scenarios are as those in Denmark, The Netherlands and Germany in 2007 respectively [269]. The number of potential WWTP was 25, their correspondent node ID are from 40 to 64 in Figure 11-7. The specific values fed in the DSS are shown on Table 13-4.

The performance variables used by the **Combined Technologies** strategy were chosen by the author since it was not possible to make a survey with decision-makers in the city of Rio the Janeiro to select the performance variables and their respective acceptability functions due to time constraints (although a questionnaire was drafted). The criteria to propose the

performance variables were based on discussion with experts with the field. Although the selection might be contested its purpose is to convey how to implement the approach.

Table 13-4 DSS data input overview.

| Data input required to compute Performance Variables (Urban Area Attributes) | Scenario | | | |
|---|---|---|---|---|
| | Relapse | Mixed | Innovative | Sustainable |
| Average Annual Population Growth (%) | +0.6 | +0.55 | + 0.5 | + 0.5 |
| Average Water consumption ($m^3$/month per hab) | 4.5 | 3.9 | 3.75 | 3.45 |

## 13.8 INFRASTRUCTURE STRATEGY EVALUATION

*Rationally the decisions supported by the DSS would compare the key performance sustainability indicators of interest* (see Figure 13-4) *of each strategy in each scenario, and as shown in Table 13-5 the evaluation decision would be different in each scenario*.

Although the DSS targets design engineers as its user, the data presentation should aim to be user-friendly. To this end it was adopted a multi-level pie chart visualisation [160], see Figure 13-4, to give an instant overview of the performance of the recommended SUWWTS. The colour represents the scenario to which the information is assigned.

The concentric circles are used to visualize the evaluation of the SUWWTS' performance, which is the difference between the decision-makers expectations and the reality. For the context of this research, the innermost segment represents "low performance" because from the decision makers' point of view the SUWWTS is considered to have high cost, high land requirements, high energy requirements and high emissions. Two concentric rings indicate "medium performance" because the SUWWTS is considered to have medium cost, medium land requirements, medium energy requirements and medium emissions. Finally, three concentric rings signify "high performance" because the SUWWTS is considered to have low cost, low land requirements, low energy requirements and low emissions.

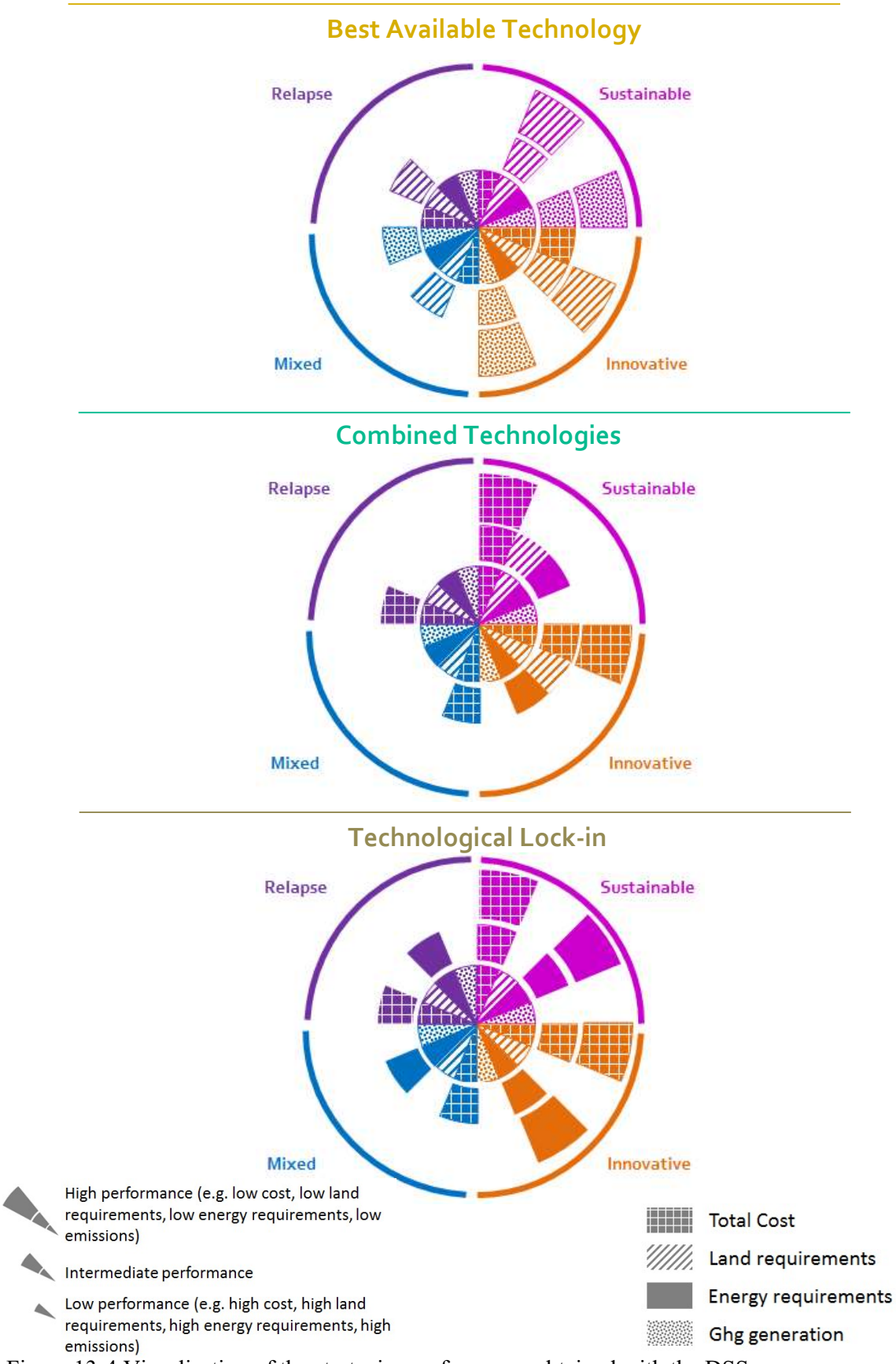


Figure 13-4 Visualisation of the strategies performance obtained with the DSS.

The right half of the multi-level pie chart visualisation for all strategies in Figure 13-4 have better performance given that both scenarios (**Sustainable** and **Innovative**) have less wastewater in comparison to the left half (**Relapse** and **Mixed**).

It has been proposed that all decisions are about making two guesses [319]: (1) the future consequences of current actions and (2) future sentiments with respect to those consequences. In this research these guesses are assumed to be stable and consistent, although they might be neither because they are rather moment-based [320]. It is further assumed that (3) the needs and the criteria used now will be the ones that will be required and used in the future, and (4) due to people's cognitive limitations decision-makers "rational" choice will aim to satisfice their goals. To be precise, a semi-centralised system design decision will be based on the level of satisfaction of a certain set of desired outputs in a particular range of environments [321].

The empirical data generated by the DSS is used to drive the qualitative evaluation process of each infrastructure strategy against each plausible future, known as "wind-tunnelling" of strategic options [280] (see Table 13-5). This table serves as a platform for examining technologies available at present from a future perspective, thus the usefulness of Table 13-5 is that its structure helps decision-makers evaluate the trade-offs of adopting a technology and opens the possibility of finding the most effective strategies. *The evaluation decision would be different in each scenario* because each strategy is rated based on decision-makers' prevailing values of in the "world" of each scenario.

The scoring method used in Table 13-5 uses the signs +, - and ○ to illustrate their relative values. A ( ○ ) means that the strategy's performance generates neither advantage nor disadvantage; it is the reference. The **TLI** was used as the reference given that in Brazil Lagoons is a very popular wastewater treatment technology. A (++) indicates the strategy is highly socio-politically accepted. A (+) indicates the strategy's performance is acceptable because it is better than the reference. A (-) means that the strategy's performance is not as good as the reference. A (- -) indicates the strategy is highly social-politically rejected.

