

**AN INVESTIGATION INTO OPTIMISING WATER
FLOW OF INDUSTRIAL SYMBIOSIS: DEVELOPMENT
AND APPLICATION OF A MODEL**

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Australia

October 2022

DECLARATION

I declare that this is my own work and this thesis does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or Institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text. I retain the right to use this content in whole or part in future works (such as articles or books).

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ABSTRACT

An investigation into optimising water flow of industrial symbiosis: Development and application of a model

The concept of Industrial Symbiosis (IS) has obtained world concern as a new initiative for achieving collaborative benefits through exchange of resources between industries including water. Even though, these initiatives became prominent as successful projects in the early stages, many of them have resulted in failures in the long term without achieving the expected results due to deficiencies in IS planning. In the current process, no prior evaluation and optimisation are taking place before implementing the identified water synergies. There is therefore a need to have a standardised method to assess the optimum water flow of IS. Accordingly, the current study aimed to develop a model to assess the optimum water flow of IS. In order to achieve the aim, the research stands within the pragmatism philosophical stance. The abductive approach was applied as the appropriate research approach. Sequential exploratory research design was adopted consisting three phases: Phase I: Desk study; Phase II: Interviews with industry experts; and Phase III: Case study. Phase I - Desk study was conducted to collect and review the data from reliable published sources to identify water inputs and outputs of industrial entities. Based on the key literature reviewed, the conceptual model was developed by integrating mathematical formulae. In Phase II, sixteen interviews were conducted with industry experts in Sri Lanka to collect the data. The collected data were analysed using the code-based content analysis technique with the application of QSR International's NVivo. 12. As key findings derived from analysis, current methods & issues of industrial water management and enablers & barriers for initiating water exchange networks in Sri Lanka were identified. Furthermore, the conceptual model and mathematical formulae were also refined to the selected context. The applicability and feasibility of the model were evaluated during Phase III. An IS network in an export processing zone (EPZ) in Sri Lanka, comprising three geographically co-located industrial entities, was selected as a suitable case study. Seven semi-structured interviews were conducted with professionals within the selected case to collect the data, which were analysed using the mixed integer linear programming (MILP) approach. The assessment model was developed and tested using SageMath software. Finally, environmental, economic and social feasibility of the developed model were also determined. The developed model forms a unique foundation for assessing the optimum water flow of IS, applying in any context subject to context-specific enhancements. The novelty of the current research is its objective of reducing freshwater consumption of the IS network through maximum wastewater recovery in assessing the optimum water flow of IS. Thus, the research outcomes provide a role model for all developed and developing countries for reducing the environmental impact of industrialisation through optimum water sharing between industrial entities.

Key Words: Industrial Symbiosis, Mathematical Programming, Optimisation Modelling, Optimum Water Flow, Water Network

DEDICATION

I dedicate this piece of work to my beloved family who encouraged me, with emotional and spiritual effort in this endeavour...

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TABLE OF CONTENT

DECLARATION	II
ABSTRACT	III
DEDICATION	IV
ACKNOWLEDGEMENT	V
TABLE OF CONTENT	VI
LIST OF FIGURES	IX
LIST OF TABLES	XI
LIST OF EQUATIONS	XIII
LIST OF ABBREVIATIONS	XIV
LIST OF APPENDICES	XVI
LIST OF PUBLICATIONS AND AWARDS	XVII
CHAPTER 1: INTRODUCTION TO THE RESEARCH	1
1.1 RESEARCH BACKGROUND	1
1.2 RESEARCH PROBLEM STATEMENT AND RATIONALE	3
1.3 RESEARCH AIM AND OBJECTIVES.....	6
1.4 RESEARCH METHODOLOGY.....	6
1.5 SCOPE AND LIMITATIONS	8
1.6 SIGNIFICANCE OF THE RESEARCH.....	9
1.7 STRUCTURE OF THE THESIS	10
1.8 CHAPTER SUMMARY	10
CHAPTER 2: LITERATURE REVIEW	12
2.1 INTRODUCTION.....	12
2.2 CONCEPT OF INDUSTRIAL WATER MANAGEMENT (IWM).....	12
2.2.1 <i>The need of water for industries</i>	12
2.2.2 <i>Issues in obtaining water for industries</i>	13
2.2.3 <i>Wastewater discharge and related issues in industrial systems</i>	14
2.2.4 <i>Industrial water management (IWM)</i>	15
2.3 THE CONCEPT OF INDUSTRIAL SYMBIOSIS (IS)	21
2.3.1 <i>Evolution of industrial symbiosis concept</i>	21
2.3.2 <i>Industrial symbiosis in the context of circular economy</i>	24
2.3.3 <i>Definitions of industrial symbiosis</i>	25
2.3.4 <i>Fostering industrial symbiosis</i>	29
2.3.5 <i>Initiating procedure of industrial symbiosis systems</i>	33
2.4 RESOURCE EXCHANGE IN INDUSTRIAL SYMBIOSIS.....	35

2.5 WATER FLOW OF INDUSTRIAL SYMBIOSIS: THE GLOBAL CONTEXT.....	38
2.6 INDUSTRIAL WATER MANAGEMENT (IWM) IN SRI LANKA.....	41
2.7 CHAPTER SUMMARY	43
CHAPTER 3: RESEARCH METHODOLOGY	44
3.1 INTRODUCTION.....	44
3.2 RESEARCH DESIGN.....	44
3.2.1 <i>Formulate the research problem, aim and objectives</i>	47
3.2.2 <i>Literature review</i>	47
3.2.3 <i>Philosophical worldview of the research: Pragmatism stance</i>	47
3.2.4 <i>Research approach: Abductive approach in theory redevelopment</i>	52
3.2.5 <i>Research strategy: Sequential exploratory mixed research strategy</i>	55
3.2.6 <i>Drawing conclusions and making recommendations</i>	65
3.3 VALIDITY OF THE RESEARCH.....	66
3.4 CHAPTER SUMMARY	67
CHAPTER 4: DEVELOPMENT OF CONCEPTUAL MODEL AND MATHEMATICAL FORMULAE (PHASE I)	68
4.1 INTRODUCTION.....	68
4.2 OPTIMISATION MODEL DEVELOPMENT PROCESS	68
4.2.1 <i>Input and output water flow</i>	69
4.2.2 <i>Step 1 - Data compilation and initial processing</i>	80
4.2.3 <i>Step 2 - Optimisation model design and development</i>	87
4.2.4 <i>Step 3 - Assessment of the optimal configuration</i>	98
4.2.5 <i>Step 4 - Evaluation of the economic, environmental and social feasibility</i>	99
4.3 CHAPTER SUMMARY	99
CHAPTER 5: DEVELOPMENT OF A CONTEXT-SPECIFIC MODEL (PHASE II).....	100
5.1 INTRODUCTION.....	100
5.2 THE PROFILE OF INTERVIEWEES AND DEMOGRAPHIC INFORMATION.....	100
5.3 DATA COLLECTION AND ANALYSIS.....	103
5.4 RESEARCH FINDINGS - INDUSTRIAL WATER EXCHANGE IN SRI LANKA	103
5.4.1 <i>Existing methods of industrial water management</i>	103
5.4.2 <i>Existing issues of industrial water management</i>	107
5.4.3 <i>Enablers and barriers to initiate water exchange networks in Sri Lanka</i>	112
5.5 RESEARCH FINDINGS - DEVELOPMENT OF A CONTEXT-SPECIFIC ROBUST MODEL TO ASSESS THE OPTIMUM WATER FLOW OF IS IN SRI LANKA.....	119
5.5.1 <i>Context-specific model requirements and enhancements of the conceptual model</i>	120
5.5.2 <i>Key variables of the context-specific model</i>	122
5.5.3 <i>Parameters of the context-specific model</i>	123

5.5.4 <i>Context-specific model development and testing</i>	125
5.6 CHAPTER SUMMARY	127
CHAPTER 6: EVALUATION OF THE APPLICABILITY AND FEASIBILITY OF THE CONTEXT SPECIFIC MODEL (PHASE III).....	128
6.1 INTRODUCTION.....	128
6.2 PROCEDURE ADAPTED IN MODEL EVALUATION.....	128
6.3 INDUSTRIAL SYMBIOSIS NETWORK OF AN EXPORT PROCESSING ZONE IN SRI LANKA: THE CASE STUDY	128
6.4 ANALYSIS OF THE CURRENT STATUS OF THE SELECTED CASE STUDY	132
6.4.1 <i>Current status - Industrial Entity A</i>	132
6.4.2 <i>Current status - Industrial Entity B</i>	134
6.4.3 <i>Current status - Industrial Entity C</i>	137
6.5 INITIATION OF OPTIMUM WATER EXCHANGE NETWORK BETWEEN SELECTED INDUSTRIAL ENTITIES	141
6.5.1 <i>Planning of industrial symbiosis and identification of water synergies</i> .	142
6.5.2 <i>Application of the developed model for assessing the optimum water flow of the proposed industrial symbiosis network</i>	146
6.6 ENVIRONMENTAL, ECONOMIC AND SOCIAL FEASIBILITY OF THE PROPOSED OPTIMAL NETWORK.....	154
6.6.1 <i>Environmental feasibility of the proposed optimal network</i>	155
6.6.2 <i>Economic feasibility of the proposed optimal network (life cycle cost analysis)</i>	157
6.6.3 <i>Social feasibility of the proposed optimal network</i>	166
6.7 A WAY FORWARD OF THE DEVELOPED MODEL	167
6.8 UNIQUENESS OF THE MODEL AND GENERALISATION	167
6.9 CHAPTER SUMMARY	168
CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS.....	169
7.1 INTRODUCTION.....	169
7.2 OVERALL CONCLUSIONS OF THE RESEARCH	169
7.3 LIMITATIONS OF THE MODEL APPLICATION	174
7.4 CONTRIBUTION TO KNOWLEDGE	175
7.5 RECOMMENDATIONS FOR INDUSTRY PRACTITIONERS	176
7.6 RECOMMENDATIONS FOR FURTHER RESEARCH.....	177
REFERENCES.....	178
APPENDICES	196

LIST OF FIGURES

Figure	Description	Page
Figure 2.1	United Nation’s 17 sustainable development goals	16
Figure 2.2	General principles for valuing water	18
Figure 2.3	Drivers and benefits of zero liquid discharge	19
Figure 2.4	Resource flow in linear and circular industrial systems	20
Figure 2.5	Conceptual framework of industrial ecology	23
Figure 2.6	The elements of IE seen as operating at different levels	24
Figure 2.7	Definitions of industrial symbiosis	26
Figure 2.8	Industrial symbiosis at Kalundborg, Denmark	30
Figure 2.9	Key characteristics of self-organising, planned and facilitated IS	31
Figure 2.10	“3-2 heuristic” criterion	36
Figure 2.11	The proposed re-development	40
Figure 3.1	A framework for research design	45
Figure 3.2	Research design framework	46
Figure 3.3	Sequential exploratory mixed design of this research	58
Figure 3.4	Case selection and unit of analysis	63
Figure 4.1	Optimisation model development process flow chart	69
Figure 4.2	Water flow network of Kalundborg IS Project, Denmark	72
Figure 4.3	Water flow network of Choctaw Eco-Industrial Park, USA	73
Figure 4.4	General water inputs and outputs	79
Figure 4.5	Water inputs and outputs of a typical industrial entity	80
Figure 4.6	Selection of industrial entities	82
Figure 4.7	A typical water input and output flows of an industrial entity	83
Figure 4.8	Water synergies between participating industrial entities	84
Figure 4.9	Source-sink relationships between the industrial entities A, B and C	85
Figure 4.10	Theoretical framework	86
Figure 4.11	The conceptual model for assessing the optimum water flow of IS (before mathematical formulae development)	92
Figure 4.12	The conceptual model for assessing the optimum water flow of IS (after mathematical formulae development)	97
Figure 5.1	Years of experience	101
Figure 5.2	Areas of expertise	102
Figure 5.3	Key categories of enablers and barriers (author defined)	113
Figure 5.4	Enablers for exchanging water among the industries in Sri Lanka	113
Figure 5.5	Barriers for exchanging water among the industries in Sri Lanka	115
Figure 5.6	Enablers and barriers for initiating water exchange networks	118
Figure 5.7	Context-specific model to assess the optimum water flow of industrial symbiosis in Sri Lanka	126
Figure 6.1	Geographical plan of the selected case study	131
Figure 6.2	Conventional water network of the selected case study	140
Figure 6.3	Possible water synergies between selected industries	144
Figure 6.4	Typical IS based water exchange network in the selected case study (proposed)	146
Figure 6.5	A screen shot of test results obtained from the SageMath software - TWW flow between industries	150
Figure 6.6	Optimal water flow network	151

Figure 6.7	A screen shot of test results obtained from the SageMath software - freshwater consumption	152
Figure 6.8	A screen shot of test results obtained from the SageMath software - wastewater discharge	153
Figure 6.9	Results of sensitivity analysis	165

LIST OF TABLES

Table	Description	Page
Table 2.1	Resources flow of IS projects	38
Table 3.1	Philosophical assumptions in research	48
Table 3.2	Characteristics of the research approach	53
Table 3.3	Rationale for single case study design selected in this research	61
Table 4.1	Selection of published IS projects for desk study	70
Table 4.2	Articles availability of the selected cases	71
Table 4.3	Water inputs and outputs of Kwinana Industrial Area, Australia	74
Table 4.4	Water inputs and outputs of Qijiang Industrial Park, China	75
Table 4.5	Water inputs and outputs of Songmudao Chemical Industrial Park, China	76
Table 4.6	Typical water inputs and outputs of IS networks	78
Table 4.7	Nomenclatures	94
Table 4.8	Input and output data extraction	94
Table 5.1	Profile of interviewees	100
Table 5.2	Summary of the methods of industrial water management in Sri Lanka	105
Table 5.3	Summary of the issues of industrial water management in Sri Lanka	108
Table 5.4	Comparison of the model requirements and enhancements: Conceptual vs context specific models	121
Table 5.5	Selection of water sources and water sinks in Sri Lankan context	124
Table 6.1	Criteria adopted in selecting industrial entities in the selected case study	129
Table 6.2	Details of selected industrial entities	130
Table 6.3	Profile of interviewees	132
Table 6.4	Freshwater consumption – Industrial Entity A	133
Table 6.5	Wastewater generation – Industrial Entity A	134
Table 6.6	Freshwater consumption – Industrial Entity B	135
Table 6.7	Wastewater generation – Industrial Entity B	136
Table 6.8	Freshwater consumption – Industrial Entity C	138
Table 6.9	Wastewater generation – Industrial Entity C	139
Table 6.10	Water quality standards for drinking water and wastewater discharge	141
Table 6.11	Industrial and cooling water requirement of each industrial entity	142
Table 6.12	Availability of treated wastewater supply of each entity after preliminary and secondary treatment	143
Table 6.13	Source and sink relationships between entities A, B and C in the proposed IS network	147
Table 6.14	Limiting water data for water sources	148
Table 6.15	Limiting water data for water sinks	149
Table 6.16	Optimal water exchange network	150
Table 6.17	Reduction of freshwater consumption in the optimal water network	152
Table 6.18	Reduction of wastewater discharge in the optimal water network	153
Table 6.19	Reduction of the environmental impact through optimal water exchange network	156
Table 6.20	Cost details of the existing conventional water network	158

Table 6.21	LCCA summary for the existing conventional water network	159
Table 6.22	Cost details of the optimal water exchange network	160
Table 6.23	LCCA summary for the optimal water exchange network	162
Table 6.24	Comparison of cost savings of existing and proposed water networks	163
Table 6.25	Calculation of real rates adopting $\pm 7\%$ of change in Production Price Index (PPI)	164
Table 6.26	Results summary of sensitivity analysis	165

LIST OF EQUATIONS

Equation	Description	Page
Eq. 1	Freshwater utilised by water sink	90
Eq. 2	Wastewater generated by water source	90
Eq. 3	Treated wastewater from water source to water sink	91
Eq. 4	Objective function	94
Eq. 5	Water balance at sink	94
Eq. 6	Water balance at source	95
Eq. 7	Quality of treated wastewater	95
Eq. 8	Quality of freshwater	95
Eq. 9	Additional constraint ensuring single inlet and outlet streams of TWW from one entity to another	96
Eq. 10	Freshwater utilised by water sink (modified)	122
Eq. 11	Wastewater generated by water source (modified)	122
Eq. 12	Treated wastewater from water source to water sink (modified)	123

LIST OF ABBREVIATIONS

Abbreviation	Description
ADB	Asian Development Bank
BOD	Biological Oxygen Demand
BOI	Board of Investment
CE	Circular Economy
CE-EIP	Circular Economy Eco-Industrial Park
CEA	Central Environmental Authority
CKD	Chronic Kidney Disease
CLD	Casual Loop Diagram
COD	Chemical Oxygen Demand
CPI	Consumer Price Index
CSR	Corporate Social Responsibility
CWWT	Common Wastewater Treatment
DGM	Deputy General Manager
EIP	Eco-Industrial Park
ENA	Ecological Network Analysis
EPZ	Export Processing Zone
FTZ	Free Trade Zone
FW	Freshwater
GPL	General Public License
GWP	Global Water Partnership
HR	Human Resource
IE	Industrial Ecology
IS	Industrial Symbiosis
IWM	Industrial Water Management
IWRM	Integrated Water Resource Management
LCA	Life Cycle Analysis
LCC	Life Cycle Costing
LCCA	Life Cycle Cost Analysis
LP	Linear Programming
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Non-Linear Programming
MRQ	Main Research Question
NASL	National Audit Office Sri Lanka
NISP	National Industrial Symbiosis Programme
NWSDB	National Water Supply and Drainage Board
PEIP	Planned Eco-Industrial Park
PLS	Plain Language Statement
PPI	Producer Price Index
PV	Present Value
RIP	Retrofit Industrial Park
SDGs	Sustainable Development Goals
SLSI	Sri Lanka Standards Institute
SNA	Social Network Analysis

SOS	Self-Organising Symbiosis
TAC	Technical Advisory Committee
TDS	Total Dissolved Solid
TOC	Total Organic Carbon
TSS	Total Suspended Solid
TWW	Treated Wastewater
UN	United Nations
USA	United State of America
UWW	Untreated Wastewater
WHO	World Health Organisation
WW	Wastewater
ZLP	Zero Liquid Discharge

LIST OF APPENDICES

Appendix	Description	Page
Appendix 1	Semi-structured interview guideline used for Phase II: interviews with industry experts and a sample of transcribed copy	196
Appendix 2	Semi-structured interview guideline used for Phase III: case study and a sample of transcribed copy	212
Appendix 3	Test run results of the model obtained from SageMath software	224
Appendix 4	Coding developed to solve the optimisation problem and the experimental results obtained from SageMath software	225
Appendix 5	Proposed design of CWWT alteration	228
Appendix 6	Life cycle cost analysis for existing conventional water network	231
Appendix 7	Life cycle cost analysis for proposed optimal water exchange network	237
Appendix 8	Sensitivity analysis – calculations and results	242

LIST OF PUBLICATIONS AND AWARDS

- Mallawaarachchi, H., Sandanayake, Y.G., Karunasena, G., & Liu, C. (2020). Unveiling the conceptual development of industrial symbiosis: Bibliometric analysis. *Journal of Cleaner Production*, 258, 120618 (Q1 Journal indexed in Science Citation Index Expanded and Scopus)
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Research Awards

- Winner (School level) of Three Minute Thesis Competition 2022, organised by School of Architecture and Built Environment, Deakin University Australia.