Table 13-5 Scenario/strategy evaluation matrix. A (○) means that the strategy's performance generates neither advantage nor disadvantage, it is the reference. A (++) indicates the strategy is highly socio-politically accepted. A (+) indicates the strategy's performance is acceptable because it is better than the reference. A (-) means that the strategy's performance is not as good as the reference. A (- -) indicates the strategy is highly social-politically rejected.

| | Relapse | Mixed | Innovative | Sustainable |
|---|---|---|---|---|
| Best Available Technology (BAT) | - - | - | ++ | ++ |
| Combined Technologies (MT) | - - | + | + | + |
| Technological Lock-in (TLI) | ○ | ○ | ○ | ○ |

That is, in each scenario, decision makers will have a particular mindset from which each management strategy will be examined; this methodological framework is a useful insight of the robustness of current decisions in view of how they will be regarded in the future. Such insight is important since it serves as a platform for examining how the interactions between mind-sets and technology availabilities might unfold. Consequently, aiding decision-makers to minimise risk of failure or to guarantee that a strategy will work in all the possible instances, or scenarios [322].

The need for a *robust* design appears since in design decision two issues must be considered: the socioeconomic environment that will exist when the semi-centralised system comes into actual use, and the technical obsolescence [321]. Robustness is "*the degree of tolerance of the system to be insensitive to variations in both the system itself and the environment*" [89]. A robust design is one that is relatively insensitive to small changes in the uncertain quantities.

An example of a SUWWTS for the **Best Available Technology** strategy in the **Innovative** scenario is illustrated in a 3D visualization in Figure 13-5. The 3D context provides the decision-maker with a display closer to reality and brings orientation.

The sewerage system and the wastewater collection points are in purple, the pipe to the reclaimed water demand points and the collection points are in yellow, the wastewater treatment plants are the circles. For visualization purposes, the vertical exageration is x5 to emphasize height in the surface.

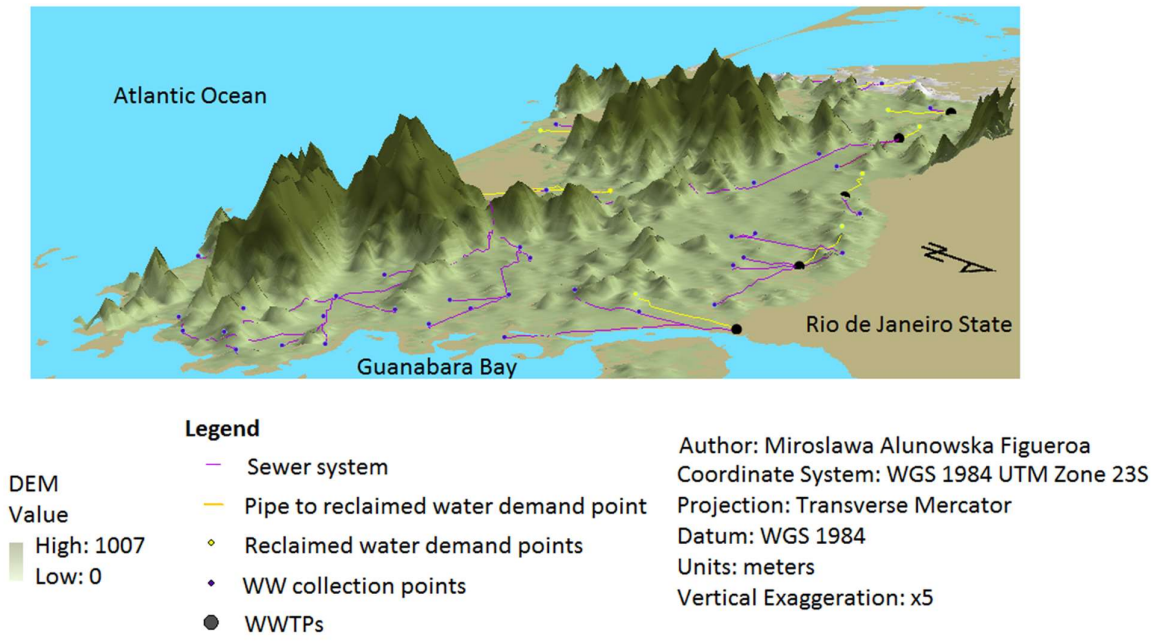



Figure 13-5 Visualization of the SUWWTS for the **Best Available Technology** strategy in the **Innovative** Scenario.

## 13.9 IMPLEMENTATION BUSINESS MODEL

The author of this Thesis agrees that "*thinking about an efficient future might look like and how to get there are worthy and urgent goals*" [323]. Thus, to achieve the long-term goals of semi-centralisation of a wastewater treatment system in the city of Rio de Janeiro an implementation initiative is proposed.

From discussion between the author of this Thesis and experts on the field to bridge the gap between the present and the desired future of semi-centralised wastewater treatment systems a business model which takes advantage of ANA's "output-based aid" (which pays for results given that it is more effective to pay for an actual result than for a promise, see Section13.3.2) for its success is proposed.

The business model describes the specific goals to guarantee that the SUWWTS will benefit the whole community. Two types of concessions are proposed: Sewerage system service providers and Wastewater treatment plants service provider. The concessions are described as follows:

- **Sewerage system service providers**. Several small local companies will construct and operate neighbourhood-scale sewerage systems in a tailor-made fashion. These small companies will be subsidised in terms of the volume of wastewater conveyed to the wastewater treatment plant.

  The rationale is that in this way the following outputs will be financially incentivised: (a) the connectivity of all the dwellings in the neighbourhood to the sewerage system, given that with more volume of wastewater transmitted the service providers will receive more money, (b) the creation of jobs for the construction, operation and management, and (c) the efficiency in operation and management e.g. reduce leakage.

- **Wastewater treatment plants service provider**. A single company will construct, manage, and operate the wastewater treatment plants in the semi-centralised system.

  The company will be financially incentivised in terms of: (a) the quality and quantity of water, sludge and nutrients recovered from the wastewater treatment process, (b) the $CO_2$e not released by the wastewater treatment process, and (c) the kWh not used from the grid.

Additionally, to encourage private investment, it is suggested that a centralized management of all the WWTPs. In this way it is possible to gain benefits of scale, that is, it is cheaper to contract specialist technicians, management, and replacement parts. It could be hypothesised buying the WWTPS from the same supplier means the opportunity to negotiate big discounts off the 'list' price, such as it happens in the aviation sector in which discounts vary between 20% and 60% [324].

Furthermore, it should be considered possible actions in order to overcome any existing barriers of semi-centralisation e.g. public confidence, legislation or institutional capacity. Given that to the author of this Thesis it is sometimes these factors that outweigh any benefit from an innovative technical/management solution.

## 13.10 SUMMARY

The DSS enabled the evaluation of three potential strategies for implementing SUWWTS in Rio de Janeiro in the context of four scenario stories. Although hypothetical and simplified, the feasibility study conveys the essence of the approach and demonstrates the DSS's functionality to systematize the study of semi-centralisation in wastewater treatment systems. Yet, it is recommended to engage into collaboration with a local engineering firm to incorporate technical options into the analysis, such as anaerobic-aerobic sequence reactors. In this author's view, such collaboration should be sponsored by the city's government, NGO, or academic institution [325,326].

The demonstration case examined how three strategies affect the local wastewater management system layout in terms of sustainability performance. Each of the four scenarios stories is a stimulus for creative thinking and is useful in the development of a longer-term vision of sustainable water security. Although none are predictions, they are an exercise to bring into the decision-makers attention issues of how possible courses of action might define the future.

This research expands current professional emphasis with complementary approaches: scenario analysis. *Rationally the decisions supported by the DSS would compare the key performance sustainability indicators of interest of each strategy; the decision would be different in each scenario.* Ultimately, which future the city of Rio de Janeiro will 'enter' depends on many uncertain factors e.g. population growth and cultural values that shape behavioural choices (e.g. water demand). Yet, it is important to highlight that choices are something we can influence and that those made today shape the future [323].

# PART VI
# SUMMARY, CONCLUSIONS AND FUTURE WORK

# CHAPTER 14
# CONCLUDING REMARKS

## 14.1 SUMMARY

The novel methodological framework presented in this Thesis defines a logical set of research steps. The methods integrated into the framework are from three key areas: engineering (e.g. the probabilistic specification-based design model, sensitivity analysis), operations research (e.g. branch and bound) and management (e.g. scenario analysis). Then a DSS was developed using the methodological framework's guidelines.