CHAPTER 1: INTRODUCTION TO THE RESEARCH

1.1 Research Background

The industrial sector consumes water in large volumes for various direct and indirect industrial processes. Due to rapid industry development, conventional water resources have been critically depleted. Among other agricultural and domestic sectors, industrial sector is a major water consumer, accounting for between 10-57% of global water consumption (Voulvoulis, 2018). As stated in the National Bureau of China Statistical Yearbook on the Environment, from 2000–2012, the total amount of industrial water used in China increased from 113.9 billion tons to 138.1 billion tons, while the industrial wastewater discharge increase from 19.4 billion tons to 22.2 billion tons (as cited in Zheng et al., 2019).

The wastewater produced by various industries contributes to potential health and environmental issues (Venkatesan & Subramani, 2018). Industry's less investment in wastewater treatment has caused in degradation of the quality of ground water and surface water (Ding et al., 2019). Due to the high level of contamination in ground water and surface water sources caused by wastewater discharge, many people inevitably consume unsafe water (Wang & Yang, 2016). Further, in the *Global Risks Report* of the World Economic Forum held in 2015, the water supply crisis was identified as a high-impact risk (Liu et al., 2018). The United Nations (UN)'s Sustainable Development Goals (SDGs), established in 2015, recognised the presence of the burdens on water bodies (UN General Assembly, 2015). Further to the review by UN General Assembly (2015), SDGs denotes that out of 17 SDGs, several goals are directly and/or indirectly associated to the sustainable management of water bodies (refer Section 2.2.4). In this context, increasing attention is being directed towards development of the water sector, efficient utilisation of water resources, and wastewater recovery & reuse, for sustainable water resources management.

Accordingly, the reuse of wastewater is receiving a great attention due to its' importance in water supply planning especially in industries. As evidenced by previous studies, wastewater reuse systems are currently implemented in many countries in which the reuse of wastewater with or without regeneration or treatment is being considered (Wang & Yang, 2016; Voulvoulis, 2018; Zheng et al., 2019). As discussed by Aviso et al. (2010), wastewater generated from industrial plants can be reused for non-potable water use in industries. Moreover, treated or regenerated wastewater provides an alternative source of water which, if treated to the right quality, can replenish the water supplies and reduce the gap between demand and availability.

In recent decades, reusing water in industries is becoming highly important, especially when adopting circular economy principles (Becker et al., 2019). However, owing to the long-term rate of return, some companies are not willing to invest in industrial water treatment and reuse project initiatives (Navarro-Ramírez et al., 2020). Nevertheless, wastewater has been considered as a probable resource, as it generates

significant economic benefits while reducing the impact on raw water extraction complementing the corporate social responsibility (Becker et al., 2019).

The wastewater reuse can be extended to multiple industries in which wastewater from one industrial entity can be reused directly by other co-located industrial entities provided that the quality requirements are satisfied (Aviso et al., 2010). This exchange between entities was initially recognised by Frosch and Gallopoulos (1989) who also considered the flow of waste between manufacturing organisations to initiate waste exchange networks.

This waste exchange, that is the concept of Industrial Symbiosis (IS) has emerged to integrate the complexity of industries encouraging the use of materials' by-products, water and energy as feedstock sources instead of these resources being wasted (Frosch & Gallopoulos, 1989, Gertler, 1995; Boons et al., 2014). The IS replicates the behaviours of natural ecosystems so that waste from one organism becomes a resource for another (Grant et al., 2010; Milani et al., 2018). As defined by Chertow (2007, p.12), "IS engages the separate industrial entities in a collective approach to gain a competitive advantage by involving physical exchange of materials, energy, water and by-products" for mutually agreed economic and environmental payback (Christensen, 2006). The evolution of the industrial symbiosis concept as a part of industrial ecology (IE), with definitions of industrial symbiosis and the initiation procedure of different industrial symbiosis systems are further reviewed and described in Section 2.3.

According to van Beers et al. (2007), among the other resources exchanged in IS, water can be considered as a utility synergy flow. As reported by Domenech and Davies (2011), industrial symbiosis at the Kalundborg Eco-Industrial Park in Denmark usually includes three types of flows, that is, material, energy and utilities. The authors added that wastewater exchange is mainly viewed as a utility flow in which the inputs of regenerated or treated water and freshwater are considered. As stated by Chertow (2007), water exchange is often the beginning for sharing other resources between industries.

Several industrial symbiosis initiatives have been launched across the globe (European Commission, 2017; Sun et al., 2017; Tao et al., 2019) with the expectation of achieving benefits through the exchange of wastewater and other resources. For example, the first model of IS was fully realised in the Eco-Industrial Park (EIP) at Kalundborg, Denmark (Chertow, 2000). Moreover, at least 60 state-level industrial parks have been established in China during the past decade, accounting for a large proportion of the world's industrial parks (Liu et al., 2018). Choctaw Eco-Industrial Park, USA; Qijiang Industrial Park, China; and Songmudao Chemical Industrial Park, China are other examples of IS projects initiated with the aim of exchanging wastewater (Carr, 1998; van Beers et al., 2007; Li et al., 2017; Zhang et al., 2017). Indeed, the IS networks in European countries have impacted considerably on their environmental and economic development through water savings, and reduction of raw materials extraction and

carbon emissions. For instance, Scotland has experienced 13,018m³ of water savings during the period from 2007–2012 (Domenech et al., 2019).

As further identified by Domenech et al. (2019) and Chertow (2007), IS projects, in the long term, have failed and/or discontinued due to inefficiencies in the resources flow, including wastewater. An investigation of IS collaborations in EIPs in the United States of America (USA) (30 EIPs) and in Europe (33 EIPs), conducted by Gibbs et al. (2005) found that not all projects had succeeded. As stated by Chertow (2007), planned IS projects have failed more than the self-organised IS projects due to the difficulty of planning a stable IS relationship between industries unknown to each other. As found in prior research, IS relationships can fail even after reaching the planning stage (Chertow, 2007; Gibbs & Deutz, 2007). Gibbs et al. (2005) recognised the difficulty involved in planning stable synergistic relationships, with having less initiative for exchanging resources in IS another identified issue. The authors provided Brownsville Eco-Industrial Park, Texas and Plattsburgh Eco-Industrial Park, New York as examples of projects, which had failed due to inefficiency in the planning process. Even though they were identified as successful projects in the early stages, 15 IS projects in Londonderry, New Hampshire, and Cape Charles, Virginia failed in the long term (Bakke, 2005 as cited in Chertow, 2007). Similar to other resources exchanged in IS, the synergetic relationships of water networks have failed due to deficiencies in planning as well as inefficiencies in the water flow of IS in the long term.

Furthermore, the lack of measures to ensure the feasibility of IS network prior to its implementation has hindered the success of IS networks, leading to various disputes between participating industries due to non-informed modifications by the individual industrial entities, risk of long-term interdependence of industries, and industry-community conflicts, to name a few (Maqbool et al., 2019). As Yu et al. (2014) stated, a lack of concern about shortages of resources and price fluctuations of by-products has led to discontinuous symbiotic exchanges over time. As stated by Grant et al. (2010), the relevance of the planned IS network to the selected industrial park is dependent on its economic, environmental and social feasibility in long run. Hence, it is also essential to consider the economic, environmental and social feasibility aspects of IS networks.

1.2 Research Problem Statement and Rationale

The synergistic relationships of water networks in IS have failed in the long term due to discrepancies in the IS planning procedure as well as inefficiencies in the water flow. Although, possible water synergies between participating industries in an IS network are recognised through pre-industrial workshops, the current IS planning process distresses having the means to evaluate the identified water synergies to determine the optimum water flow between the participating industrial entities.

Accordingly, the identified knowledge gaps are explained under three (03) key headings as follows:

- **Lack of research on optimisation modelling of individual resources flows (materials, water, energy and by-products flows) of IS systems**

The structural characteristics of the resources flows of IS systems have been analysed and the technique of 'Social Network Analysis' (SNA) has been extensively used to analyse the structural attributes of IS networks (Domenech & Davies, 2011; Zhang et al., 2016; Song et al., 2018). For example, Domenech and Davies (2011) studied the IS network of Kalundborg, Denmark to identify the number of relationships and their density levels. Zhang et al. (2016) conducted IS network analysis by using SNA which mainly considered network degree centralisation and network density.

Furthermore, Song et al. (2018) used both SNA and Freeman's Degree Centrality Analysis for structural, power quantification and characteristics analysis of IS networks. Zhang et al. (2015) used Ecological Network Analysis (ENA), utility analysis and ecological hierarchical analysis techniques to analyse the IS network in Shandong Lubei Industrial Park in China. Ashton (2009) applied the combination of four different techniques: SNA, correlation analysis, quadratic assignment procedure analysis and multidimensional scaling algorithms to evaluate an IS network in Barceloneta, Puerto Rico.

Other techniques used to analyse and model IS networks include, cascading failure mode analysis (Li et al., 2017); geographical proximity analysis; causal loop diagram (CLD) analysis (Morales et al., 2019); mass balance analysis; input-output analysis; life cycle assessment; and emergy analysis (Chen et al., 2010). However, less attention has been given to utilising optimisation methodologies for evaluating the resources flow of industrial symbiosis systems, with most of the above-mentioned studies having analysed structural characteristics of the resources flow.

- **Less consideration given to analysing the water flow of industrial symbiosis**

Research on IS has increased over the past two decades, with the time ripe for a comprehensible review of the concept, its applications and the collective benefits in selected case studies (Patrucco, 2009; Yu et al., 2014; Diemer, 2017; Morales et al., 2019; Romnée et al., 2019). The research efforts described in the literature first focused on understanding the evolution and development of IS. For example, Frosch and Gallopoulos (1989) introduced "industrial ecosystems" as an important solution for achieving productive use of waste and by-products and minimising environmental degradation. Chertow (2007) attempted to unveil the IS concept and its development by revealing the existing symbiosis. Furthermore, Paquin et al. (2014) demonstrated empirically how a new, facilitated IS initiative developed and evolved.

A study by Huang et al. (2019) evaluated the current status and development trends of IS in a global scenario. Moreover, Morales et al. (2019), Milani et al. (2018) and Yu et al. (2014) conducted studies that investigated the drivers of and barriers to IS projects in China and Denmark. There are studies focused on exploring the concept of IS, its applications in respective countries and its expected outcomes through subjective evaluations. Moreover, case studies have been used to explore different

ways of utilising waste between different companies in IS projects in various countries, such as Oman, the United Kingdom (UK), Australia, China and Denmark (Zhu et al., 2007; Costa & Ferrão, 2010; Gavrish, 2017).

As mentioned in the above discussion, various studies in the literature have focused on exploring materials and waste flows of industries and evaluating the benefits of existing IS networks based on qualitative analysis (Zhu et al., 2007; Ashton, 2009). However, only limited consideration has been given to analysing the water flow of IS.

- **Less consideration given to optimising the water flow of industrial symbiosis by considering the maximum wastewater recovery**

Industries engaging in IS networks each have their own individual goals. As reported by Heeres et al. (2004), many IS collaborations found in the United State of America (USA) and the Netherlands are targeting the enhancement of industries' economic and environmental performance. Wastewater reuse in industrial plants has been considered by many studies, with most having given their main attention to achieving cost reductions in individual plants (Aviso et al., 2010; Taskhiri et al., 2011). Many studies have analysed the economic and environmental gains of individual industries (Aviso et al., 2010), with their focus mostly being on economic indicators (Tiu & Cruz, 2017). A study by Jacobsen (2006) analysed the wastewater flow network of IS based on environmental effects, with the study only considering the possibility to reducing the freshwater intake.

Moreover, many studies have been conducted to develop optimisation models for water exchange with economic and environmental objectives (Boix et al., 2015). Kim and Lee (2007) designed a Pareto optimal network based on the context of benefit sharing among participants. Furthermore, water minimisation and integration were the key objectives considered in studies on optimisation networks (Chew et al., 2008; Rubio-Castro et al., 2011). Most optimisation models in the previous literature have considered cost reduction in water treatment and transportation. Optimisation models have focused on the minimisation of capital and operating costs of treatment facilities and the quantity of water consumed by EIPs (Aviso et al., 2010; Aviso, 2014). Aviso et al. (2011) also studied the input output modelling of water supply chains in industrial parks. Tiu and Cruz (2017) conducted a study that developed an optimisation model for water flow in EIPs by means of water quality. Nobel and Allen (2000) studied the use of geographic information systems (GIS) for industrial water reuse modelling.

Similarly in Sri Lanka context, many studies were found related to reuse of wastewater within the same industrial boundary, applicable standards, guidelines and treatment methodologies. However, a limited consideration has been given on implementing the wastewater exchange networks since the concept of IS is a novel technology that is lack in research and application.

In summary, from published literature, it is apparent that limited consideration has been provided to optimising water flow between industrial entities. Most optimisation models in the previous literature have considered cost reduction of water treatment and

water transportation. Furthermore, existing evaluation emphasises the need to have a standardised way to assess the optimum water flow of IS.

Consequently, the main research question (MRQ) is developed as:

“How to assess the optimum water flow of industrial symbiosis?”

In addressing this research problem, the aim and objectives for this study have been formulated and are presented in the next section.

1.3 Research Aim and Objectives

The aim of this research is to develop a model to assess the optimum water flow of industrial symbiosis.

In order to achieve the research aim, the following objectives are formulated to:

1. review the current status and issues of water exchange between multiple industries in industrial symbiosis
2. develop a conceptual model and mathematical formulae to assess the optimum water flow of industrial symbiosis
3. investigate the existing methods & issues of industrial water management and enablers & barriers to initiate water exchange networks in Sri Lanka
4. develop a context-specific robust optimum water flow assessment model for industrial symbiosis in Sri Lanka
5. evaluate the applicability and feasibility of the developed model to an industrial zone in Sri Lanka

1.4 Research Methodology

This research stands within the pragmatism philosophical stance, complying with the ontology, epistemology, and axiology assumptions. The abductive approach was applied as the suitable approach for theory development in the current study, with this approach beginning with the observation of an empirical phenomenon, followed by conducting the study with the aim of deriving a conclusion grounded on the available evidence (Saunders et al., 2019).

The sequential exploratory mixed research design, comprising both quantitative and qualitative data in sequential order, was adopted. The research design consisted of three phases: Phase I: desk study; Phase II: interviews with industry experts; and Phase III: case study.

The research process was used to connect the research methods and objectives to its conclusion. Reviewing the background and related knowledge gaps led to definition of the research problem. An in-depth literature review was conducted next in relation to the current status and issues of water exchange between industries, the application of IS in industrial estates and the review of optimisation and simulation studies in water flow optimisation to achieve the first objective of the research.

According to Wabiri et al. (2016), a desk study is a quick and easy method for collecting data from existing sources as it reduces data collection time. It also contributes to the accuracy of the conclusion, as the data are collected from reliable published sources. Hence, in Phase I, a desk study was conducted to identify water synergies, key variables, objectives and constraints related to water flow optimisation to develop the conceptual model. Accordingly, data on industrial symbiosis projects were collected from reliable published sources. An in-depth review was conducted by selecting existing industrial symbiosis projects in operation across the globe. A desk study was chosen as the most suitable method for selecting published case studies over the period of time considered, for in-depth investigation and to collect published data.

In Phase II, interviews were conducted with industry experts to investigate the current methods and status of industrial water management (IWM) in Sri Lanka to further refine the research gap in relation to the Sri Lankan context. The developed conceptual model was further refined by identifying context-specific requirements and enhancements, thus achieving the second and third objectives of this research. Sixteen (16) interviews were conducted with industry experts in Sri Lanka to collect the data which were analysed using the code-based content analysis technique. The interview findings were applied to revise the model's variables and parameters as per the context-specific variants and constraints. QSR International's NVivo.12 software was used for analysis and visualisation of the data.

The applicability and feasibility of the model were evaluated by its application to a real-life context through a case study in Sri Lanka during Phase III. According to Yin (2009), a case study approach is more appropriate for gaining an understanding of a complex issue or object and can extend experience or add strength to what is already known through previous research. Hence, an IS network in an export processing zone (EPZ) in Sri Lanka was selected as a suitable case study to evaluate the applicability of the developed model. Seven (07) interviews using a semi-structured interview guideline were conducted with industry professionals in the selected case to collect data relating to the nature of the organisation, its industrial process, input-flow and output-flow of water and possible water synergies. Documentary evidence from the selected industrial entities, such as utility (water) bills, freshwater consumption sub-meter readings, wastewater treatment records, and environmental and water quality norms and standards, etc. were also reviewed to gather the required data. The collected data were analysed using optimisation methods and techniques. Single objective optimisation was used, with the main objective of the study's optimisation being to reduce freshwater consumption through maximum wastewater recovery. The mixed integer linear programming (MILP) approach was used to solve the optimisation problem by finding the optimal value of the targeted objective. The model was developed and tested using SageMath.v3 (open-source mathematical software licensed under General Public License [GPL]).

The feasibility of the model was evaluated in terms of its environmental, economic and social viability. The reduction of the environmental impact was calculated under the model's environmental feasibility compliance with ISO 14040:2006. As stated by

Johansson et al. (2018), life cycle cost analysis (LCCA) on planned industrial symbiosis networks will be useful for mitigating the risk of uneven distribution of cost. Hence, LCCA and sensitivity analysis techniques were used in assessing the economic feasibility of the developed model. The social benefits and contributions towards enhancing social development were finally presented under social feasibility.

1.5 Scope and Limitations

Within the broader areas of resource exchange, industrial symbiosis and optimisation, this research focuses on developing a context specific robust model to assess the optimum water flow of IS and evaluating its applicability and feasibility in the context of Sri Lanka. To address the research problem, the flow of water was optimised, analysed and assessed with the aim being the reduction of freshwater consumption through maximum wastewater recovery.

The limitations of the research are as follows:

- Among the other resources flows of IS, this research was limited to optimise the water flow of IS.
- In model development, water flow of IS was limited to the freshwater intake, wastewater outflow and the exchange of treated wastewater between industries.
- The assessment of the optimum water flow was considered by achieving the objective of minimising the freshwater consumption through maximum wastewater recovery.
- Each industrial plant was viewed as a 'black box' with only a single stream of water considered to enter and exit the plant. Only the input and output water flow characteristics were thus used in assessing the optimum water flow. Therefore, information regarding the internal sub-processes of the selected industrial entities is not considered.
- Only the symbiotic exchanges available among the participating industries were considered in the assessing the optimum water flow of IS by assuming that each entity in the network will go through already integrated treatment or recycling facility within the manufacturing process and willing to exchange treated wastewater with or without own reuse.
- The evaluation of the applicability and feasibility of the developed model was limited to an industrial zone in Sri Lanka. The model's application and validation were limited to one case study of an industrial zone in which three industrial entities were selected complying with the selection criteria developed. The feasibility of the developed model was evaluated in terms of environmental, economic and social viability.

1.6 Significance of the Research

Water scarcity is a significant global threat due to rapid industrialisation in many developed and developing countries. Environmental degradation has rapidly increased due to elevated freshwater utilisation and effluent discharge by industries generating severe health and environmental hazards. The contribution of industries to this environmental deterioration can be addressed through the extension of treated wastewater reuse to multiple industries under the concept of IS. As the existing process for IS initiation is not having a universal method for assessing the optimum water flow of IS and its relevance to industry, many IS networks have failed in the long term without maximum recovery and reuse of wastewater. Hence, this research aims to develop a model to assess the optimum water flow of IS. Based on the research problem's contextualisation, it is believed that this research will significantly contribute both theoretically and empirically.

Firstly, many IS-based water exchange networks across the globe have failed and/or discontinued in long term due to inefficiencies in water flow and deficient planning. However, as no pre-evaluation of water synergies is taking place in the existing top-down approach, this has hindered the continuity of the water exchange among industries. It is hoped that this research will provide a holistic re-development of the top-down approach, providing an innovative solution. As it facilitates a pre-evaluation of IS networks prior to implementation, this will bring about a decline in the discontinuity ratio of IS-based water exchange networks.

Secondly, many studies have focused on developing optimisation models for water exchange by means of economic and environmental objectives which include water minimisation, reduction of water transportation and treatment cost. However, the novelty of the current study is its objective of reducing freshwater consumption of the IS network through maximum wastewater recovery in assessing the optimum water flow of IS. The variables, functions and formulae embedded in the conceptual model form a unique foundation for assessing the optimum water flow of IS, thus adding value for further research by contributing to new knowledge on IS.

Thirdly, it is anticipated that this study's key findings will serve as a benchmark for future researchers, as well as academics, industry professionals and policy makers who are willing to investigate this initiative from different perspectives and to call for actions towards the reduction of water stress through eco-industrial development globally. The outcomes of the research can be adopted in achieving SDGs specially to overcome the presence of the burdens on water bodies (UN General Assembly, 2015). Hence, this research signifies its implication to achieve "SDG14: Life below water" and "SDG6: Clean water and sanitation" ensuring the preservation of ground and surface water bodies. In addition to that, this research exclaims a significant contribution in achieving good health and well-being, decreasing environment pollution including water pollution (SDG3) and ensuring the efficient use of natural resources, including water bodies through responsible consumption and production (SDG12).

Most importantly, the proposed conceptual model can be applied in any context to optimise the water flow of IS, subject to context-specific variants and constraints. Hence, the research's overall outcome regarding the successful application of the developed model for initiating an IS-based optimum water exchange network in Sri Lanka would provide a role model for all developed and developing countries for reducing the environmental impact of industrialisation through optimum water sharing while enhancing economic and social gains.

1.7 Structure of the Thesis

Chapter One provides an introduction to the research. This presents the background, research problem statement, research aim, objectives and research methodology in brief, as well as outlining the thesis structure.

Chapter Two presents the in-depth review of the key literature related to the current status and issues of water exchange between industries and the application of IS in industrial estates, as well as the review of optimisation and simulation studies in water flow optimisation. Thus, the key concepts of industrial water and wastewater management and industrial symbiosis are comprehensively reviewed.

Chapter Three describes the research design and methodology. The research philosophy, research approach, research strategies and techniques including data collection and analysis techniques applied in this research are presented in this chapter.

Chapter Four presents the conceptual model in Phase I for assessing the optimum water flow of IS, with the model based on the key literature reviewed. The key steps of the model development process, and the model's systematic paths and functions are also presented.

Chapter Five presents the analysis and findings related to the Phase II interviews. Hence, the current status and issues in industrial water and wastewater management in Sri Lanka are analysed. The developed context-specific robust optimum water flow assessment model is also presented.

Chapter Six comprises the case study analysis undertaken in Phase III and presents the findings on the applicability of the developed model in the Sri Lankan context, with this followed by life cycle cost analysis (LCCA), environmental and social benefits.

Chapter Seven presents a summary of key research findings answering the research question. The significance of the research and the scope for further research are also highlighted.

1.8 Chapter Summary

This chapter sought to review the background of the research problem. The gaps in the existing literature were recognised under three key headings, based on which the main research question was developed, while also considering the rationale of the research.

The research aim and objectives were presented with the aim being to develop a model to assess the optimum water flow of IS. The research design was also described, along with justification for the reasons for selecting this design. The scope and limitations of the research and its significance were described. The structure of the thesis was finally presented.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter reviews the literature on industrial water management (IWM) and industrial symbiosis. Industries' need for water, and issues and strategies of IWM are reviewed in Section 2.2. This chapter also presents the evolution and definitions of industrial symbiosis in Section 2.3. The key literature findings on resource exchange in IS and water flow of IS are presented in Sections 2.4 and 2.5 respectively. Section 2.6 is devoted to review the industrial water management in Sri Lanka summarising the need for the establishment of IS networks with optimum water exchange between industries to minimise freshwater utilisation and wastewater discharge by industries.

2.2 Concept of Industrial Water Management (IWM)

The limited availability of freshwater, coupled with the growing industrial demand for water and its increasing domestic use, has led to a global water crisis (Ram & Irfan, 2021). The industrial sector especially consumes water in large volumes for various industrial processes which has created severe pressure on available water sources (Voulvoulis, 2018). Furthermore, inappropriate site location for industries has resulted in pollution of surface water and groundwater sources limiting the accessibility of safe water. Hence, initiating an efficient IWM strategy at the process level through a safe manufacturing operation is desperately needed (Haque et al., 2021). This section describes the need for water for various industrial processes, issues in obtaining water for industries and various types of IWM strategies that can be adopted to lower the demand for freshwater consumption and water pollution by industries.

2.2.1 The need of water for industries

Poor management, misuse, over-extraction of groundwater and contamination of freshwater have increased water stress in the world. As stated in the United Nations (UN)'s "Summary Progress Update 2021: SDG6 – Water and Sanitation for All", the demand for water has also increased due to rapid population growth and ever-increasing water needs for agricultural, industrial and energy sectors (UN–Water, 2021). Among them, an average of 20% of the accessible freshwater is consumed by the industrial sector specifically the water intensive industries (Navarro-Ramirez et al., 2020), such as chemical industry, metal, food & beverage, paper and textile industries (Becker et al., 2019). For example, a typical average sized textile mill producing about 8000kg of fabric daily could consume 1.6 million litres (Kant, 2012). As stated by Phan et al. (2021), industries are demanding an ever-increasing volume of freshwater while, at the same time, producing waste and effluent that pollutes surface water and groundwater. Water is broadly used in different stages of the production process which generates industry effluent with high toxicity. Furthermore, industrial freshwater demand in manufacturing sector around the world is anticipated to upsurge by 400%

by the year 2050. Among the other industries, the textile industry is the third largest consumer of global raw water resources (Haque et al., 2021).

The primary source of degradation of water bodies has been proven to be the massive rate of growth of industries and urbanisation (Arif et al., 2020). The ever-increasing industrial water demand has escalated the negative environmental impacts of industrial effluent at the same time (Saidan, 2020). For example, water shortage and water pollution are severe issues in China's industrial development (Zou & Cong, 2021). According to the National Bureau of Statistics of China (2016, cited in Zou & Cong, 2021), the available water resources in China totalled 3,246.64 billion m³ in 2016, of which 18.61% (604.02 billion m³) of water has been utilised. Furthermore, Jordan is another freshwater-deprived country in the world. The situation has intensified by climatic conditions, geography and the region's geopolitical environment. Further, Jordan has ranked as the second in the list of countries, which are suffering from water scarcity (Saidan, 2020).

2.2.2 Issues in obtaining water for industries

The availability of water for industries has been increasingly affected by various challenges driven by the complexities of hydrological cycles, socio-economic factors and various stakeholder perspectives (Susnik et al., 2013; Phan et al., 2021). Moreover, as predicted by Distefano & Kelly (2017) in their study, more than 50% of the world's population could be affected from a threatful water scarcity by 2025 where freshwater could become an unavoidable challenge for the society. In the *Global Risks Report* of the World Economic Forum held in 2015, the water supply crisis was identified as a high-impact risk (Liu et al., 2018). As stated by Amarasiri (2008), many countries are anticipated to face water shortages not previously confronted. For example, it is predicted that the per capita availability of water in India could be reduced from 3,074 m³ / year to 1,434 m³ / year by 2025. Therefore, most issues related to the environment and sustainability, including the present global water crisis, are viewed as "wicked" problems which need immediate attention (FitzGibbon & Mensah, 2012; Streefland & Krozer, 2017; Ram & Irfan, 2021). Other regions suffering from moderate to severe water scarcity during more than half the year include Northern Mexico, parts of the Western USA, parts of Argentina, Northern Chile, North Africa, Somalia, Southern Africa, the Middle East, Pakistan and Australia (Mekonnen & Hoekstra, 2016).

Due to the discharge of industry effluent to groundwater and surface water bodies, the presence of chemicals in water is relatively high (Arif et al., 2020). Furthermore, the available water resources can also be affected by contaminant concentration due to the impact of climate change on the hydrological cycle, with the rising water temperature leading to upsurges in the growth of bacteria in water (Zhao et al., 2019). Due to increased temperatures created by climate change, water availability has been affected by increased evapotranspiration and precipitation and river flow changes (Hristov et al., 2021).

Another very important issue in relation to the industrial sector is that it mostly relies on freshwater which could be used to meet the domestic needs of households. The industrial sector consumes freshwater for industrial purposes, such as, among others, manufacturing processes and operations, power generation, cooling and domestic purposes within industry premises. As stated by Haque et al. (2021), the continuous growth rate in the use of residential, rural and forest land for industrial use has created a serious scarcity in the drinking water supply.

The large amounts of water consumption for industrial operations relative to water availability have resulted in decreased surface and groundwater levels. Inappropriate location of industries has become another critical issue that has also increased the pollution rate of bodies of surface water and groundwater (Wijesinghe et al., 2020). These authors indicated that locating industries in the upper stream of water bodies has created a severe impact on the availability of freshwater. As stated by Haque et al. (2021), the land collapsing risk is present due to the reasons of intense water pollution and overdependence on groundwater sources to fulfil both domestic and industrial needs. The inefficient resources consumption, lack of awareness and unavailability of sufficient groundwater management policies were found by these authors as other reasons for groundwater decline in Bangladesh.

As Seckler et al. (1999) indicated, rapid degeneration of freshwater aquifers is occurring mostly due to the explosion used in wells for the purposes of irrigation, domestic and industrial needs. Although many countries have a high level of water availability based on the main hydrological indicators, severe difficulties have been faced in water usage due to institutional inefficiencies, lack of infrastructure, underinvestment in water infrastructure and lack of robust water governance processes and policies (Vallino et al., 2020).

In summary, as stated above, decreased surface water and groundwater levels, extreme pollution of existing bodies of surface water and groundwater, inefficient consumption of resources, lack of awareness, institutional inefficiencies, lack of infrastructure, underinvestment in water infrastructure and lack of robust water governance processes and groundwater policies are identified as issues in obtaining water for industries.

2.2.3 Wastewater discharge and related issues in industrial systems

Water bodies worldwide have been affected by toxic effluent from industries and are continuously deteriorating as industrialisation, coupled with urbanisation, has caused the excess release of wastewater (Salvatore et al., 2009, cited in Hina et al., 2021). As stated by Shakil and Mostafa (2021), industries with large volumes of effluent discharge are tannery industries, pulp and paper mills, textile mills, sugar mills, thermal power plants, oil refineries and fertiliser industries. Further to the authors, the key drivers of water pollution include ever-increasing municipal and industrial waste generation, its improper discharge and the limited wastewater abatement capacity. For example, over 80% of rivers have been contaminated in China due to improper effluent discharge (Zhang et al., 2011). Untreated or poorly treated industrial effluent

discharged onto land and into surface water bodies generates a huge cost to the environment (Shakil & Mostafa, 2021). Wastewater discharged from industrial and municipal sewage systems is an important cause of water degradation (Piwowar et al., 2021). Contaminated water has become a world-wide concern, causing morbidity and health illnesses on a global level where the deaths rate in both developed and developing countries exceeds 14,000 people per day (Arif et al., 2020).

Industrial wastewater typically contains detectable amounts of organic compounds with the possibility of very complex compositions depending on the exact industrial source (Premachandra et al., 2021).

However, various industries generate industry effluent comprising various concentrations of contaminants that is rigid in defining within a specific quality range. Furthermore, in comparison to municipal wastewater, industrial wastewater contains high number of pollutants, with some components refractory or bio-toxic (Zhang et al., 2020). As Bu et al. (2021) stated, sewage discharge has led to a high pollutant concentration in water bodies. As added by these authors, statistical reports indicate that nearly 190 million people become sick annually in China, of which 60,000 die, from sicknesses related to water pollution. Specifically, the high concentrations of heavy metals, organic compounds and pathogens contained in wastewater are considered the major threats to people's health.

Therefore, implementing improved water management strategies at institutional, national and international levels is vital which may effectively reduce the freshwater demand for industrial purposes that ultimately reduces the cost of water while satisfying environmental policies and regulatory requirements. Furthermore, this assist meeting the United Nations (UN)'s Sustainable Development Goals (Haque et al., 2021).

2.2.4 Industrial water management (IWM)

In developing the society in any nation, sustainable water resources management plays a critical role assisting the various aspects of human endeavour (Ngene et al., 2021). Furthermore, sustainable water management is vital to achieving the Sustainable Development Goals (SDGs) (Wang et al., 2021). The United Nations (UN)'s Sustainable Development Goals, established in 2015, recognised the presence of the burdens on water bodies, with the 17 SDGs shown in Figure 2.1 (UN General Assembly, 2015).