The DSS is comprised of two building blocks: (1) a Graphical User Interface, and (2) an Analytical Kernel Module which is comprised of a Decision Making (Layout Option Generator) module, Engineering Design Libraries module, and a Geographic Information System module. The inputs of the DSS include engineering quantities and costs, decision-makers' preferences, regional technological preferences, and socio-economic and geographic factors. The output is a SUWWTS layout, which consists of the number, location, type of technology and basic sizing of a series of semi-centralised WWTP, main sewerage lines and reclaimed water supply networks.

The initial experiments conducted showed that urban circumstances greatly influence the layout of a SUWWTS. The DSS is useful in assessing the impacts of several parameters, such as the number and location (spatial distribution) of potential WWTPs. Furthermore, it was demonstrated that the DSS can assist in the evaluation of semi-centralisation infrastructure management strategies and a possible implementation plan in alignment with institutional

requirements. This was illustrated in the context of Brazilian institutional organisations. Thus, the DSS fulfilled its goal of assisting decision making through the provision of a range of software tools, methods, and models. The integration of these varied elements makes this Thesis especially relevant for urban water managers.

## 14.2 CONCLUSIONS AND FUTURE WORK

This research is already gaining acceptance in the academic community, as shown in Appendix IX. The original contributions of this research are as follows:

1. A methodological framework. An approach for incorporating of uncertainty of technical change into urban wastewater management. The benefits of the methodological framework are:
   - 1.1 The means to evaluate SUWWTS as an urban water management alternative.
   - 1.2 Arguably it could help steer technological change by assisting technological research strategy evaluation. It is a platform to analyse new technologies vs strategies at a system scale, thus it is possible to identify where the biggest needs for technical innovation are or where the technological improvements would give the best benefits.
   - 1.3 The SUWWTS design automation steps, which saves time in an otherwise very time-consuming process.
2. An application of the methodological framework.
   - 2.1 A Decision Support System (DSS) which can be applied to any city with any socioeconomic, demographic, and geographic variables. A demonstration case based on the city of Rio de Janeiro which tested the workings of the model. It was possible to explore the influence of some parameter values. The DSS prove that it can be used as a planning tool that can be applied to any urban area input to compare alternatives and determine a recommended solution.

2.2 The DSS can arguably be used to explore the benefits of new technologies at a system scale.

This research overcame several challenges related to the complex nature of the problem:

a. it dealt with the engineering complexity,
b. proposed an approach to account for the high number of stakeholders,
c. incorporated regional socio political and technological preferences, and
d. dealt with uncertainty regarding future social conditions.

This research is inherently complex because of the need to integrate data from different sources and because the functionality must accommodate several requirements from decision-makers. Some of the key engineering insights that have been gained from the demonstration case presented in this Thesis are:

- A semi-centralised system is a viable option from the engineering point of view. Its layout and the wastewater treatment cost are largely defined by the wastewater transmission cost. The variables that most influence the cost are:
  - The wastewater quantity. This is a function of population growth, population distribution, average water demand values and earnings.
  - The distance the wastewater must be conveyed. This is a function of the number and distribution of WWTP site options and the network connectivity.
  - Terrain height. This parameter determines the energy required to pump the wastewater or the construction cost.
- The influence that decision-makers preferences had on the design layout increased dramatically depending on the shape of the probability of acceptance functions (see Figure 8-3.a). For example, if too much emphasis is put on costs, the search is severely restricted and may not be able to find a solution e.g. they might want a cheap system with the highest reclaimed quality which is physically impossible given that the highest reclaimed quality is only achieved with expensive treatment technologies. The upshot

of this situation is that decision-makers can gain insight into the potential trade-offs involved in the design of such a system. Thus, the DSS is most useful given that decision-makers are involved from the very beginning of the design process.

- The evaluation of strategies in several scenarios is a helpful approach to assist decision makers to improve their infrastructure proposals. It allows the exploration of stakeholder preferences and provides a platform with which to contest possible preconceptions and alternative approaches.
- It is important to note that the level of detail and accuracy of the results reflect the quality and quantity of the data input. This work depended on information being made available in the public domain. On several occasions, the available information was not as detailed as required. For example, the construction costs and footprint models used for wastewater treatment plants and the construction and operating costs for wastewater and water conveyance are only valid within a certain range of design parameters. Public access to accurate and validated design and cost equations is difficult to obtain as these are generally held by private engineering design firms. Consequently, the accuracy and validity of the values used in the current DSS equations can be contested. However, the logic underlying the analysis is valid and the output rational. Thus, the DSS serves as a conceptual model and provides an example of how to move forward in semi-centralisation research.
- In its present form, the DSS is a prototype, but has the potential to be converted into a release version. One barrier to be considered to accomplish this goal is how to sort out the lack of availability of suitable data because engineering design firms and water companies protect their information. To overcome this challenge, it would be necessary to collaborate with both entities, putting into place a culture of information exchange. Contextualised data will allow the proposed solutions from the DSS to be

more accurate and consequently decision-makers will be aware of the benefits of the application of a DSS to use it as an integral part of planning.

- A feature of the genetic search algorithm is that it requires the operator to undertake multiple runs of the same configuration as multiple optima are possible. This obviously raises the question of how many runs would be necessary as a standard. From a statistical standpoint it is likely that the larger and more complex the city to which the DSS is applied the greater the number of possible optimums. An analysis of this relationship between complexity and required model runs is a possible are for future research.
- It was a challenge to establish data interconnectivity between the different computer-based tools and novel methodologies required to generate the interdisciplinary information. It is in overcoming these challenges that the relevance of this body of work has once again been demonstrated.

As discussed in earlier chapters, one of the reasons for the absence of a framework and a DSS is the complexity of wastewater management, in particular existing infrastructure. The key reason for such complexity is that most sanitation systems develop organically, on a project-by-project basis, resulting in an unstructured, inefficient network. So, the transition to an alternative solution, such as semi-centralisation, can require major upheavals of existing systems.

A big issue in designing a SUWWTS is that it will be difficult to retrofit existing sanitation systems in highly densely populated urban areas either because of existing infrastructure since existing assets define water company decisions, lack of technology, social attitudes, and behaviours. The challenge for the future is to promote innovation in the wastewater sector. Most decisions in water resources management remain mainly driven by short-term economic and political considerations. Practitioners arguably will have to learn how to integrate old infrastructure with new solutions.

These could be regarded as wastewater environmental externalities issues pertinent to the demonstration case of the city of Rio de Janeiro. These include:

- Most of the water and sanitation companies' shareholders only care about profits, are risk-averse and are not necessarily interested in innovation (there are no financial incentives to do so),
- Citizens have an obvious preference for unlimited cheap/free service without having to care about externalities, such as pollution/system inefficiencies. Citizens can illegally connect to any pipe in their sewer or to a water supply pipe to get free water. Also, it seems that they only care about their own sanitation when they are suffering the consequences (waterborne diseases),
- Poor/ignorant people tend to have larger families increasing demand in poorer areas where services may be less profitable or perceived as dangerous to work at.
- Impact of existing infrastructure investment. Existing assets define wastewater infrastructure investment.

In general, without rules that are well implemented (without corruption) people will overlook the "collective good" even if it might be better for them in the long run than the "selfish good". In such situations governments need to intervene to ensure more Pareto efficient outcomes "because markets alone are not always capable of delivering the appropriate innovations at the right time" [327].

Thus, *it is recommended that the introduction of an alternative solution will require a major shift in network management and stakeholder engagement*. Such a paradigm shift in decision-making will allow a more holistic innovation within the water and wastewater sector that could benefit even the more materially developed countries, such as the UK [328]. In terms of stakeholder engagement, government/society needs to radically change their approach to sustainability away from such infrastructure improvement projects being perceived as a "cost" rather than as an "investment".

The development of this framework and the DSS should be considered as an iterative process with improvements to both arising naturally from their application and as user requirements grow as well as research in the areas of resource recovery and wastewater management areas advance. Table 14-1 summarises the strengths and limitations of this research. Some recommendations for future developments are based on insights gained from the initial experiments conducted; Table 14-2 lists such enhancements.