Figure 2.1

United Nation's 17 sustainable development goals



Source. UN General Assembly (2015)

Two of the 17 SDGs, namely, “SDG14: Life below water” and “SDG6: Clean water and sanitation” are directly related to the preservation of ground and surface water bodies. In addition, SDG3 is aiming to achieve good health and well-being as well as to decrease environment pollution including water pollution. The efficient use of natural resources, including water bodies through responsible consumption and production has considered under SDG12 where SDG13 calls for taking action for climate change adaptation and mitigation, while SDG15 focuses conservation, restoration and sustainable use of terrestrial and inland water ecosystems and their services and reduction of the degradation of natural habitats and biodiversity loss (UN General Assembly, 2015). This review of the SDGs denotes that out of 17 SDGs, several goals are directly and/or indirectly associated to the sustainable management of water bodies.

In UN Resolution 71/222, the General Assembly proclaimed the period from 2018–2028 as the International Decade for Action titled “Water for Sustainable Development”. One of the objectives for the decade is to focus more attention on “sustainable development and integrated management of water resources for the achievement of social, economic and environmental objectives” (United Nations [UN], 2016). In line with the 17 SDGs, various strategies have been established across the globe for industrial water management (IWM), as it is significant to efficiently consume water resources by industries and to settle the contradictions between industrial development, supply of water and protection of water environment (Zou & Cong, 2021).

As the industrial sector significantly contributes for environment pollution coupling with diminution of resources, which especially includes water pollution and less availability of raw water sources, many industries are focusing on reducing the risk of water scarcity by improving their industrial processes (Klemeš, 2012). Furthermore,

increased water demand and the cost of water have encouraged industrial entities to initiate water conservation projects (WCPs) and to enhance their efficiency in the utilisation of water resources (Wang et al., 2021).

2.2.4.1 Integrated water resources management (IWRM)

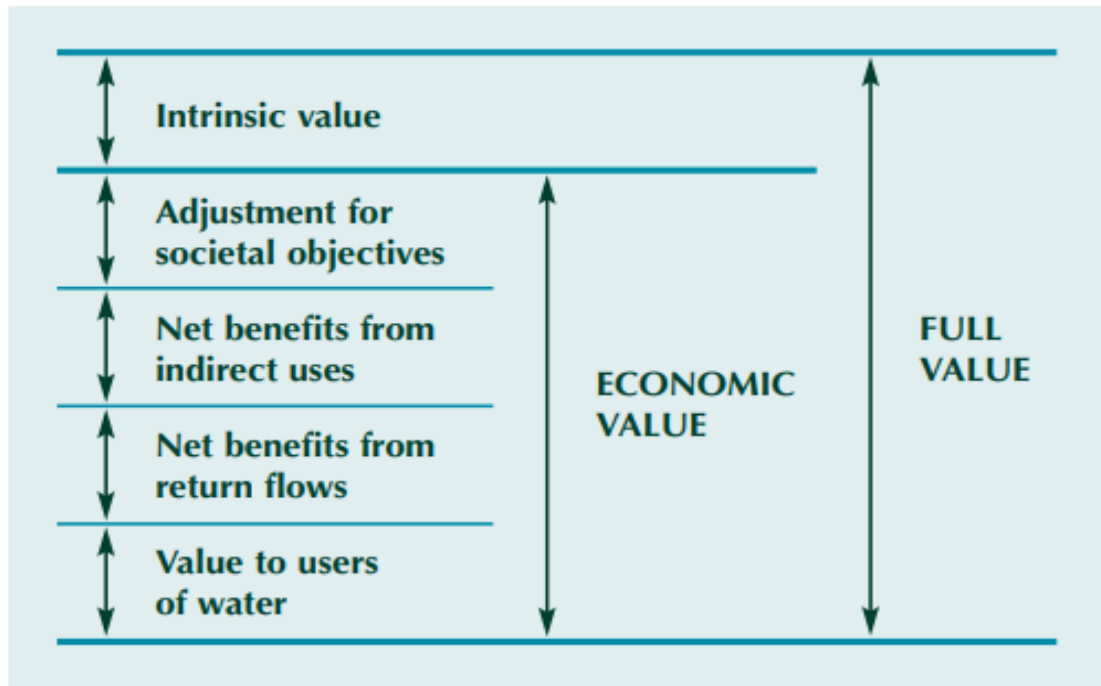
Water resources management (WRM) is an integral aspect of the preventive management of drinking-water quality (World Health Organisation [WHO], 1993). As reported by Agarwal and Karahanna (2000), in the Global Water Partnership (GWP)'s Technical Report, integrated water resources management (IWRM) is defined as:

a process which promotes the coordinated development and management of water, land and related resources, in order to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems (p.22).

As also stated by Agarwal and Karahanna (2000), in IWRM, planned reuse of water which can be obtained from the return flows of non-consumptive industrial needs has a potential to enhance the efficiency of the resources flow. On the other hand, the participation of stakeholders in the decision-making process at all levels of the social structure is an important aspect of IWRM for effectively managing water. Another important point derived from the GWP Technical Advisory Committee (TAC) papers is the “value of water as an economic good” (United Nations [UN], 2022). Industries are generally focusing on increasing the production while reducing the cost of production however, their consideration given upon reducing freshwater consumption is limited due to very low economic value of water (Walsh et al., 2016). As stated by Agarwal and Karahanna (2000), in most countries, many past failures have been accrued since water is considered as a free good in most countries. The full value of water consists of its use value and its intrinsic value. The economic value be contingent by the user and the way it is used. This includes the value to users of water, net benefits from water that are getting absent through evapotranspiration or other sinks and the contribution of water towards the achievement of social objectives, as shown in Figure 2.2.

Figure 2.2

General principles for valuing water



Source. Agarwal and Karahanna (2000)

Through IWRM, countries are assisted to engage in water management issues in a cost-effective and sustainable way through which industries can follow the IWRM principles and guidelines to ensure the efficient use of water in their industrial processes, thus reducing the effects on the quantity and quality of available water.

2.2.4.2 Alternative water sources for fulfilling industrial water demand

Water availability is a challenge for industrial development in any country (Yang et al., 2016). Limited availability of freshwater and growing industrial demand have led industries to alternative water sources (Bianchi et al., 2021). Hence, two common sources which can be alternately used are onsite desalination (treatment) and offsite water sourcing (transport) (Wreyford et al., 2020). The first alternative is the use of treated wastewater through onsite desalination. The grey water and production process-oriented effluent can be reclaimed through the desalination process and reused for the industrial operation (Bianchi et al., 2021). For example, due to urban and industrial development, delta regions have restricted water availability as freshwater sources have been affected by saltwater intrusion and salinisation. Thus, the region of the river Scheldt delta in the Netherlands suffer from a severe water stress due to the high demand of water to be used for industry, agriculture, public and recreational needs. Hence, the importation of freshwater from a source 120 km away has been adopted to fulfil the drinking and industrial needs.

As another alternative, water transport can alleviate pressure on local resources and can assist balancing the water supply complying with the localised demand (Oude Essink et al., 2010; Pauw & Louw, 2012). Further to the authors, examples for water

transport alternatives include lakes, rivers and aquifers, aqueduct water tankers, etc. In addition to that, harvested rainwater and captured condensate are other possible alternatives to replace industrial water requirement (Karunasena et al., 2013; Greer et al., 2010).

2.2.4.3 Reuse of water

Reuse of treated wastewater has become increasingly important, especially in view of the circular economy concept (Becker et al., 2019). As investing in technology for wastewater treatment and reuse in industrial sector generates a long-term rate of return, some industrial enterprises are not willing to engage in water reusing initiatives (Navarro-Ramírez et al., 2020). However, treated wastewater is progressively being considered as a probable resource to generate economic benefits while minimising the pressure on water resources or complementing corporate social responsibility (CSR) (Becker et al., 2019). Hristov et al. (2021) also showed that the reuse of treated wastewater produces significant environmental return.

2.2.4.4 Zero liquid discharge (ZLD)

Zero liquid discharge (ZLD) is an aspiring IWM strategy to avoid any liquid waste from leaving the industrial entities or facility and recovers water maximally. This prevents the risk of pollution due to wastewater discharge while maximising water usage efficiency (Tong & Elimelech, 2016). The solids stored in evaporation ponds are recycled or separated for disposal (Becker et al., 2019). Tong and Elimelech (2016) showed that strict environmental regulations, ever-increasing wastewater disposal cost and scarcity of freshwater are the main drivers of ZLD, as show in Figure 2.3.

Figure 2.3

Drivers and benefits of zero liquid discharge



Source. Tong & Elimelech (2016)

Although ZLD has been recognised as a great initiative for reducing water pollution from wastewater discharge by industries, the application of ZLD has been hindered by the intensive use of energy and high cost. However, many countries have provided the national regulatory support for ZLD operation as a way of facing the challenge of

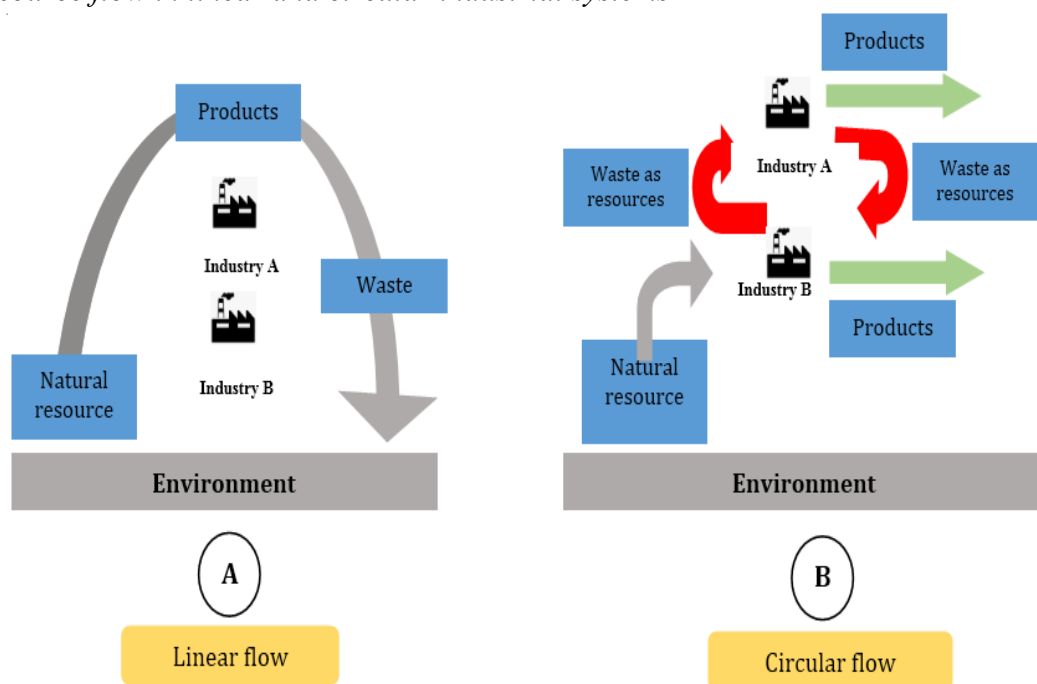
rising water consumption and water pollution. For example, in its new action plan for tackling water pollution, China has provided regulatory coverage for installing ZLD to control pollutant discharge, thereby promoting water recycling and reuse by industries (Jiang, 2015).

2.2.4.5 Industrial symbiosis (IS)

Industrial activities, especially those in the manufacturing sector, create a heavy environmental burden with ever-increasing use of both renewable and non-renewable resources and disposal of waste (Duflou et al., 2012). The concept of industrial symbiosis has emerged as one of the major solutions for enhancing environmental benefits, and especially for reducing the consumption of water as a primary resource through efficient resource exchange (Chertow, 2000). Industrial symbiosis shifts industries from a linear model of production to a more circular model in which waste of one firm is transformed into feedstock for another co-located firm and vice versa (Gibbs, 2008; Bocken et al., 2016). The resources flow of both linear and circular industrial systems is shown in Figure 2.4.

Figure 2.4

Resource flow in linear and circular industrial systems



As Figure 2.4 illustrates, linear industrial systems usually approach the model of take-make-use-disposal of waste directly into the environment. As stated by Bocken et al. (2016), in the linear model, the freshwater extracted and used by the industries ultimately flows back to the environment without any reuse. In circular industrial systems, the ‘one’s trash is another’s treasure’ approach is considered which is cyclical in nature in which one industry can use the waste of another industry as a substitute for raw materials (Frosch & Gallopoulos, 1989; Chertow, 2000). The sharing and circular nature of industrial systems enhances the overall efficiency of the resources

flow by reducing waste generation and greenhouse gas (GHG) emissions (Chertow, 2000; Chertow & Lombardi, 2005; Domenech et al., 2019). As a circular industrial model, IS engages separate industrial entities in a collaborative way in the physical exchange of materials, energy, water and by-products (Chertow, 2007). As industrial parks comprising various different industries are a significant source of wastewater discharge (Dong et al., 2021), the concept of IS has been implemented as a major solution for reducing the increasing demand for water supply and deteriorating water quality due to direct discharge of wastewater from industrial parks. As stated by van Berkel et al. (2009), industrial symbiosis ensures the closing of resource loops by transforming waste into a precious material to reduce the extraction of raw materials in the industrial system. Furthermore, IS has a collaborative sharing platform of resources including water between industries in which the achievement of collective economic and environmental benefits is possible (Maqbool et al., 2019).

2.3 The Concept of Industrial Symbiosis (IS)

Industrial symbiosis has been recognised as an effective way to improve resource-sharing efficiency in closed-loop industrial systems as it reduces raw material extraction, water and energy use, and waste discharge by individual industries through a collaborative approach. This section describes the evolution of the industrial symbiosis concept as a part of industrial ecology (IE), with definitions of industrial symbiosis and the initiation procedure of different industrial symbiosis systems in the following sections.

2.3.1 Evolution of industrial symbiosis concept

The concept of industrial symbiosis finds its origin in the field of industrial ecology (Baldassarre et al., 2019). The world's concern about the importance of reducing resource consumption has resulted in the development of various strategies and pathways. As a result, the industrial symbiosis concept has emerged, supporting the principles of industrial ecology, a concept which has increasingly grown over the last few decades due to its cooperative benefits. Furthermore, the industrial ecology perspective provides a good understanding of how industrial symbiosis has come into being and how it has evolved theoretically over time (Boons et al., 2014).

The discipline of industrial ecology emerged in the early 1990s following the fundamental concerns raised during discussions at the 1972 United Nations Conference on the Human Environment in Stockholm regarding the problem of waste, the value of materials and the control of pollution (Frosch, 1992). The 1972 Stockholm conference can be seen as a milestone in the global environmental movement in which environmental declarations have been developed for environmental preservation (Graedel & Lifset, 2016). Indeed, in 1989, the concept of industrial ecology was propagated through a *Scientific American* article published by two research scholars named Robert Frosch and Nicholas E. Gallopoulos (Clift & Druckman, 2015). This article titled "Strategies for manufacturing" inaugurated an innovative approach called

“industrial ecology” to address the future challenges of the environmental impacts of manufacturing, such as resource depletion and waste generation.

Since then and over the years, the concept of industrial ecology has been defined by various scholars. Industrial ecology is “industrial” in that it focuses on the implementation of environmentally sound product design and manufacturing processes (R.U. Ayres & Ayres, 2002). As the authors further explained, it is also “ecological” which emphasises two main aspects: (a) non-human natural ecosystems such as efficient recycling of materials and energy in industry and (b) industrial ecology which places a link between the use of resources in society and the sinks that act to absorb or detoxify waste.

In 1971, Barry Commoner in his book named *The Closing Circle: Nature, Man and Technology* introduced four laws of ecology which played an important role in academic debate regarding industrial ecology in the following years (Commoner, 1979). These four laws are briefly described below:

1. **“Everything is connected to everything else** – *All living organisms are in the same environment: in this way, something that affects a particular organism also has an effect on others, with this being species-dependent (e.g., symbiosis) or connected in various ways.*
2. **Everything must go somewhere** – *Therefore, a particular focus is made on waste: it cannot disappear. No waste occurs in nature: human “waste” has to end up somewhere and is going to have an impact, based on the choices made about it.*
3. **Nature knows best** – *Humans have always shaped technology to improve upon nature but this change is “likely to be detrimental to that system”.*
4. **There is no such thing as a free lunch** – *If something is exploited, or worse, misused, this is going to have negative effects on natural resources. Both sides of the natural equation must balance; everything taken from one side is going to have a consequence on the other.”*

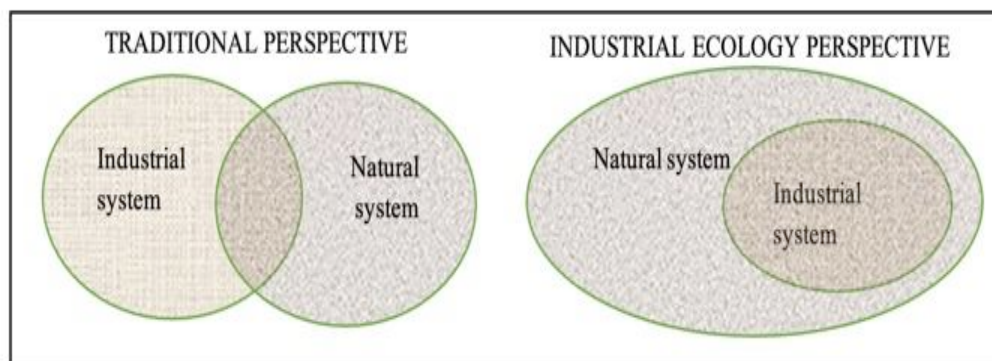
Connelly and Koshland (1996), in arguing about the laws introduced by Commoner (1979), stated that the concept of industrial ecology can be elaborated with two major interpretations, that is, two broad and practical goals: (a) achieving closed material cycles and (b) changing the paradigm in our thinking within the industry–environment relationship. White (1994, cited in Graedel & Lifset, 2016) identified that industrial ecology includes studying the materials and energy flows in industrial and consumer sectors, effect of these flows on the environment, and of the influences of economic, political, regulatory and social aspects on those flows, its usage and conversion of resources. Erkman (1997) demonstrated that most of the sub-parts of industrial ecology, such as the ecosystem concept, quantification of materials and energy flow and the relationship of technology to the general economy were grounded in the 1970s and 1980s.

As identified by Lowe and Evans (1995), industrial ecology obviously provides a new potential model for reconstruction of traditional industrial systems, guiding them

towards a sustainable basis. Furthermore, Lowe (2001) defined IE as an approach to manage industrial activities on a sustainable basis by integrating human and natural systems together, minimising the usage of energy and materials, and the ecological impact of human activity to levels able to be sustained by natural systems. As explained by Gertler (1995, cited in Milani et al., 2018), whereas traditional industrial systems focus on individual processes and units, IE takes a more systemic approach, creating the analogy between human economy and natural ecosystems showing closed-loop flows between materials and energy. Consequently, a great effort is under way to define the attributes necessary to handle resources flow problems in various industries (Puente et al., 2015). Moreover, Xu (2005) demonstrated IE by comparing the traditional and industrial ecology perspectives through a conceptual framework, as shown in Figure 2.5.

Figure 2.5

Conceptual framework of industrial ecology



Source. Xu (2005)

As Xu (2005) explained in his framework, the activities of human ecology can interact with the local ecosystem, the regional ecosystem and the ecosphere, with the principles of ecosystems considered in industrial designs. R.U. Ayres and Ayres (2002) stated that the key elements of IE include biological analogy, use of systems perspectives, role of technological change, role of companies, dematerialisation and eco-efficiency, and forward-looking research and practice. Drawing on the ecosystem analogy, the functioning of eco-industrial clusters is labelled as IS (Baldassarre et al., 2019).

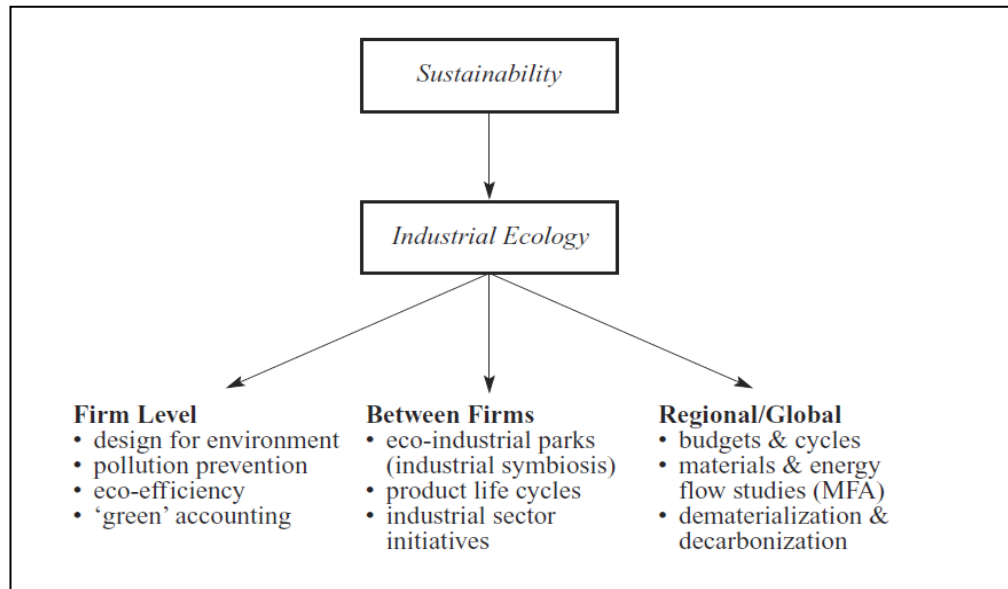
IE highlights the importance of a systems perspective in environmental analysis and decision making, which includes several different forms, such as use of the life cycle perspective; use of materials and energy flow analysis and use of system modelling, to name a few. Technological change is another key theme in IE as a central means of solving environmental problems (Chertow, 2000). Business also plays a key position in IE as it is an important means for achieving environmental benefits.

Dematerialisation refers to the decrease in quantity of materials used to complete a task, which decouples resource consumption and environmental impact. Reducing resource consumption and environmental issues are considered under eco-efficiency

(Lifset & Graedel, 2002). Furthermore, eco design is also a significant aspect in IE to design out environmental harms (Ayres & Ayres, 2002).

Figure 2.6

The elements of IE seen as operating at different levels



Source. Ayres & Ayres (2002, p.10)

As presented in Figure 2.6, the above key themes can be integrated by the view of IE as operating at a variety of levels. IE can be operated at the firm level, at the inter-firm level, and at the regional or global level. At firm level, environmentally friendly designs, pollution prevention, eco-efficiency and green accounting are considered as the most suitable strategies to be added to achieve IE. The authors further considered budgets & cycles, materials and energy flow studies and dematerialisation & decarbonisation at regional level to achieve IE. Moreover, IS occurs at the inter-firm level as it includes exchange of resources among several organisations (Chertow, 2000; Ayres & Ayres, 2002).

Furthermore, IE is useful to adopt circular economy (CE) transition of industries as CE promotes more efficient reuse and recycling of resources and their waste within a circular nature (Han et al., 2017; Saavedra et al., 2018).

2.3.2 Industrial symbiosis in the context of circular economy

Circular economy is an economic concept which optimise the use of resources by adopting recovery, reuse, recycling, sharing and collaboration practices (Moktadir et al., 2020). As Nobre and Tavares (2021) stated, CE targets achieving zero waste and pollution through material lifecycles. CE concept is based mainly on 3R principles namely, Reduce, Reuse and Recycle. However, in 2020, Rovanto and Bask (2020) introduced 4R principles under CE, such as Reduce, Reuse, Recycle and Recover. A widely accepted 9R framework, which was introduced by Potting et al. (2017) includes

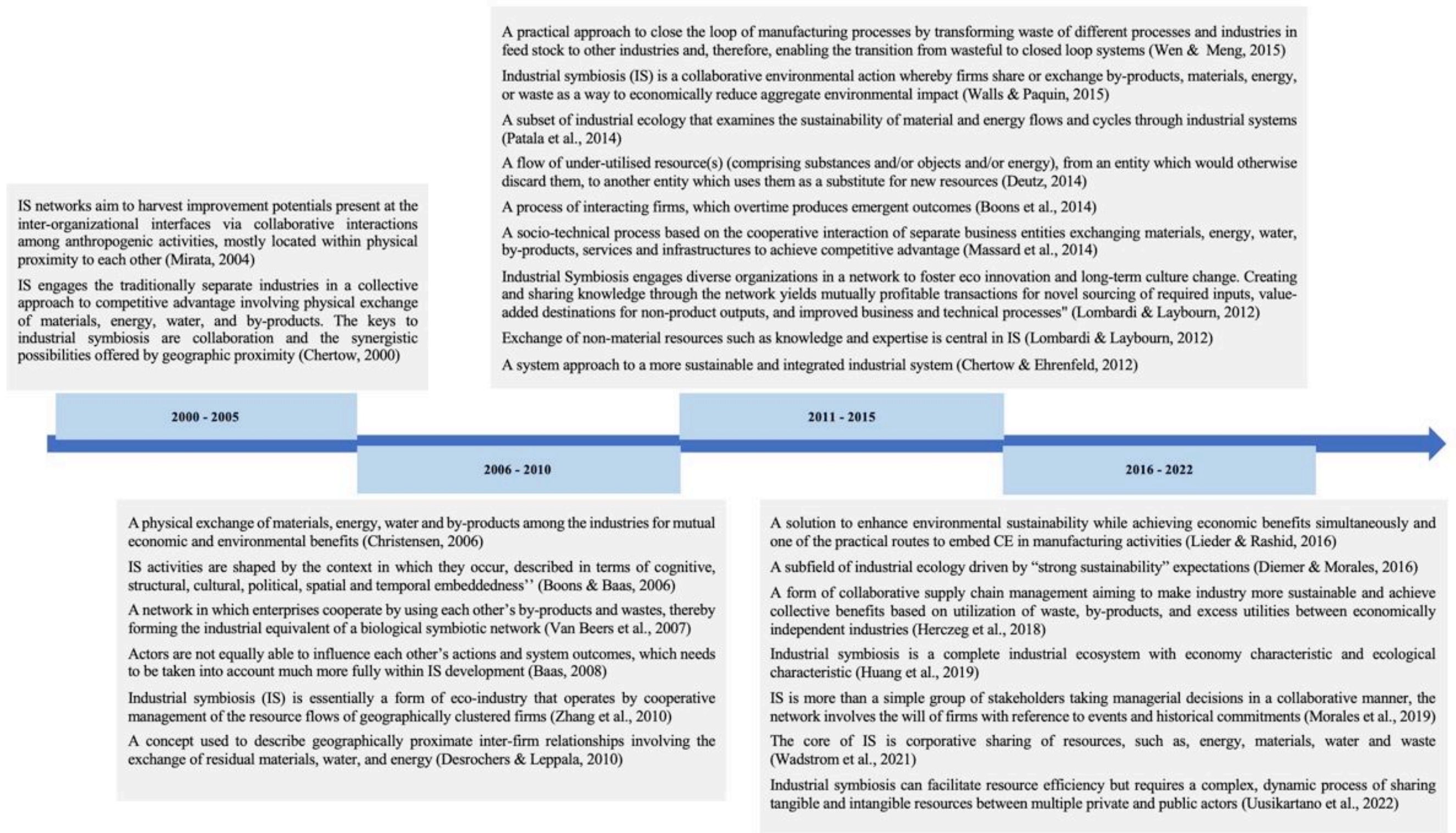
10R principles, such as Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle and Recover.

As stated by Prosman et al. (2018), under the umbrella of IE, IS is a key strategy to closing resources flows, such as materials, water, energy and by-products between industries and the environment through synergetic exchanges. Further to the authors, IS allows adopting many CE principles, including Reuse, Recycle and Recover. Accordingly, a significant link between industrial ecology, industrial symbiosis and circular economy can be found (Saavedra et al., 2018).

2.3.3 Definitions of industrial symbiosis

Symbiosis is a biological term referring to “*a close sustained living together of two species or kinds of organisms*”. The term was used by a German botanist De Bary in early 1873 to describe the coupling of fungi and algae in lichens (Miller, 1994, cited in Ayres & Ayres, 2002). The expression “symbiosis” in IS has been built on the notion of biological symbiotic relationships in nature known as “mutualism” in which at least two otherwise unrelated species exchange materials, energy or information in a mutually beneficial manner (Chertow, 2000). The concept of IS first gained popularity through discussions by Frosch and Gallopoulos (1989) who suggested that one company’s waste can be used by another company as productive input (Chertow, 2000). Since its emergence, research scholars have interpreted this novel concept in various ways by tracking its development, as shown in Figure 2.7.

Figure 2.7
Definitions of industrial symbiosis



Empirical studies have revealed that the literature on IS has been developed and disseminated over the past decade by prominent research scholars. Several industrial symbiosis projects initiated across the globe present an amalgam of various IS theories and literature, thus providing evidence of how vital the industrial symbiosis application is towards achieving its ultimate outcomes. In 2010, IS was presented within a similar boundary as in the previous decade. IS has been defined as an approach to develop inter-firm relationships between industries that are geographically proximate for the exchange of residuals, water and energy (Desrochers & Leppälä, 2010; Weerasinghe & Sandanayake, 2017). This definition denoted the profound influence of Chertow (2000) in the previous decade on the concept of IS over the years. Zhang et al. (2010) presented IS as an eco-industry system which cooperatively manages the resources flow between co-located firms. Similarly, the authors presented the importance of engaging geographically clustered firms. IS can also emerge as an eco-industrial practice in which the flow of resources is operated by a cooperative management procedure. This creates a vivid deliberation of the emergence of possible linkages between IS and strategic management domains.

Chertow and Ehrenfeld (2012) deliberated on ways to improve the concept as a systematic approach for implementing environmentally sound industrial systems. The authors suggested that industrial symbiosis engaged organisations from different sectors to achieve mutually favourable relationships by reusing waste and by-products in an innovative manner. Geographical proximity of the firms was regarded as a key for the emergence of industrial symbiosis. However, this is still under debate as some scholars have claimed that, as flows of knowledge and the supply chain through technology are possible, proximity would not be critical for industrial symbiosis (Gregson et al., 2012).

Chertow (2000, p.12), as a key scholar in the IS domain, introduced an in-depth definition in 2000, stating that IS is “an approach to collaborate the traditionally separated industries to obtain a competitive advantage through the physical exchange of materials, energy, water and by-products”. The author further stated that IS can occur at the inter-facility level as it exchanges waste between co-located industries as raw inputs. As indicated by the author, the availability of synergistic possibilities and the geographic proximity of firms are the keys to initiating industrial symbiosis relationships. Another definition, introduced by Mirata (2004), states that the purpose of IS networks is to achieve the industry improvement potential by interaction between co-located industries. This supports Chertow’s (2000) definition which refers to the exchange of by-products and waste, as well as physical proximity. This latter definition, however, clarifies the exchange of products between collaborating industries within inter-firm boundaries through their interactions.

The definition presented by Christensen (2006) also came up with a similar view that industrial symbiosis is the exchange of materials, energy, water and by-products between industries to achieve a collective advantage. This definition recognised that industrial symbiosis involves the exchange of organisational resources between industries; however, no specific consideration was given to the characteristics or the

number of firms in the collaboration. The advantage of industrial symbiosis has been recognised as its economic and environmental benefits which can be obtained mutually by the engaged firms under the IS collaboration. At roughly the same time, another concern was presented by Boons and Baas (2006, cited in Costa et al., 2010), as they argued in their definition that IS activities can be shaped by the different contexts in which they occur. The authors added that the industrial symbiosis contexts can be based on six different aspects: cognitive, structural, cultural, political, spatial and temporal embeddedness. As proposed by van Beers et al. (2007), industrial symbiosis creates networks that are similar to biological networks as they also exchange waste and by-products. Baas (2008) recognised this point, supporting the interpretation of Boons and Baas (2006, cited in Costa et al., 2010). However, as Baas (2008) stated, the actors in an industrial symbiosis network could not influence each other in the same way, with this needing to be considered in developing IS relationships.

Most importantly, Lombardi and Laybourn (2012) introduced the point that the industrial symbiosis network exchanges not only material resources, like waste and by-products, but also immaterial resources, such as knowledge, expertise and technology, etc., thus transforming improved business and technical processes. The authors added that industrial symbiosis could adopt eco-innovative and cultural belongingness through diversity (Lombardi & Laybourn, 2012). In line with interpretations by various scholars, Deutz (2014) presented IS as an exchange of materials, energy, water and by-products. Patala et al. (2014) and Boons et al. (2014) also confirmed that IS is a subset of industrial ecology to produce environmentally healthy outcomes in which the sustainability of materials and energy flow is observed.

A study by Massard et al. (2014, as cited in Baldassarre et al., 2019) added an overview of industrial symbiosis as a socio-technical process. Authors further extended the flow of resources in industrial symbiosis from materials, energy, water, by-products, knowledge and expertise to services and infrastructure. As stated by Walls and Paquin (2015), industries may exchange by-products, materials and energy to economically reduce their impact on the environment. In 2015, the concept of IS evolved into a closed-loop system rather than being concerned solely with the exchange of waste between industries. Wen and Meng (2015) outlined industrial symbiosis as a way through which to circularise manufacturing processes, transforming wasteful industries into closed-loop industrial systems.

Lieder and Rashid (2016) sought to further strengthen the notion of industrial symbiosis as one of the practical ways to adopt circular economy (CE) principles in manufacturing processes. Huang et al. (2019) also stated that industrial symbiosis is a key concept of the circular economy (CE). The conceptual development of industrial symbiosis was further presented by Herczeg et al. (2018) as a collaborative supply chain management structure in which economically independent industries utilised each other's waste, by-products and excess utilities. Huang et al. (2019) presented industrial symbiosis as a comprehensive system containing economic and ecological features. Morales et al. (2019) recently argued that industrial symbiosis involves more than a simple group of stakeholders making managerial decisions in a collaborative

manner. As the authors further verified, it engages the intentional behaviour, preferences and motivation of firms in an industrial symbiosis network, related to firms' past events, obligations and commitments. Wadstrom et al. (2021) supported the thoughts about IS similar to the other scholars' definitions as a corporative sharing of resources including energy, materials, waste and water. Indeed, Uusikartano et al. (2022) came up with another important definition about IS as a complex and energetic process of exchanging tangible and intangible resources between various public and private actors.