Table 14-1 Strengths and limitations of this research.

| | Strengths and capabilities | Limitations |
|---|---|---|
| Framework | 1. The definition of the logical stages necessary to design a semi-centralised wastewater treatment model system.<br>2. Its holistic and integrated approach.<br>3. The ability to create scenarios providing freedom for users to define sustainability in their own terms, which is important in supporting political dialogue.<br>4. The integration of lifecycle assessment principles, the $CO_2e$ generation potential of the water treatment process.<br>5. The incorporation of the water-energy nexus.<br>6. The conceptual design of the wastewater treatment plants, and their corresponding pipe network given a socio-economic and geographical urban context. | The limitations stem chiefly from the simplifications, idealisation and assumptions involved, many of which were dictated by the data availability and the complexity of the problem:<br>• It designs new wastewater treatment systems and does not consider the retrofitting of current systems.<br>• For this research project the framework had to consider only key players to limit complexity.<br>• The Framework focuses only on semi-centralisation as opposed to other innovative urban wastewater management options, but extensions can readily be made.<br>• Surrogate cost and design equations. |
| DSS | 1. The DSS is capable of being used by design engineers for analysis of alternatives.<br>2. The DSS can be applied to any city with any topology, population patterns, governance structure and technological preferences.<br>3. Automates the design of a SUWWTS. The DSS seamlessly integrates independently developed software tools and data.<br>4. Built on object-oriented principles. Its flexible design allows testing alternative technologies without recoding.<br>5. Arguably it could help steer technological change by assisting technological research strategy evaluation. | • Expert knowledge from different fields has been integrated, so the user might not be able to appreciate the full complexity contained within the “black-box” system.<br>• An alternative optimisation algorithm could have been used. The genetic search algorithm implemented operates such that the results can vary from run to run, necessitating multiple runs to capture the possibility of several optimal configurations.<br>• Given its complexity the DSS will require technical support for future updates and upgrades to functionality.<br>• The pipe and wastewater treatment plant design methods are somewhat rudimentary. The equations used have several limitations relating to a wide range of operating factors. |

Table 14-2 Proposed future work.

| | | Proposed enhancements |
|---|---|---|
| Methodological framework | | The philosophy of the framework can be applied to develop a system for procurement, finance or management of the semi-centralised wastewater treatment system. |
| | | Survey Analysis to collect data of the utility functions. |
| | | The scope of the model can be expanded by:<br>• Including existing infrastructure<br>• Including the implications of scale<br>• Allowing for retrofitting of existing urban wastewater treatment systems. It will be useful, particularly in developing countries, to have a step-by-step building strategy.<br>• Including a model of infrastructure interdependencies<br>• Incorporating land use and capacity restrictions<br>• Incorporating other technologies e.g. Biofilters, Nutrient Recovery technologies<br>• Including sludge disposal management and its different technologies<br>• Including Combined Heat and Power (CHP) design<br>• Incorporating more detailed models for water-energy, water climate change and the water-food nexus<br>• Introducing regulatory incentives assessment for resource recovery from wastewater treatment<br>• Incorporation of risk analysis<br>• Incorporation of other methods in scenario planning (e.g. weighting the probability of each scenario) |
| DSS | GUI | To enhance transparency the system could allow users to:<br>• Select the decision model (e.g. simple additive weight). The probabilistic Specification-based Design Model could be the default decision model incorporated<br>• Select from a range of sustainability indicators<br>• Input pipe and wastewater treatment plant cost equations |
| | Analytical Kernel | Future versions could include:<br>• Enhanced economic analysis capabilities e.g. incorporation of methods to price reclaimed water<br>• Enhanced pipe design equations e.g. include simplified pipe design such as *condominial* system as -developed by engineer José Carlos Melo [329]<br>• Incorporation of simulation and design of wastewater treatment and resource recovery plants<br>• Incorporation of a library of decision models<br>• Incorporation of other probability density functions<br>• Explore how economies of scale could alter the results by making technologies more cost-effective at larger scales or quantities |
| | GIS | Data of high quality would greatly enhance the results of the model case study. Including:<br>• Higher resolution Digital Elevation Models (DEMs)<br>• Inclusion of road network<br>• Improved dataset of water demands, wastewater generation and city characteristics<br>• Incorporation of a way to capture the land use planning, which might be subject to regulatory regimes |

Although the DSS could certainly be improved through better programming practices, design patterns and new programming tools, it must be clarified that it is the framework that ultimately dictates the functionality and usefulness of the DSS. The evolution of the DSS's capabilities grows out of the framework, and hence provides the means to extend its behaviour.

It must be pointed out that collaboration with stakeholders is essential when working on the suggested future developments. The time required to implement enhancements might take up to 5 person-years, although with an interdisciplinary research team this time might be significantly reduced.

Further to the proposed enhancements, which are framed from an engineering point of view, the interdisciplinary nature of this Thesis can underpin research topics in the context of pragmatic factors e.g. institutional capacity, organisational, legislation, regulatory and public confidence issues. Thus, this framework and DSS represent a major steppingstone towards the goal of more structured network-based wastewater treatment systems that incorporate stakeholders' preferences from the very outset.

## 14.3 CLOSING REMARKS

The challenge of meeting people´s needs in a world of limited resources is a key global concern. The motivation for this research project originated from a desire to find out the design of more integrated wastewater networks across a city because this represented a promising urban water management option. The methodological framework developed proved to be effective and underpinned the construction the DSS, which better equips decision-makers with relevant information useful in such scenario analysis. Yet, for the successful implementation of the proposed urban water management option it is not wise to rely exclusively on such technical solutions. Ultimately, we need more sustainable lifestyles and strong governance e.g. progressive institutional organisations.

This Thesis is a pioneering attempt to articulate the complexity, to systematize and to automate the design of a SUWWTS. Hopefully, it will contribute to the discussion among future researchers and practitioners on how to promote urban water security, to decrease urban areas' dependency on ecosystem services and to deliver improvements in social welfare.

# APPENDIX

## A.I. Complete Mix

Table A-1 Complete Mix design equations [143].

| Equation | |
|---|---|
| $$Substrate\ concentration = \frac{1}{Specific\ substrate\ utilisation\ rate\ \cdot Yield}\left(\frac{1}{Residence\ time} + k_d\right)$$ | (A -1) |
| $$MLSS\ concentration = Volatile\ suspended\ solid\ per\ suspended\ solids \cdot Solid\ concentration\ in\ reactor$$ | (A -2) |
| $$Aeration\ tank\ volume = \frac{1}{MLSS\ concentration}\ \frac{Yield\ \cdot Inflow\ \cdot Residence\ time\ \cdot\ (BODinflow - Substrate\ concen}{1 + k_d\ \cdot Residence\ time}$$ | (A -3) |
| $$Detention\ time = \frac{Volume}{Inflow}$$ | (A -4) |
| $$Return\ sludge = inflow \cdot \frac{MLSS\ concentration}{Return\ sludge\ suspended\ solids\ concentration - MLSS\ concentration}$$ | (A -5) |
| $$Net\ Volatile\ suspended\ solids = \frac{Aeration\ tank\ volume\ \cdot MLSS\ concentraiton}{Residence\ time}$$ | (A -6) |
| $$Sludge\ mass\ = \frac{Net\ Volatile\ suspended\ solids}{Volatile\ suspended\ solid\ per\ suspended\ solids}$$ | (A -7) |
| $$Sludge\ volume = \frac{Sludge\ mass}{Return\ sludge\ suspended\ solids\ concentration}$$ | (A -8) |
| $$Oxygen\ required\ carbonaceous\ demand = BOD_u\ removed - BOD_u\ of\ solids\ leaving$$ | (A -9) |
| $$BOD_u\ removed = \frac{1}{Effluent\ BOD5\ per\ BODu}(inflow\ \cdot\ Effluent\ BOD)$$ | (A -10) |
| $$BOD_u\ of\ solids\ leaving = 1.42\ \cdot\ Net\ Volatile\ suspended\ solids$$ | (A -11) |
| $$Oxygen\ required\ for\ nitrification = Oxygen\ required\ nitrification\ TKN\ \cdot (inflow\ \cdot incoming\ TKN) \cdot TKN\ removal$$ | (A -12) |
| $$Total\ oxygen\ required = Oxygen\ required\ carbonaceous\ demand + Oxygen\ required\ for\ nitrification$$ | (A -13) |

Table A-2 Complete Mix Activated Sludge design parameters [143].