Having considered the above points, the researcher developed the following working definition for the concept of IS to facilitate this research as:

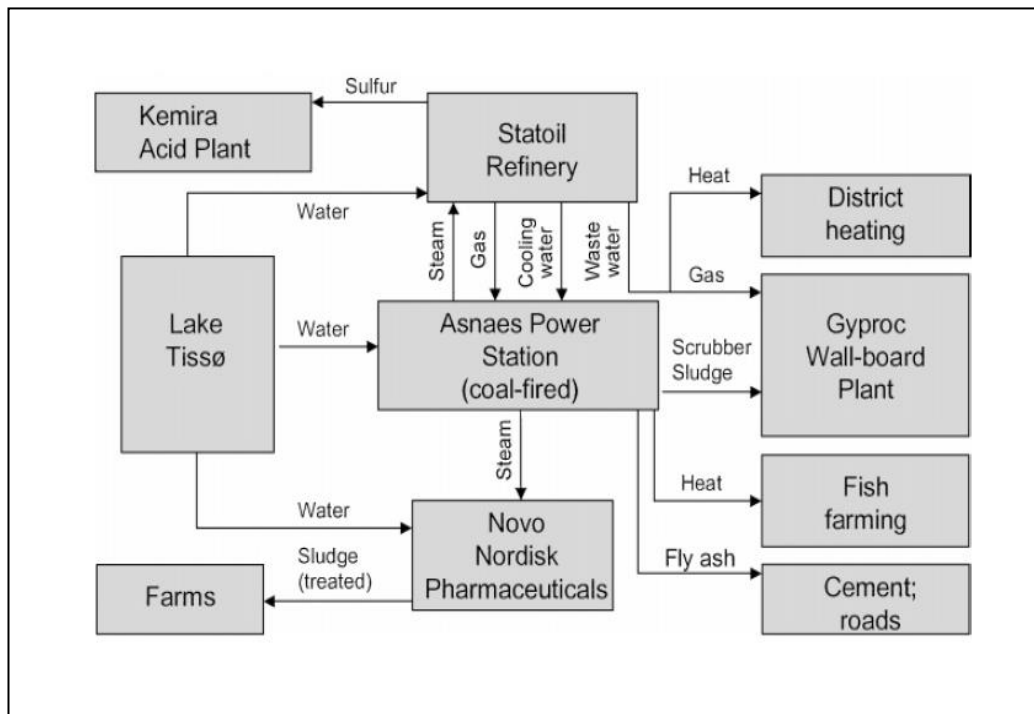
“the engagement of traditionally separated and geographically proximate industrial entities to achieve collaborative benefits through the physical exchange of resources including materials, energy, water, by-products, services and infrastructure”.

2.3.4 Fostering industrial symbiosis

The first model of industrial symbiosis in the Eco-Industrial Park (EIP) at Kalundborg, Denmark (refer to Figure 2.8), provided a solid understanding of industrial ecosystems, as hypothesised by Frosch and Gallopoulos (Chertow, 2000). Chertow (2000) clearly described that the key to IS in taking advantage of synergistic possibilities was geographical proximity of the firms, as it ensures the physical exchange of resources. However, Mirata and Emtairah (2005, as cited in Zhang et al., 2015) noted that symbiotic relationships could also happen at long distances and could include the exchange of knowledge and utilisation of shared infrastructure.

Figure 2.8

Industrial symbiosis at Kalundborg, Denmark



Source. Chertow (2000)

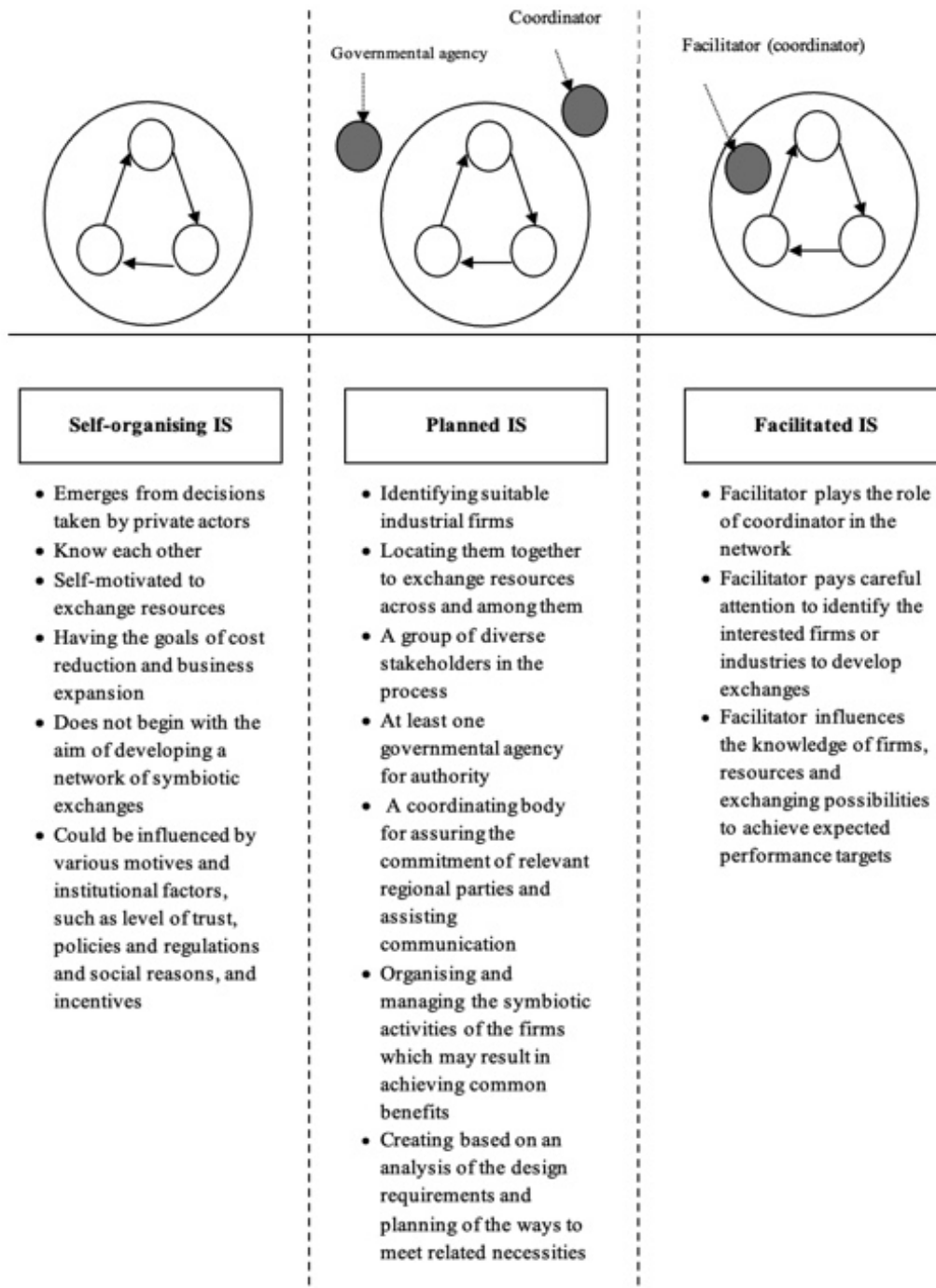
Baas and Boons (2004) introduced an important perspective on the emergence of industrial symbiosis. As stated by the authors, the concept consists of three stages: “regional efficiency”, “regional learning”, and “sustainable industrial district”. The first stage, regional efficiency, describes the self-directed decision-making ability of firms and the possibility of coordinating with local firms to reduce inefficiencies.

In the second stage, firms and other partners exchange knowledge to build sustainability based on multi-recognition and trust. The third stage presents the strategic vision of firms and collaborative activities between partners to achieve sustainability. Chertow (2007) argued that the concept proposed by Baas and Boons (2004) had various limitations which may cause symbiotic relationships to fail. The author explained that, as firms are not aware of the environmental benefits they would obtain, these benefits are not revealed before exchanges are established. Hence, with the need for a more robust way to initiate industrial symbiosis relationships, various emerging models of industrial symbiosis have been recognised and introduced by research scholars.

According to the existing literature, the models in which industrial symbiosis relationships could occur comprise self-organising industrial symbiosis, planned industrial symbiosis and facilitated industrial symbiosis (Chertow, 2007; Paquin & Howard-Grenville, 2009; Chertow & Ehrenfeld, 2012). The key characteristics in each model are illustrated in Figure 2.9.

Figure 2.9

Key characteristics of self-organising, planned and facilitated industrial symbiosis



The first model of self-organising industrial symbiosis was initially proposed by Chertow (2007) after having been first realised in the eco-industrial park (EIP) at Kalundborg, Denmark. The partners in the park focused on exchanging a variety of by-products as feedstock rather than these by-products becoming waste in the environment. Chertow (2007) further explained that, in the self-organising industrial symbiosis model, an industrial ecosystem emerges from decisions made by private stakeholders who are self-directed to exchange resources to meet, among others, the

goals of cost reduction and business development (Chertow, 2007). As Boons et al. (2017) stated, self-motivated strategies can result in the development of symbiotic activities; however, self-organised industrial symbiosis does not begin with the aim of developing a network of symbiotic exchanges. Boons et al. (2017) further stated that the decision could be influenced by various motives and institutional factors, such as level of trust, policies and regulations, social reasons and incentives given by the individual industrial entities. Mortensen and Kørnøv (2019) stated that the emergence process of industrial symbiosis relied on pre-emergence (initial conditions and inoperative potential of resources flows); emergence (awareness and interest in industrial symbiosis, exploring connections and organising); and post-emergence (formal establishment of synergistic ties, physical implementation of industrial symbiosis and industrial symbiosis development).

Chertow (2007) formulated another model for how industrial symbiosis can emerge, with this named “planned industrial symbiosis”. As Chertow (2007) further stated, planned industrial symbiosis comprises the key activities of identifying suitable industrial firms and locating them together to exchange resources across and among them. The planned industrial symbiosis model may include formation of a group of different stakeholders within the process, involvement of at least one governmental organisation with some authority and long-term financing to encourage its development. Furthermore, a coordinating body is established to ensure the commitment of relevant regional parties, facilitating information flows and assisting improved and strengthened communication between these parties (Mirata & Emtairah, 2005). Planned industrial symbiosis also involves organising and managing the symbiotic activities of firms, which may result in achieving common benefits beyond the individual industrial entities’ expectations (Baas, 2008). Conversely, it has been considered a time-consuming activity and a difficult process, whereas self-organising industrial symbiosis has taken a leading role in industrial symbiosis development as it often performs on a small scale and the actors in the network know each other (Baas, 2011). Momirski (2019) also indicated that planned industrial symbiosis can be found in eco-industrial parks (EIPs). As Zhang et al. (2010) stated, planned industrial symbiosis, as operated in EIPs, may be built based on a careful analysis of design requirements and planning for how to meet related needs. Furthermore, planned networks may be established based on a cooperative plan in which firms engaged in the network share infrastructure and services, as well as the coordination-related and promotion-related liabilities of IS exchanges (Domenech et al., 2019).

However, the question of whether to implement planned, unplanned or self-organised industrial symbiosis facilities can result in different outcomes, with mutual trust, inter-firm relationships and long-term interdependence affecting the emergence and the long-term endurance of industrial symbiosis (Baas, 2011). In this sense, Paquin and Howard-Grenville (2009) argued that, as per the industrial symbiosis literature, a distinction exists between industrial symbiosis that is serendipitous (self-organising industrial symbiosis) and that which is goal-oriented (planned industrial symbiosis),

leading to the proposal of a new model of “facilitated industrial symbiosis” as another way to achieve the emergence of industrial symbiosis. In facilitated industrial symbiosis, a planned process replaces self-organising industrial symbiosis, as the facilitator influences the knowledge of firms, resources and exchanging possibilities to achieve expected performance targets. Furthermore, the facilitator plays the role of coordinator in the network and pays careful attention to identification of firms or industries interested in developing exchanges (Paquin & Howard-Grenville, 2009). Consequently, self-organising industrial symbiosis, planned industrial symbiosis and facilitated industrial symbiosis are recognised as the key models for the emergence of industrial symbiosis in any context.

2.3.5 Initiating procedure of industrial symbiosis systems

Boons et al. (2015) viewed the initiation of IS relationships from two new perspectives, that is, technical and organisational. According to the authors, industrial symbiosis can be initiated in three different ways from the technical perspective: process-oriented, residue-oriented and place-oriented. Process-oriented IS considers the cooperative network around the industry, while the residual flow is the main concern in residue-oriented IS. In place-oriented IS, the network is confined to a specific location. The four different ways to implement IS under the organisational perspective are anchor manufacturing, eco-cluster development, government planning and the business incubator (Boons et al., 2011).

In 2012, Chertow and Ehrenfeld (2012) introduced five new ways for developing IS, which comprises the Build-and-Recruit Model, Planned Eco-Industrial Park (PEIP) model, Self-Organising Symbiosis (SOS) model, Retrofit Industrial Park (RIP) model and the Circular Economy Eco-Industrial Park (CE-EIP) model. As Chertow and Ehrenfeld (2012) further stated, the build-and-recruit model encourages eco-industrial development. The main characteristic of the PEIP model is positioning the organisational entities based on their geographic proximity. In the SOS model, decisions made by independent actors are considered, while the RIP model has been introduced in industrial parks which already existed in industry (Wen et al., 2018). The CE-EIP model is a new concept for developing more sophisticated symbiotic relationships. According to the study by Yuan et al. (2006), the circular economy (CE) emerged in China in early 2009 and is interacting with industrial symbiosis as a new development in industry (Tao et al., 2019). Tao et al. (2019) introduced four new models: the newly planned model, retrofit model, speed-dating/exogenous model and intrinsic/endogenous model. These models have fostered industrial symbiosis and are being used as criteria for the level of government involvement in helping to build industrial symbiosis synergies.

When implementing any of these models, the development of industrial symbiosis networks can be identified as occurring over several stages. Considering the three cases studied in their research, Domenech and Davies (2010) suggested three stages of industrial symbiosis development, as follows: (a) emergence, (b) probation and

(c) development and expansion. The first phase is emergence (Domenech & Davies, 2009), with initial relationships and possible collaboration opportunities identified during this phase. During the probation phase, potential symbiotic exchanges are unveiled to realise the possible dynamics for cooperating with other industrial symbiosis partners. The identified relationships are further deepened during the development and expansion phase. This phase is also concerned with the mitigation of drawbacks occurring in implementation. As outlined by Grant et al. (2010), the following five stages of the industrial symbiosis project life cycle can be identified as synergy: (a) identification, (b) symbiosis assessment, (c) barrier removal, (d) implementation and (e) follow-up (review and documentation). Furthermore, the National Industrial Symbiosis Programme (NISP) in UK came up with six processes in industrial symbiosis implementation (Boons et al., 2011) as follows:

- (i) building the industrial symbiosis network by recruiting new members,
- (ii) assessing the characteristics of the organisation (sector and business size, etc.), availability of resources and locations,
- (iii) facilitating a platform (workshop) for participants in selected firms to share information regarding possible resource exchanges,
- (iv) identifying and mapping possible synergistic opportunities between firms,
- (v) using a suitable data management tool (12d Synergy, etc.) to identify the benefits of the proposed exchanges and ways to reduce cost through effective management of resources, and
- (vi) introducing a central or intermediary position to coordinate the network and to verify the output reports of the facilitated synergies.

Tao et al. (2019) introduced five phases of industrial symbiosis development: awareness development, planning, negotiation, implementation and evaluation. Having considered the common phases from the aforementioned authors, the current study determined four key phases of industrial symbiosis development: (a) planning industrial symbiosis, (b) barrier removal and negotiation, (c) implementation and (d) evaluation and follow-up. These four key phases are explained below.

Phase 1: Planning industrial symbiosis

The initial planning phase of industrial symbiosis comprises expert-facilitated workshops, identifying the firms and their synergies, and assessing and mapping the opportunities. Pre-assessment and synergy identification occur through three primary means: new process discovery, resource matching and relationship mimicking (Grant et al., 2010). The economic gains and cost possibilities of the activities are also considered, as well as identifying the possibilities for creating job opportunities (Chertow & Lombardi, 2005).

Phase 2: Barrier removal and negotiation

After identifying suitable partners for relationships in an industrial symbiosis network, negotiation takes place to confirm the volume, quality, price and supplying frequency of the resources (waste, energy etc). Furthermore, strategies are introduced in this

phase to overcome the barriers to implementing industrial symbiosis activities. As Golev et al. (2015) identified, these barriers may include unavailability of information, lack of commitment by partners, and trust and coordination issues between partners, as well as regulatory, social and economic concerns.

Phase 3: Implementation

In Phase 3, decisions are made to implement the identified synergies (Maqbool et al., 2019). The suitable approach for managing the symbiosis is also considered prior to implementing exchanges (Chertow & Ehrenfeld, 2012). Identifying and distributing the tasks and responsibilities between firms also come under this phase. Phase 3 is completely governed by the firms that have engaged in the industrial symbiosis network (Grant et al., 2010).