| Parameter | Value | Units |
|---|---|---|
| Effluent BOD | 25 | $g/m^3$ |
| Sludge specific gravity | 1 | $kg/m^3$ |
| Effluent suspended solids | 20 | $g/m^3$ |
| Volatile suspended solid per suspended solids | 0.8 | $g/m^3$ |
| Degradable fraction of suspended solids | 0.7 | - |
| Effluent biological solids concentration | 22 | $g/m^3$ |
| Return sludge suspended solids concentration | 1 | % |
| Residence time | 5 | d |
| TKN removal | 30 | % |
| Effluent BOD5 per BODu | 0.68 | - |
| Yield | 0.6 | Kg/kg |
| $k_d$ | 0.07 | 1/d |
| Solid concentration in reactor | 4000 | $g/m^3$ |
| Specific substrate utilization rate | 0.038 | $Mg/l^{-1}\ h^{-1}$ at 18C |
| **Aeration parameters** | | |
| Oxygen capacity aerators | 0.7 | - |
| Oxygen required nitrification TKN | 4.33 | Kg/d |
| Air density | 1.2 | $kg/m^3$ |
| Air oxygen content | 0.232 | - |
| $O_2$ transfer rate for coarse bubble diffusers | 2 | kg $O_2$/kW-hr |

# A.II. Sequencing Batch Reactor (SBR)

Table A-3 SBR Design Equations [145].

| Equation | |
|---|---|
| $BOD_5 Removed = \left(BOD_{influent} - BOD_{effluent}\right) \cdot Flow$ | (A -14) |
| $Required\ Aerobic\ Mass = \frac{BOD_5\ Removed}{F/MRatio}$ | (A -15) |
| $Reactor\ Volume_{decant\ (low\ water\ level)} = \frac{MLSS\ Mass}{MLSS\ Concentration}$ | (A -16) |
| $Total\ Reactor\ volume = \frac{Reactor\ volume_{decant\ (low\ water\ level)}}{(1 - 0.6)}$ | (A -17) |
| $Total\ Decant\ Volume = Total\ Reactor\ volume - Reactor\ Volume_{decant\ (low\ water\ level)}$ | (A -18) |
| $Max.\ Detention\ Time = \frac{Total\ Reactor\ Volume}{Flow}$ | (A -19) |
| $Min\ Detention\ Time = \frac{Decant\ Volume}{Flow}$ | (A -20) |
| $Basin\ Area = \frac{Reactor\ Volume_{decant\ (low\ water\ level)}}{Minimum\ Depth}$ | (A -21) |
| $Basin\ Depth = \frac{Total\ Reactor\ Volume}{Basin\ Area}$ | (A -22) |

Table A-4 SBR Design Equations [145] (Continuation).

| Equation | |
|---|---|
| $$TKN\ Removed = \left(TKN_{influent} - TKN_{design\ parameter}\right) \cdot Flow$$ | (A -23) |
| $$Sludge\ Production = Net\ Sludge\ Yield \cdot BOD_5\ Removed$$ | (A -24) |
| $$Synthesis\ N = 0.05 \cdot Sludge\ Production$$ | (A -25) |
| $$NH_3 - N_{oxidized} = TKN\ Removed - Synthesis\ N$$ | (A -26) |
| $$Nitrogenous\ O_2\ Demand = NH_3 - N_{oxidized} \cdot \frac{kg\ O_2}{kg\ NH_3 - N_{oxidized}}$$ | (A -27) |
| $$Carbonaceous\ O_2\ Demand = BOD_5 \cdot \frac{kg\ O_2}{kg\ BOD_5}$$ | (A -28) |
| $$Actual\ Oxygen\ Requirements\ (AOR) = Carbonaceous\ O_2 Demand + Nitrogeneous\ O_2\ Demand$$ | (A -29) |
| $$Standard\ Actual\ Oxygen\ Requirements = \frac{AOR \cdot C_s \cdot \theta^{(T-20)}}{\alpha \cdot (\beta \cdot C_{sw} - C_o) \cdot Blower\ usage}$$ | (A -30) |
| $$Motor\ Requirements = \frac{SAOR}{O_2\ Transfer\ Rate}$$ | (A -31) |
| $$Standard\ Cubic\ Meter\ per\ Minute = \frac{\frac{SAOR}{Blower\ Usage}}{O_2\ Content \cdot Absorption\ Efficiency}$$ | (A -32) |
| $$Sludge\ flow\ rate = \frac{Sludge\ Mass\ Flow}{Sludge\ Density}$$ | (A -33) |
| $$Decanter\ flow\ Rate = \frac{Maximum\ Daily\ Flow\ for\ Decant}{Number\ of\ Basins \cdot Number\ of\ cycles\ per\ Basin \cdot Maximum\ Cycle\ Time\ for\ sludge\ was}$$ | (A -34) |

Table A-5 Sequencing Batch Reactor design parameters [145].

| Parameter | Value | Units |
|---|---|---|
| BOD effluent | 20 | mg/L |
| TSS effluent | 30 | mg/L |
| $NH_3N$ effluent | 1 | mg/L |
| TKN | 5 | mg/L |
| F/M Ratio | 0.13 | kg BOD applied/kg MLSS-d |
| MLSS | 3500 | mg/L |
| Number of basins | 2 | - |
| Minimum clarifier depth | 2.75 | m |
| Net sludge yield | 0.76 | - |
| Minimum solids retention time | 8 | d |
| Fraction reactor volume decanted each day | 0.6 | - |
| Net elevation above sea level | 304 | m |
| DO mixed liquor concentration | 2 | mg/L |
| Oxygen coefficient BOD | 1.28 | kg $O_2$/kg BOD |
| Oxygen coefficient N | 4.6 | kg $O_2$/kg $NH_3$-N |
| α Transfer factor for coarse bubble diffuser | 0.85 | - |
| β Transfer factor for municipal wastewater | 0.95 | - |
| $O_2$ transfer rate for coarse bubble diffusers | 1.25 | kg $O_2$/kW-hr |
| $O_2$ content at standard conditions | 0.2793 | kg $O_2$/$m^3$ air |
| Number of cycles per day | 4 | - |
| **Standard actual oxygen requirement calculation** | | |
| Θ Temperature correction factor | 1.024 | - |
| $C_S$ ($O_2$ saturation concentration at standard T and P) | 9.02 | mg/L |
| Blower usage | 14 | hr/d based on 4 cycles per day (6 hr/cycle, 1 hr fill time, 3.5 hr react time, 0.75 settle time, 0.5 decant time, 0.25 hr idle time) |
| Blower absorption efficiency | 0.75 | typical range 0.7 – 0.9 |
| Co | 2 | mg/L |
| T | 20C | |
| **Sludge** | | |
| Sludge density | 1020 | kg/$m^3$ |

# A.III. Lagoons

Table A-6 Lagoon design equations [147].

| Equation | |
|---|---|
| $$BOD_{load} = Flow\ BOD_{SO}$$ | (A -35) |
| $$N_{effluent} = TKN \frac{1}{1 + (detention\ time * ((0.000576 * T) - 0.00028) * e^{(1.08 - (0.042 * T))(pH - 6.6)}}$$ | (A -36) |
| $$Volume = Flow * detention\ time$$ | (A -37) |
| $$Area = \frac{Volume}{depth}$$ | (A -38) |
| $$width = \sqrt{\frac{Area}{2}}$$ | (A -39) |
| $$length = 2 * width$$ | (A -40) |
| $$Lagoon\ winter\ temperature = \frac{T + \left(\left(\frac{Detention\ time}{Lagoon\ depth}\ 0.49\right) T_{air\ summer}\right)}{\left(\left(\frac{Detention\ time}{Lagoon\ depth}\ 0.49\right) + 1\right)}$$ | (A -41) |
| $$kLatTcorrected_Summer = KL * \theta^{(T_{summer} - 20)}$$ | (A -42) |
| $$kperDetentionTime_{Summer} = kLatTcorrected_{Summer} * detention\ time$$ | (A -43) |
| $$PercentRemovedBOD_Summer = 22.032 * log(kperDetentionTime_Summer) + 61.659$$ | (A -44) |
| $$soluble\ BOD\ effluent\ summer = \frac{100 - PercentRemovedBOD_Summer}{100} * BOD_{SO}$$ | (A -45) |
| $$BOD\ effluent\ summer = soluble\ BOD\ effluent\ summer + BOD_{SS\ effluent\ winter}$$ | (A -46) |
| $$BOD_{summer} = \left(1 - \frac{BOD\ effluent\ summer}{BOD_{SO}}\right) 100$$ | (A -47) |
| $$BOD_{summer} = BOD_{SO} * Flow$$ | (A -48) |
| $$oxygen\ required\ summer = BOD\ removed\ efficiency\ Summer * (1.4 * BOD_{summer})$$ | (A -49) |
| $$power\ needed\ summer = \frac{Oxygen\ required\ summer}{2\ Power\ efficiency}$$ | (A -50) |
| $$energy\ requirements = \frac{power\ needed\ summer}{flow}$$ | (A -51) |
| $$electrical\ energy = 6598 * Power\ needed\ summer^{1.026}$$ | (A -52) |
| $$People\ served = \frac{flow}{average\ flow\ per\ person}$$ | (A -53) |