Phase 4: Evaluation and follow-up

This phase includes two main tasks: continuous monitoring of the impact to take follow-up action, if required, and disseminating the outcomes. This phase ensures the stability of industrial symbiosis activities through continuous improvement. Communicating the results and outcomes of the implemented industrial symbiosis relationships is a major concern (Maqbool et al., 2019).

By adopting various emerging approaches, several industrial symbiosis initiatives have been launched worldwide, with its benefits now understood. As stated by Chertow (2007), industrial symbiosis ensures resource efficiency improvements by closing resource loops between collaborating industries. Furthermore, industrial symbiosis is a practical approach to maximise resource efficiency through the exchange of materials, energy, water and by-products between traditionally separated industries (Chertow, 2007; Sunet et al., 2017).

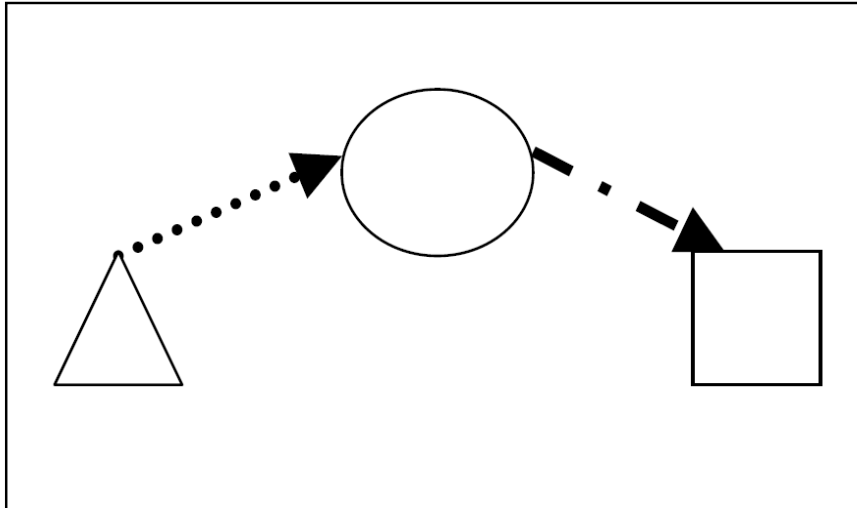
2.4 Resource Exchange in Industrial Symbiosis

The discipline of creating the industrial systems with less environmental impact came into practice by collaboratively closing the energy and resource loops of separate industries (Baldassarre et al., 2019). The design of eco-industry clusters was emerged in early 1990's by practically applying such eco-system analogy fundamentals to manage the environmental issues such as resource extraction, consumption and waste (Massard et al., 2014). Frosch and Gallopoulos (1989) deliberated the potential of IE to conserve the natural materials by reducing and reusing the waste at both firm and inter-firm levels. In 1989, an industrial cluster of companies, who sharing resources was unveiled in Denmark (Chertow, 2000). The author has considered the IS as engaging the separate industrial entities in a collaborative manner by physically exchanging materials, energy, water and by-products. Chertow (2007) propose a taxonomy of five different exchange types, namely (a) through waste exchanges, (b) within a facility, firm or organisation, (c) among firms co-located in a defined eco-industrial park, (d) among local firms that are not co-located, and (e) among firms

organised “virtually” across a broader region, in which types (c) to (e) were only recognised as IS, since it could offer the approaches for symbiotic relations.

Chertow (2007, p.13) adopted a “3-2 heuristic” criterion to distinguish IS from other types of exchanges as shown in Figure 2.10.

Figure 2.10
“3-2 heuristic” criterion



Source. Chertow (2007, p.13)

According to “3-2 heuristic” theory introduced by Chertow (2007, p.13):

“at least three different entities must be involved in exchanging at least two different resources to counter it as a basic type of IS. By involving three entities, none of which is primarily engaged in a recycling-oriented business where the 3-2 heuristic begins to recognise the complex relationships rather than the linear one-way exchanges”.

As specified in Figure 2.10, the triangular, circular and square shapes denote the three different industrial entities where two arrows signify the two different exchanges of resources in a basic type of IS.

The resource exchange between the entities was first recognised by Frosch and Gallopoulos (1989) in which the flow of waste among the manufacturing organisations was considered. Over the years, the flow of resources in IS has been extended from materials, energy, water and by-products to various intangible resources, such as information, business ideas for sustainable innovation, knowledge, expertise, technology, infrastructure, services, utilities, local habitat and social tactics. Waste flow was first recognised by Frosch and Gallopoulos (1989) in 1989, which has been extended to materials, energy water and by-products in 2017. Van Beers et al. (2007) studied the IS in the eco-industrial parks of Kwinana and Gladstone, Australia and found that the possible synergies or the types of resources could exist mostly in three broader categories: water, energy and inorganic by-product reuse. As van Beers et al. (2007) further claimed, exchanging waste and by-products can be highlighted as an important resource flow in IS since it creates networks similar to the biological

networks. Further to the authors, types of resources in IS can be categorised into two broader headings, namely utility synergies (water, steam, electricity) and by-product synergies. In 2008, Gibbs (2008) further refined the importance of exchanging the waste and by-products among the firms to preserve the raw materials. While Desrochers and Leppala (2010) identified residuals, water and energy were the types of resources exchanged at the inter-firm level, Grant et al. (2010) stated that the exchange of resources, such as materials, energy and water can also contain the information and ideas about the business practices following the sustainable innovation. Most importantly, Lombardi and Laybourn (2012) initiated a fact that the IS network exchanges not only the material resources like waste and by-products but also the immaterial resources, such as knowledge, expertise and technology.

A study by Massard et al. (2014) identified IS as a socio-technical process in which the flow of resources has been extended from material, energy, water, by-products, knowledge and expertise to services and infrastructure. Further, the symbiotic exchanges in IS can be occurred as by-product exchanges, sharing of infrastructure, utilities and services as well as the collaborating to solve common issues of the interacted firms (Chertow et al., 2008). It supported the theory introduced by Chertow (2007) that the single industry dominated clusters can have three types of exchanges, namely by-product use, utility/infrastructure sharing and joint provision of services. Liu et al. (2018) stated that IS is efficiently sharing the information, materials, water, energy, infrastructure and the local habitat while Maqbool et al. (2019) presented the findings on exchanging materials, energy, water, by-products and social aspects at both firm and multi-firm level.

Based on the types of resources exchange in IS, Wu and Wang (2016) categorised IS into two categories: (i) exchange-based IS and (ii) sharing-based IS. Further to the authors, exchange based IS consists of reuse and recycling of solid waste or by-products, reuse of water, and efficient use of energy. Sharing-based IS refers to the sharing of utilities and non-material resources, such as knowledge, techniques and services.

Based on the source, resource flow of IS can be categorised into two types of flows: natural resource flows and obsolete resource or waste flows. The waste flow contains the reused resources and waste (Shi & Li, 2019). As Shi and Li (2019) further stated, the resources network of IS can be categorised into four categories based on its medium of flow as material network, value network, information network and the knowledge network. Further to authors, material network consists of resources and waste networks wherein resource network considers the extraction, production, transportation and consumption of raw materials while the waste network concerns the restoring of waste. Value network contains the money flows accompanied to the material flow of IS. Information network supports the exchange of symbiosis related raw data to identify the opportunities for material exchange. Knowledge network flows the knowledge on symbiosis related objectives and rules which were drawn from IS activities to support the growth of symbiosis systems.

In summary, the typical resource flow of IS includes materials, energy, water and by-products. The identified resources in typical resource flow are further investigated into the selected IS projects as shown in Table 2.1.

Table 2.1

Resources flow of IS projects

Name of the IS project	Typical resource flow			
	Materials	Water	Energy	By-products
Kalundborg IS Project, Denmark	X	X	X	X
Gujiao Eco Industrial Park, China	X	-	-	X
Shandong Lubei IS Project, China	X	X	-	-
Choctaw Eco-Industrial Park, USA	X	X	-	-
Dunkirk IS Project, France	X	-	X	X
Guitang Group IS Project, China	X	-	-	-
Kwinana Industrial Area, Australia	X	-	X	X
Gladstone Industrial Area, Australia	X	-	-	X
Barceloneta IS Project, Puerto Rico	-	X	-	X
Qijiang Industrial Park, China	X	X	X	X
Tianjin IS Project, China	X	X	X	X
Ulsan Eco Industrial Park, Korea	-	-	X	X
Songmudao Chemical Industrial Park, China	X	X	X	X

Further to the analysis of the identified IS projects, most of the IS projects have been designed mainly to exchange materials, by-products, energy and water. Further, many of studies have been focused on material and by-product flows. The exchange of raw materials and waste has been considered under the material flow. Out of the 13 IS networks, firms have collaborated to exchange more than one types of resources to obtain a collective economic and environmental benefits including resource efficiency, cost efficiency, water savings and waste reduction. As this research focused, the water flow of IS was further investigated in order to identify the possible water inputs and outputs as described below.

2.5 Water Flow of Industrial Symbiosis: The Global Context

Water is one of main resources exchange in IS networks. Wastewater reuse in industrial plant is a strategy, which has been considered by many studies in recent

decades (Taskhiri et al., 2011). The adoption of water minimisation strategy through wastewater reuse can effectively reduce overall freshwater demand in water using processes and subsequently reduce the amount of effluent generated. On the other hand, wastewater reuse can be extended to multiple industries in which the wastewater from one industrial plant can be reused directly by other co-located plants as long as the quality requirements are satisfied (Aviso et al., 2010). Various case studies were found on exploiting wastewater in IS projects in various countries, such as Oman, United Kingdom, Australia, China and Denmark (Zhu et al., 2007; Costa & Ferrão, 2010; Gavrish, 2017).

Even though many of IS-based water networks exist across the globe, it is a well-known fact that many of those in IS projects have resulted in failures without achieving the expected results (Gibbs, 2008). As Chertow (2007) identified, IS projects have been failed and discontinued in long term due to inefficiencies of the resource flow including water. While its numerous benefits motivate the formation and development of symbiotic relationships among the industries, the obstacles toward implementing synergies can also be observed in systems, which could undermine the expected collaborative gains (Golev et al., 2015). Industrial symbiosis relationships can fail even after reaching the planning stage (Chertow, 2007; Gibbs & Deutz, 2007). The majority of cases of failure in IS development have been attributed to shortcomings of the top-down approach (Desrochers, 2004; Aissani et al., 2019; Tao et al., 2019).

Furthermore, the risk of interdependency among industry partners and the authority of control over decisions can influence the stability of the flow of resources (Fichtner et al., 2005). Industrial symbiosis networks fundamentally exchange the resources; however, the stability of resources flows could subside due to the lack of quality, continuity, and quantity of flows and/or the inability to achieve the expected efficiencies (Chertow & Lombardi, 2005; Fichtner et al., 2005; Tao et al., 2019). Gibbs et al. (2005) recognised the difficulty in organising stable synergistic relationships and a fewer number of initiatives for exchanging resources as the key issues. For example, Brownsville Eco-Industrial Park, Texas, and Plattsburgh Eco-Industrial Park, New York, are examples of projects, which have failed due to deficiencies in the process (Gibbs et al., 2005).

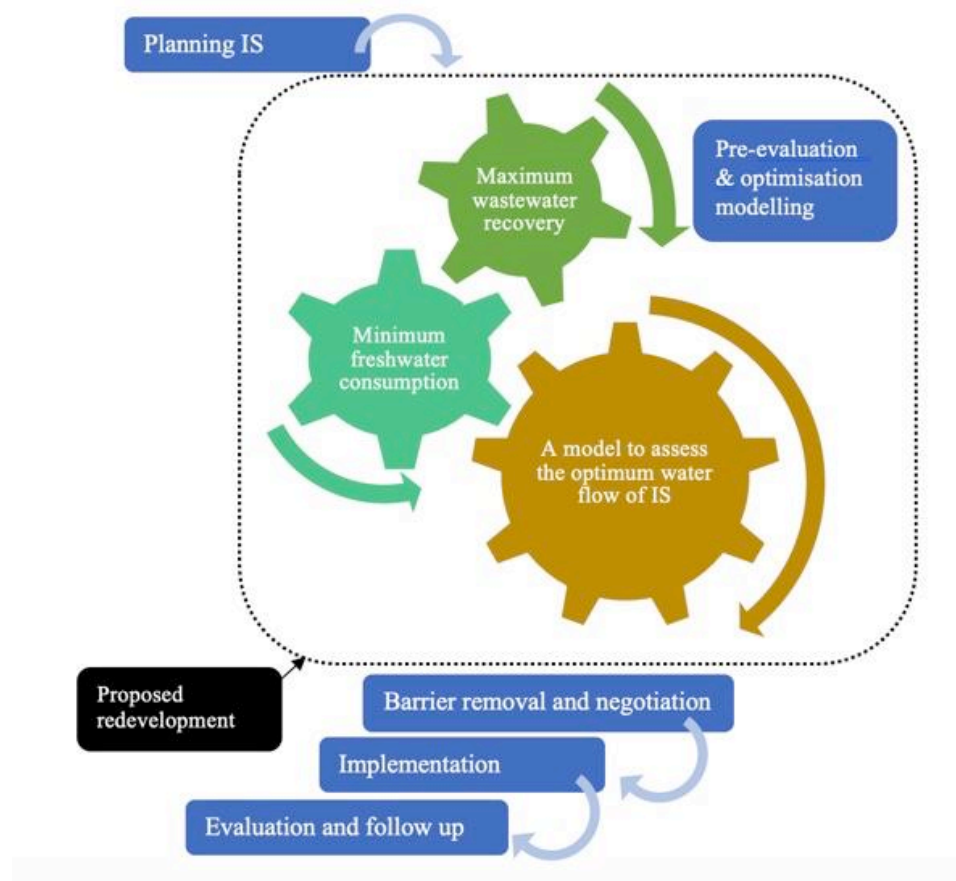
As with other resources exchange in IS, the synergistic relationships in water networks have failed due to the deficits in IS planning as well as owing to inefficiencies in the water flow of IS in the long term. Unstable and inefficient water flows of IS have resulted in long term inefficiencies. The planning stage of IS and the stage of barrier removal & negotiation of water exchange networks include conducting expert-facilitated workshops to identify the firms and their synergies to assess and map possible exchanges between the selected firms. Furthermore, the economic gains and cost savings of water exchange are also considered during the planning stage (Grant et al., 2010). Further to the authors, assessment during the planning stage includes the cost analysis of water treatment and transportation. Subsequently, and before implementation, negotiations between participating industrial entities must take place to reach agreement about the volume, quality, price and the supply frequency of the

water inputs to be shared (Golev et al., 2015). Although, the stage of evaluation & follow-up is carried out as the final phase to analyse the new job opportunities and cost savings through the proposed water exchange network (Tao et al., 2019; Maqbool et al., 2019), no pre-evaluation and optimisation are undertaken of the identified water synergies to ensure that the water flow is optimal with maximum wastewater recovery (Chertow, 2007; Schaffartzik et al., 2014). This has hindered the achievement of the expected efficiencies and the long-term stability of the water flow in IS networks. However, it is evident in the published literature that no method exists to assess the optimum water flow of IS through maximum wastewater recovery. Furthermore, this has been identified as a timely need by most researchers (Chertow, 2007; Golev et al., 2015). This necessitates the need to have a standardised way to optimise the water flow of IS to achieve the expected economic, environmental and social gains.

Figure 2.11 shows the proposed enhancement of the IS development process to optimise the water flow through maximum wastewater recovery.

Figure 2.11

The proposed re-development



As illustrated in Figure 2.11, the process begins with planning of IS, which may occur through existing or planned business relationships of the firms. As identified in key literature, identifying possible water synergies may take place. In the proposed re-development, the second stage is formalised to identify the optimum water flow of the IS network. Hence, it was proposed to include a new stage of “pre-evaluation and

optimisation modelling” as the second stage of the IS development process followed by barrier removal & negotiation, Implementation and evaluation & follow-up. In the proposed stage of “pre-evaluation and optimisation modelling” minimising freshwater consumption of participating industrial entities in IS network will be considered through maximum wastewater recovery. As this research aimed, a model will be developed to assess the optimum water flow of IS during the stage of “pre-evaluation and optimisation modelling” prior to the implementation of planned water synergies. The proposed optimisation in assessing and modelling the optimum water flow is shown in Figure 4.10.

2.6 Industrial Water Management (IWM) in Sri Lanka

With respect to water resources, spatial variability of water availability and the severe pollution of freshwater bodies are main challenges faced by Sri Lanka due to domestic and industrial waste (National Audit Office Sri Lanka [NASL], 2019). The water uses in Sri Lanka include household water supply, sewerage and sanitation, irrigation and industrial processes.

According to the current institutional and regulatory framework in Sri Lanka, the National Water Supply and Drainage Board (NWSDB) is the primary institution to fulfil water supply and sanitation needs in the country (Wijesekara et al., 2020). As specified in the ADB (2017) report the current water supply service delivery in Sri Lanka is at a satisfactory level when compared with the other countries in the region. Nearly, 15% of the population (three million people) have been identified as the unserved population (Asian Development Bank [ADB], 2017).

Approximately 80% of freshwater is used for agricultural needs, while industries consume 7% of freshwater (Amarasiri, 2008). The author described some of the numerous purposes for which water is used in industry, such as the initial washing of raw materials; generating steam, cleaning factory premises, to name a few. Due to improper discharge of effluent, nutrients, pesticides, industrial effluent, faecal contaminants, other microorganisms and waste sediments could pollute the surface water and groundwater bodies (Amarasiri, 2008).