Table A-7 Lagoon design equations [147] (Continuation).

| Equation | |
|---|---|
| $Volume_{sludge} = Sludge\ accumulation\ rate * Cleaning\ interval * People\ served$ | (A -54) |
| $sludge\ flow = \frac{Volume_{sludge}}{cleaning\ interval}$ | (A -55) |
| $Mass_{sludge} = sludge\ flow * sludge\ density$ | (A -56) |
| $Depth_{extra} = \frac{Volume_{sludge}}{Area_{lagoon}}$ | (A -57) |
| $Depth_{total} = Depth_{design} + Depth_{extra}$ | (A -58) |

Table A-8 Lagoon design parameters [147].

| Parameter | Value | Units |
|---|---|---|
| kT | 3.3 | - |
| kL | 0.7 | 1 $d^{-1}$ |
| Θ at 20ºC | 1.035 | - |
| SS effluent | 35 | g $m^{-3}$ |
| Lagoon depth | 4 | m |
| Detention time | 5 | d |
| Dispersion Factor | 0.2 | - |
| Cleaning interval | 5 | yr |
| Sludge accumulation rate | 0.05 | $m^3$ $person^{-1}$ $yr^{-1}$ |
| Power efficiency | 0.8 | - |

# A.IV. Trickling filter or biofilter

Table A-9 Biofilter design equations [147].

| Equation | |
|---|---|
| $Volume = -\left[Q\ ln\left(\frac{L_{effluent}}{L_{influent}}\right)\right](K_T S)^{-1}$ | (A -59) |
| $Modified\ rate\ constant, K_T = 0.037\ (1.08)^{T-15}$ | (A -60) |
| $Efficiency, E_T = E_{20}(1.035)^{T-20}$ | (A -61) |
| $E_{20} = \frac{100}{1 + 0.225(W/VF)^{0.5}}$ | (A -62) |
| $\frac{W}{V} = \frac{L_{influent} Q_{influent}}{V}$ | (A -63) |
| $Recirculation, F = \frac{1+R}{(1+0.1R)^2}$ | (A -64) |
| $R = \frac{Q_{recirculation}}{Q_{influent}}$ | (A -65) |

Table A-10 Biofilter design parameters [147].

| Parameter | Value | Units |
|---|---|---|
| Medium, rock | 50-100 | mm |
| W, BOD load | | g $day^{-1}$ |
| V, volume | | $m^3$ |
| Q, flow rate | | $m^3$ $day^{-1}$ |
| S, Effective linear cross-sectional dimension (flow perimeter) | 40 | $m^2$ /$m^3$ |
| Depth | 2 - 3 | m |

# A.V. MBR

Table A-11 Biological and aeration operating parameters and design equations [141].

| Equation | |
|---|---|
| $Specific\ growth\ rate\ of\ nitrifying\ bacteria, \mu_n = \left(\frac{\mu_{n,m} N_e}{K_n + N_e}\right)\left(\frac{DO}{K_n + DO}\right) - k_{e,n}$ | (A -66) |
| $Aerobic\ SRT, \theta_{X,aer} = SF\ \frac{1}{\mu_n}$ | (A -67) |
| $Sludge\ yield, M_{X,bio} = \frac{QY(S - S_e)}{1 + k_e\theta_{X,aer}} + \frac{f_d k_e QY(S - S_e)\theta_{X,aer}}{1 + k_e\theta_{X,aer}} + \frac{QY_n(NO_x)}{1 + k_e\theta_{X,aer}}$ | (A -68) |
| $Effluent\ BOS, S_e = \frac{K_s(1 + k_e\theta_{X,aer})}{\theta_{X,aer}(\mu_n - k_e) - 1}$ | (A -69) |
| $Concentration\ of\ TKN\ oxidized\ to\ form\ nitrate, NO_x = TKN - N_e - \frac{0.12 M_{X,bio}}{Q}$ | (A -70) |
| $Total\ sludge\ yield, M_{X,TSS} = \frac{M_{X,bio}}{0.85} + Q(nbVSS + iTSS)$ | (A -71) |
| $Influent\ non - biodegradable\ VSS, nbVSS = \left(1 - \frac{bpCOD}{pCOD}\right) VSS$ | (A -72) |
| $Influent\ inert, iTSS = TSS - VSS$ | (A -73) |
| $Aerobic\ tank\ volume, V_{aer} = \frac{M_{X,TSS}\theta_{X,aer}}{X_{aer}}$ | (A -74) |
| $Sludge\ wastage\ flow, Q_w = \frac{V_{aer}}{\theta_{X,aer}}$ | (A -75) |
| $Nitrate\ recirculation\ ratio, r_{int} = \frac{NO_x}{NO_e} - 1$ | (A -76) |
| $Active\ biomass\ concentration\ in\ anoxic\ zone, X_{b,anox} = \left(\frac{Q\theta_{X,aer}}{V_{aer}}\right)\left(\frac{Y(S - S_e)}{1 + k_e\theta_{X,aer}}\right)\left(\frac{r_{int}}{r_{int} + 1}\right)$ | (A -77) |
| $Nitrate\ load\ to\ anoxic\ zone, NO - loading = Qr_{int}\left(TKN - N_e - \frac{0.12 M_{X,bio}}{Q}\right)$ | (A -78) |
| $Food\ to\ active\ biomass\ concentration\ in\ anoxic\ zone, F/M_b = \frac{QS}{V_{anox} X_{b,anox}}$ | (A -79) |
| $Denitrification\ capacity, NO_r = V_{anox}\ SDNR\ X_{b,anox}$ | (A -80) |
| $SRT, \theta_{x,process} = \frac{V_{aer}X_{aer} + V_{anox}X_{anox}}{Q_w X_{aer}} = \theta_{X,aer} + \theta_{X,anox}$ | (A -81) |

Table A-12 Biological and aeration operating parameters and design equations [141] (Continuation).

| Equation | |
|---|---|
| $Oxygen\ requirement, M_O = Q(S - S_e) - 1.42M_{X,bio} + 4.33QNO_x - 2.86Q(NO_x - NO_e) = M_m + M_b$ | (A -82) |
| $MLSS\ concentration\ in\ anoxic\ zone, X_{anox} = X_{aer}\left(\frac{r_{int}}{1 + r_{int}}\right)$ | (A -83) |
| $MLSS\ concentration\ in\ aerobic\ zone, X_{aer} = X_m\left(\frac{r_{mr}}{1 + r_{mr}}\right)$ | (A -84) |
| $Anoxic\ tank\ as\ fraction\ of\ total\ volume, f_{anox} = \frac{V_{anox}}{V_{process}}$ | (A -85) |
| $Minimum\ required\ membrane\ tank\ volume, V_{m,min} = \frac{A_m}{\varphi_{tank}}$ | (A -86) |
| $Biodegradable\ particulate\ COD, bpCOD = f_{bp}COD$ | (A -87) |
| $Total\ particulate\ COD, pCOD = (f_{bp} + f_{up})COD$ | (A -88) |
| $Sludge\ waste\ per\ unit\ permeate, Q'_w = \frac{Q_w}{J_{net}A_m}$ | (A -89) |
| $Hydraulic\ retention\ time\ for\ tank\ x, HRT_x = \frac{V_x}{Q}$ | (A -90) |
| $Total\ process\ volume, V_{process} = V_{anox} + V_{aer}$ | (A -91) |
| $Total\ process\ HRT, HRT_{process} = HRT_{anox} + HRT_{aer}$ | (A -92) |
| $Suspended\ solids\ correction\ factor, \alpha = e^{-\omega_x X}$ where x refers to fine or coarse bubble | (A -93) |
| $Temperature\ correction\ factor, \theta = 1.024^{(T-20)}$ | (A -94) |
| $Membrane\ aeration\ rate, Q_{A,m} = SAD_m A_m$ | (A -95) |
| $O_2\ tranferred\ by\ membrane\ aeration, M_m = Q_{A,m}\rho_A(SOTE_{coarse}y_{coarse})O_{A,m}\alpha\beta\theta$ | (A -96) |
| $Net\ air\ flow\ for\ biological\ requirements, Q_{A,b} = \frac{M_0 - M_m}{\rho_A(SOTE_{fine}y_{fine})O_{A,m}\alpha\beta\theta}$ | (A -97) |

Table A-13 Membrane Bioreactor design parameters [141].

| Parameter | Value | Units |
|---|---|---|
| Permeability | 100 | l $m^{-2}$ $h^{-1}$ $bar^{-1}$ |
| Flux | 13.65 | l $m^{-2}$ $h^{-1}$ |
| NO effluent | 12 | - |
| N effluent | 0.68 | - |
| Ks | 20 | $g/m^3$ |
| ke | 0.12 | g/g.d |
| µm | 6 | g/g.d |
| Θ Mass transfer correction temperature | 1.024 | |
| Θ µM | 1.07 | - |
| Θ kd | 1.04 | - |
| SRT Sludge Retention Time | 20 | days |
| Y Heterotrophic yield coefficient | 0.4 | g VSS/g bCOD |
| ken | 0.08 | - |
| $\mu_{m,n}$ Maximum nitrification specific growth rate | 0.75 | g VSS/(gVSS/day) |

Table A-14 Membrane Bioreactor design parameters [141] (Continuation).

| | | |
|---|---|---|
| Kn | 0.74 | - |
| Yield coefficient (nitrification) | 0.12 | g VSS/g BOD |
| Inlet temperature | 15 | C |
| Ratio of oxygen transfer efficiency (OTE) in wastewater to OTE in pure water (coarse bubble diffuser) | 0.43 | - |
| Ratio of oxygen transfer efficiency (OTE) in wastewater to OTE in pure water (fine bubble diffuser) | 0.5 | - |
| Value relating oxygen saturation in wastewater compared to clean water | 0.95 | - |
| Design MLSS XTSS concentration | 10000 | $g/m^3$ |
| Membrane recirculation ration, is the transfer rate between the membrane tank and the biological tank (return activated sludge) | 4 | - |
| fd, fraction of cell mass remaining as cell debris | 0.15 | - |
| Security Factor | 1.5 | - |
| $\rho_A$ Air density | 1.2 | $kg/m^3$ |
| kg O2 per kg Air | 0.232 | kgO2/kgAir |
| Oxygen saturation concentration for pure water at 20C | 9.08 | - |
| oxygen saturation concentration for pure water at 20C | 2 | $gO_2/m^3$ |
| Diffuser fouling factor | 0.9 | - |
| Standard oxygen transfer efficiency | 0.28 | - |
| Standard oxygen transfer efficiency coarse bubble | 0.02 | %/m |
| Standard oxygen transfer efficiency fine bubble | 0.05 | %/m |
| $y_{coarse}$ Aerator depth coarse bubble | 2.3 | m |
| $y_{fine}$ Aerator depth fine bubble | 5 | m |
| Hidraulic retention time anoxic tank | 3.2 | h |
| Ko | 1 | - |
| Endogenous decay coefficient (nitrification) | 0.07 | g VSS/(g VSS/day) |
| Physical cleaning (backflush) interval | 0.167 | h |
| Physical cleaning (backflush) duration | 0.013 | h |
| Backflush flux | 17 | $l\ m^{-2}\ h^{-1}$ |
| Chemical cleaning interval | 4320 | h |
| Chemical cleaning duration | 2 | h |
| Cleaning reagent strength | 0.25 | $kg/m^3$ |
| Flux cleaning reagent | 45 | $l\ m^{-2}\ h^{-1}$ |
| | 101.32 | |
| Pa1 inlet air pressure | 5 | kPa |
| Pa2 outlet air pressure kPa | 9.792 | kPa/m |
| Pump efficiency | 0.45 | - |
| Blower efficiency | 0.5 | - |
| Gravity | 9.81 | $m/s^2$ |
| Ratio of specific heat capacity at constant pressure to constant volume | 1.4 | - |
| Density at sea level, 15C | 1.23 | $kg/m^3$ |
| Density pumped fluid | 1003 | $kg/m^3$ |
| Membrane aeration demand per unit membrane area for FS module | 0.3 | $N\ m3\ h^{-1}\ m^{-2}$ |
| To calculate Aerobic SRT | 1.5 | |
| $\phi_{tank}$ Membrane packing density | 45 | $m^2/m^3$ |

# A.VI. Anaerobic Sludge

Table A-15 Anaerobic sludge digestion design equations [231].

| Equation | |
|---|---|
| $Sludge\ solids\ weight\ = Flow * TSS\ removed$ | (A -98) |
| $Flow\ sludge\ = \frac{total\ sludge\ weight}{sludge\ specific\ gravity * specific\ weight\ water}$ | (A -99) |
| $Sludge\ solids\ concentration\ = \frac{sludge\ solids\ weight}{flow\ sludge}$ | (A -100) |
| $Hydraulic\ Residence\ Time, \theta\ = \frac{1}{\left((Y * K) - Kd\right) * Safety\ factor}$ | (A -101) |
| $V\ = Flow\ sludge * \theta$ | (A -102) |
| $Volumetric\ loading\ rate\ = \frac{(Organic\ removed * Flow)}{V}$ | (A -103) |
| $Effluent\ COD\ concentration, S\ = \frac{Ks * (1 + (\theta * Kd))}{(\theta_design * ((Y * K) - Kd)) - 1}$ | (A -104) |
| $Biomass\ production\ rate, \frac{lbVSS}{d} = Y_{obs} * (Cs - S) * Flow\ sludge$ | (A -105) |

Table A-16 Anaerobic sludge digestion design parameters [231].

| Parameter | Value | Units |
|---|---|---|
| T | 36 | ºC |
| organic removed per Mgal of wastewater | 1200 | lb COD |
| TSS removed per Mgal of wastewater | 1200 | lb |
| Moisture content (by weight) | 0.96 | fraction |
| K | 1.4 | d-1 |
| Ks | 2000 | mg COD/L |
| Y | 0.1 | mg VSS/mg COD |
| Kd | 0.03 | $d^{-1}$ |
| Safety factor | 2 | |
| Conversion factor from cell mass to COD | 1.42 | |
| Methane energy value | 950 | BTU/ $ft^3$ |
| Specific weight water | 62.4 | $lb/ft^3$ |
| Tank height | 24 | ft |

# A.VII. Nutrient removal

Table A-17 A2/O Design equations [146].

| Equation | |
|---|---|
| $P_{X,T} = \left[\frac{QY(S_0 - S_e)}{1 + b\theta_c}\right] + \left[\frac{f_d bQY(S_0 - S_e)\theta_c}{1 + b\theta_c}\right] + \left[\frac{QY_n NO_x}{1 + b_{n,T}\theta_c}\right] + Flow\ (Nonbiodegradble\ VSS) + Flow\ (SS_{inf} - VSS_{inf})$ | (A -106) |
| $b_T = b\ b_n^{(T-20)}$ | (A -107) |
| $b_{N,T} = b_N\ b_n^{(T-20)}$ | (A -108) |
| $\theta_{c,aerobic} = \theta_{c,system} - \theta_{anoxic} - \theta_{anaerobic}$ | (A -109) |
| $Solids\ in\ aeration\ tank = \frac{\theta_{c,aerobic}\ Solids\ in\ system}{\theta_{c,system}}$ | (A -110) |
| $Solids\ in\ anoxic\ tank = \frac{\theta_{anoxic}\ Solids\ in\ system}{\theta_{c,system}}$ | (A -111) |
| $Solids\ in\ anaerobic\ tank = \frac{\theta_{anaerobic}\ Solids\ in\ system}{\theta_{c,system}}$ | (A -112) |
| $V_{aeration} = \frac{Solids\ in\ aeration\ tank}{MLSS}$ | (A -113) |
| $V_{anoxic} = \frac{Solids\ in\ anoxic\ tank}{MLSS}$ | (A -114) |
| $V_{anaerobic} = \frac{Solids\ in\ anaerobic\ tank}{SS_{anaerobic}}$ | (A -115) |
| $Phosphorus\ removed, Ps = influent\ COD\left\{\left[\frac{(1 - unbiodegradable, soluble\ COD\ \ influent - unbiodegradable\ particulate\ COD\ influent)Y_h}{(1 + b_{hT}\theta_c)}\right](\gamma + f_p b_{hT}\theta_c) + f_p\left(\frac{f_{up}}{ratio\ of\ COD\ to\ VSS}\right)\right\}$ | (A -116) |

Table A-18 A2/O Design parameters [146].

| Parameter | Value | Units |
|---|---|---|
| COD primary effluent | 224 | mg/L |
| Effluent COD | 6 | mg/L |
| $\Theta_{c,\ system}$ Total mean cell residence time | 15 | d |
| $\Theta_{anoxic}$ Mean cell residence time anoxic tank | 1.5 | d |
| $\Theta_{anaerobic}$ Mean cell residence time anaerobic tank | 0.8 | d |
| Effluent biological solids concentration | 15 | mg/L |
| Effluent $NH_4N$ | 0.5 | mg/L |
| Yield | 0.5 | mgSS/mgCODremoved |
| Half saturation constant | 20 | mg/L |
| Decay rate at 20C | 0.18 | $d^{-1}$ |
| Dissolved oxygen aeration tank | 2 | mg/L |
| TKN peak average safety factor | 1.5 | - |
| Fraction decayed MLVSS nonbiodegradable | 0.2 | SS/L |
| $NO_x = NO_3N$ | 28 | mg/L |
| Return sludge ratio | 0.6 | - |
| $SS_{anaerobic}$ concentration in anaerobic tank | 1200 | mg/L |
| **Nitrification kinetic coefficients** | | |
| $\mu_{m,n}$ Maximum growth rate for nitrogen conversion organisms | 0.75 | g VSS/g VSS . d |
| $K_n$ Half saturation constant nitrogen_organisms | 1 | g NH4N/$m^3$ |
| $Y_n$ Yield nitrogen organisms | 0.2 | mg SS/mg N oxidized |
| $b_N$ Decay rate nitrogen organisms | 0.1 | $d^{-1}$ |
| $K_0$ Half saturation constant dissolved oxygen | 0.5 | mg/L |
| **Beta values for temperature corrections** | | |
| $\mu_m$ | 1.07 | - |
| | 1.05 | |
| $k_n$ | 3 | - |
| $b_n$ | 1.04 | - |
| **Phosphorous removal** | | |
| $b_{hT}$ Decay coefficient for heterotrophic bacteria | 0.24 | $d^{-1}$ |
| $Y_h$ , Yield heterotrophic organisms | 0.45 | mg VSS/mg COD removed |
| $\gamma$ , Coefficient of excess removal (p content of vs) | 0.06 | - |
| $\Theta_c$, Mean cell residence time in anaerobic tank | 0.8 | d |

## A. VIII. General Interview Questions

Questions about the person's role and organisation

1. Can you please describe your role
2. What role does your organisation play in wastewater management?

Questions about current wastewater management practice

3. Can you please describe the practice of wastewater management state of affairs
    - Water demand and supply (including sources)
    - Current infrastructure (including electricity)
    - Future infrastructure
    - Construction codes: pipes and wastewater treatment plants
    - Regulation
    - Standards
    - Policies: current and discussed
    - Key stakeholders (power structure)
    - Population density, average growth, and distribution
    - Monthly income distribution and other relevant socio-economic indices
    - Access to qualified personnel, materials, and technology
    - Climate
    - Ownership
    - Social approach to paying wastewater treatment services
    - Sludge management
    - Reclaimed water uses. If there is no current reclaimed water use, what are the barriers?
    - Financial resources (e.g. federal bank, international organisations)
4. What are the limitations of the current practice of wastewater management?
5. In your opinion what are the effective methods for wastewater management and what are the largest barriers to achieve it?
6. What worries you?

Questions about future wastewater management practice

7. How would you like the practice of water management change?
8. Are there any social, economic, or environmental aspirations?
9. Are there any desired technologies to be considered?
10. Are there any policies that could be introduced?
11. What issues do you foresee?
12. How might these issues be addressed?

Questions to gather additional contextual information

13. Is there anything that you feel is important that has not been asked?
14. Do you have questions for me?

Please indicate persons that you think I should contact

# A.IX. Interdisciplinary relevance of the Thesis

Table A-19 Interdisciplinary relevance of the Thesis.

| | |
|---|---|
| **Posters** | 23, 24 and 25 April 2014. "*15th UK National Young Water Professionals Conference."* This three-day international conference was organised by the International Water Association (IWA) and held at Manchester Metropolitan University (MMU) Business School. Alunowska-Figueroa M., Bañares-Alcántara R., Field R. (2014) "A framework for the design of SUWWTS".<br>The International Water Association (IWA) is a renowned international organisation which brings togetherwater professionals to generate innovative solutions and new opportunities to tackle urban and basin-related water challenges. Each year IWA organises and sponsors specialised conferences. |
| | 2-3 October 2013. "*Oxford Biodiversity Institute Symposium 2013: Biodiversity Resilience*". This two-day international conference was organised by the Oxford Martin School and Biodiversity Institute Oxford and was held at the Department of Zoology, University of Oxford. Alunowska-Figueroa M., Bañares-Alcántara R., Field R. (2013) "Resilience of urban water security: A decision support system for integrated SUWWTS". |
| | 20-21 September 2011. "*Energy and People: Futures, Complexity and Challenges*". This two-day international conference, held at Lady Margaret Hall, University of Oxford, was organized by The Lower Carbon Futures research team at the Environmental Change Institute, University of Oxford, and the UK Energy Research Centre's (UKERC) Meeting Place. Alunowska-Figueroa M., Bañares-Alcántara R. (2011) "Spatial Decision Support System for Semicentralised urban wastewater treatment system". |
| **Presentations** | IWA World Water Congress & Exhibition. 21-26 September 2014. Alunowska-Figueroa M. "A Spatial Decision Support System for integrated SUWWTS".<br>This Congress is the main IWA's biennial event, and it attracts around 5,000 water professionals, companies and institutions from over 90 countries. The Congress features parallel sessions of technical presentations, scientific poster displays, workshops and discussion groups, and a large exhibition of products and services. |
| | Europaeum International Forum & Graduate Workshop. "Climate change, waters & cities: what future for Europe?" Leiden University and International Water Week in Amsterdam. 5-7 November 2013. Alunowska-Figueroa M. |
| | Workshop: "Maps as a tool to inform public policy". Radcliff Science Library, University of Oxford. 30 October 2013. Alunowska-Figueroa M. |
| | Graduate Networking Seminars, Oxford Energy Society, University of Oxford. 25 January 2013. Alunowska-Figueroa M. "A Spatial Decision Support System for integrated SUWWTS". |
| | Water security brown bag lunches - DPhils showcase-. Water Security Network, Oxford University Centre for the Environment, School of Geography and the Environment, University of Oxford. 21 November 2012. Alunowska-Figueroa M. "A Spatial Decision Support System for integrated SUWWTS". |
| | Clarendon Talking Heads Seminars, Clarendon Council, Clarendon Fund, University of Oxford. 1 December 2009. Alunowska-Figueroa M. "Climate change and water supply & sanitation management". |
| **Papers** | Two papers are in process. The first one describes the DSS and results (based on Part V and Chapter 12), and it will be submitted to "Environmental Modelling Software". The second one discusses the use of semi-centralisation as an urban water management option (based on Chapter 13), and it will be submitted to the journal "Long Range Planning". |
| **Invitations** | 25-27 November 2013, Rio de Janeiro, Brazil. "World Science Forum 2013: Science for Global Sustainable Development". Though for financial reasons was not able to attend. |

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