Solid and liquid waste of industries is a cause of threatening living organisms in water bodies. Across the country, wastewater generated by industries has become one of the main contributors to the pollution of both groundwater and surface water bodies (Jayathilake et al., 2020). For an example, around 138 megatonnes (MT) of sewage are discharged daily into water sources due to inadequate sewerage systems (Ministry of Forestry and Environment, 2001). Hence, sewage, industrial waste, and agricultural and physical pollutants can be identified as major causes of water pollution in Sri Lanka (Imbulana, 2010). For example, heavy metals and other concentrations from industry effluent can be found in many lakes and rivers (Amarasiri, 2015). The pollution of bodies of surface water and groundwater has created severe health and sanitation issues in Sri Lanka. Most surface water sources are not appropriate for drinking as they are contaminated by bacteria, viruses and other pathogenic organisms

(Jayathilake et al., 2020). As reported by the authors, in some areas, wastewater from hospitals and industries is discharged directly into canals, streams and rivers, creating severe health and environmental issues. According to recent reports, chronic kidney disease (CKD) has become a significant health problem specifically in the North Central Province (Wijesekara et al., 2020). As stated by Wanasinghe et al. (2018), one of the main risk factors influencing the occurrence of CKD is utilising contaminated water.

Various international and national strategies and guidelines have been implemented for industrial water and wastewater management in Sri Lanka as stated below:

- World Health Organisation (WHO)'s Guidelines for Drinking-Water Quality
- Drinking water quality standards by Sri Lanka Standards Institute (SLSI)
- Ambient water quality standards and Water Quality Index by the Central Environmental Authority (CEA)
- Wastewater discharging standards by the CEA (CEA, 2019)
- ZDHC wastewater guidelines by ZDHC (ZDHC Foundation Roadmap to Zero Programme (ZDHC), 2019)
- Environmental norms by Board of Investment (BOI, 2011)

The quality of drinking water or freshwater is governed by the WHO guidelines, SLSI water quality standards and the CEA's Water Quality Index. The CEA conducts quality monitoring for wastewater discharge by industries. The *National Environmental Act No. 47 of 1980* and Gazette No 1534/18 provide provisions relating to wastewater discharge. The discharge of wastewater from industrial activities into the environment is regulated by the Environmental Protection Licenses (EPL) scheme implemented under the provisions of Section 23(a) of the *National Environmental Act of 1980*. As specified in the Act, it is mandatory to obtain an EPL to discharge wastewater from an industry into the environment. To qualify for an EPL, industries which discharge wastewater into the environment are mandatory to treat their own wastewater to the specific standards given (Central Environmental Authority [CEA], 2019). Industries must follow the given quality limits when they discharge treated wastewater to inland surface water, land irrigation, marine coastal areas, etc. Textile, tanning and rubber manufacturing industries have different quality parameters to maintain when they dispose of treated water into inland surface water (CEA, 2019).

The ZDHC Foundation Roadmap to Zero Programme (ZDHC) is a collaboration of brands, value chain affiliates and associates committed to eliminating hazardous chemicals from the textile, apparel and footwear value chain. This is not only for conventional wastewater parameters, but also for hazardous chemicals (ZDHC Foundation Roadmap to Zero Programme, 2019).

Furthermore, as a governing body of free trade zones in Sri Lanka, the Board of Investment (BOI) has introduced environmental norms for investors who invest in BOI zones for new industries. According to BOI guidelines, all industries are required to pre-treat wastewater within their premises and must send for common wastewater

treatment (CWWT) (Board of Investment [BOI], 2011) as industrial effluent not matching to the required quality limits are not allowed to discharge directly into CWWT. However, in the current practice, treated wastewater is discharged into waterbodies with no reuse of wastewater found. Furthermore, where direct discharge is permitted within the given water quality limits, the existing policies and guidelines are not supporting the reuse of industry effluent. Many industries are directly discharging untreated industrial effluent into the nearest waterbodies especially where these industries are located on riverbanks and upstream of waterbodies (Wijesekara et al., 2020). Hence, establishing an appropriate water management mechanism to support island-wide industrial development is identified as a timely need. In line with this thought, establishing industrial symbiosis networks with optimum water exchange between industries was identified as a significant attempt to minimise freshwater utilisation and wastewater discharge by industries. Additionally, the regulations and guidelines of freshwater quality and effluent discharge of industries in Sri Lanka were considered in defining the constraints of the optimum water flow assessment of IS networks (refer Section 5.5.3).

2.7 Chapter Summary

This chapter initially presents a comprehensive literature review on the concept industrial water management, industrial symbiosis (IS), the existing strategies and guidelines and issues in water and wastewater management in global context. Since there is an ever-increasing water demand for industries, the importance of having an initiative for industrial water management is recognised. Accordingly, the use of IS for initiating water exchange between industries is reviewed. As reviewed in key literature, various issues were found in the initiating procedure of IS networks. A new stage of pre-evaluation and optimisation modelling was proposed as the second stage in IS development process before implementation of the identified synergies. Accordingly, among the other resources, the need of having a way to optimise the water flow of IS is recognised. Finally, the need for initiating and optimising the industrial water exchange in Sri Lanka was identified. The next chapter explains the research methodology adopted in this research.

CHAPTER 3: RESEARCH METHODOLOGY

3.1 Introduction

This chapter explains the research design adopted to achieve the aim and objectives of this research. In relation to the research problem, the research was designed by adopting suitable research methods and techniques. The philosophical stance, research approach, strategies and techniques adopted in the research are explained with relevant justifications, particularly for the research design framework developed. Furthermore, the measures taken to assure the validity of the research findings are also explained.

3.2 Research Design

The research design is developed as a plan for fulfilling the research objectives by answering the research questions (Adams et al., 2007). As stated by Yin (2009), research design provides a logical sequence connecting initial research questions, empirical data, and conclusions of the study. According to the author, the research design helps to eliminate the issues that arise when the research evidence does not answer the questions of the research. Instead, research design is a plan to guide the researcher in the research process of collecting, analysing and interpreting of results (Nachmias & Nachmias, 1992 as cited in Yin, 2009). These authors added that it is a logical model of proof which permits the researcher to draw implications by considering the causal relationships between research variables. Thus, the nature of the research problem, personal experiences of the researcher and the targeted audience of the research are key concerns assisting the definition of suitable research design (Creswell, 2009).

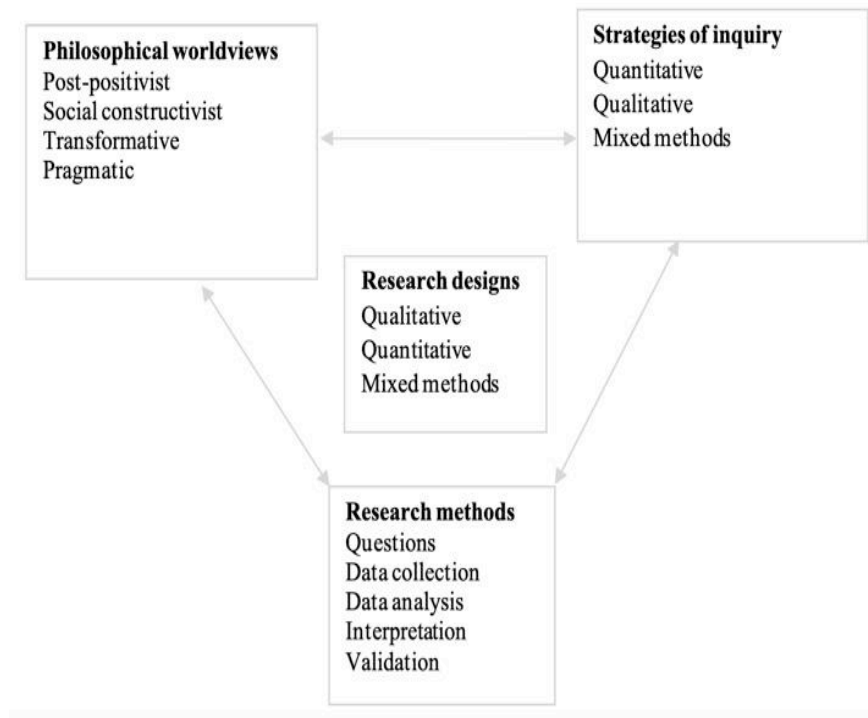
Various research methodological models have been developed by discussing the philosophical aspects of a study (Kagioglu et al., 2000; Creswell & Creswell, 2018; Saunders et al., 2019). In the hierarchical model proposed by Kagioglu et al. (2000), three rings: research philosophy, research approach and research techniques have nested together in which outer ring (research philosophy) guides the inner rings, such as research approach and techniques making them compatible to each other.

Saunders et al. (2019, p.108) proposed a “research onion” consisting of six layers: from the outer layer, research philosophy, through the approach to theory development, methodological choice, strategies, time horizon, and techniques and procedures. As Saunders et al. (2019) further explained, positivism, critical realism, interpretivism, postmodernism and pragmatism are the worldview states under the philosophical stance. As added by these authors, the approach to theory development includes deduction, induction and abduction, where qualitative, quantitative and mixed methods stand under methodological choice. Experiment, survey, archival research, case study, ethnography, action research, grounded theory and narrative inquiry were research strategies within the research onion, as explained by the authors. Longitudinal and cross-sectional studies were considered under the time horizon, with the sixth layer

belonging to data collection and data analysis techniques. Moreover, Creswell and Creswell (2018) proposed a framework comprising three elements of research design, as shown in Figure 3.1.

Figure 3.1

A framework for research design



Source. Creswell and Creswell (2018)

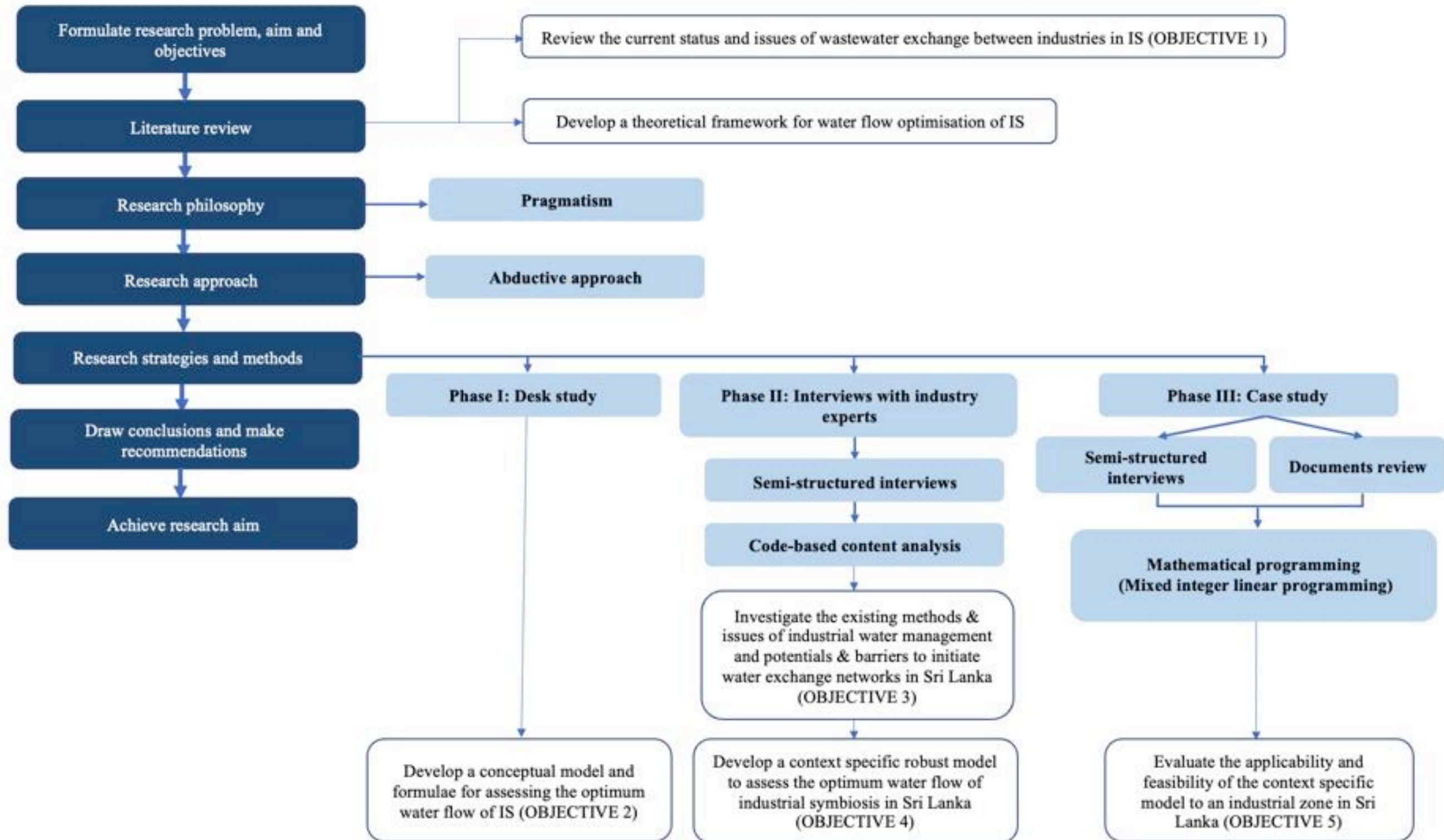
As stated by J.W. Creswell and Creswell (2018), the three main elements of research design are as follows:

- Philosophical worldview,
- Strategies of inquiry (research approach) and
- Research strategies and methods.

Considering the similarities of the research design frameworks proposed by the above scholars, the research design framework of Creswell and Creswell (2018) was adopted for determining the methodological design of the current research. Further, the framework proposed by Creswell and Creswell (2018) represented all key elements of research design elaborated by other scholars. Hence, philosophical worldview mainly consisting post-positivism or positivism, social constructivism, transformative and pragmatism, research approach comprising qualitative, quantitative and mixed methods, and research strategies & methods including data collection and analysis are described.

The logical sequence of the key elements in the research design is shown in Figure 3.2. The philosophical stance, research approach, research strategies and methods including data collection and analysis techniques, are described in the following sections.

Figure 3.2
Research design framework



3.2.1 Formulate the research problem, aim and objectives

Formulating the research question is a significant step in the research process (Yin, 2009). With the necessity to have a robust model for assessing the optimum water flow of IS, the main research question (MRQ) is developed as: “*How to assess the optimum water flow of industrial symbiosis?*”. The aim of this research is to develop a model to assess the optimum water flow of industrial symbiosis. In order to achieve the aim, five objectives were formulated (refer to Section 1.3).

3.2.2 Literature review

A comprehensive literature review was conducted by reviewing books, journal articles, conference publications, official websites, and government and institutional reports relating to the key research terms, namely, “industrial water management”, “industrial symbiosis” and “water flow of industrial symbiosis”. The research problem was further refined by justifying its importance and its significant contribution to new knowledge and industry.

Based on the secondary data reviewed, the theoretical framework was developed as a guide for achieving the research aim. Theoretical framework signified the importance of having a robust solution for designing optimum water exchange networks in order to reduce operational inefficiencies.

3.2.3 Philosophical worldview of the research: Pragmatism stance

As stated by Saunders et al. (2019), a system of beliefs and assumptions concerning the new knowledge generation is known as ‘research philosophy’. Creswell (2009) used the term “philosophical worldview” while others called them “paradigms” (Mertens, 1998, cited in Creswell, 2009; Lincoln & Guba, 2000). As stated by Guba (1990, cited in Creswell, 2009), the research paradigm or philosophical worldview means beliefs that guide action. As stated by Creswell and Creswell (2018) four research philosophy paradigms can be identified as post-positivism or positivism, interpretivism or social constructivism, transformative and pragmatism. As Burrell and Morgan (2016) explained, selection of the most suitable philosophical worldview is influenced by the number of types of assumptions made by the researcher. Saunders et al. (2019) further identified the three types of assumptions as: (a) ontological assumptions (assumptions about the realities encountered in the research); (b) epistemological assumptions (assumptions about human knowledge); and (c) axiological assumptions (assumptions about the extent and influence of the researcher’s own values). The ontological, epistemological and axiological assumptions positioning the philosophical stance of this research are shown in Table 3.1 and are explained in the next sections.

Table 3.1

Philosophical assumptions in research

Assumptions/ approaches	Positivism	Interpretivism	Transformative	Pragmatism	Applied in this research
Ontology	<ul style="list-style-type: none"> • One or single true reality 	<ul style="list-style-type: none"> • Multiple meanings, interpretations and realities that are socially constructed 	<ul style="list-style-type: none"> • The social reality is historically bound • Multiple realities which are shaped and constantly changing depending on social, political, cultural, gender and disability values 	<ul style="list-style-type: none"> • ‘Reality’ is the practical consequences of ideas 	<ul style="list-style-type: none"> • Reality matters as a practical effect of ideas • Exploring organizational processes, experiences and practices to provide practical solutions and outcomes • Focusing on making a difference to existing practice • Considering reality as stable in the selected context
Epistemology	<ul style="list-style-type: none"> • Positivism/objectivism • Focus on observable and measurable facts • Causal explanation and prediction as contribution 	<ul style="list-style-type: none"> • Subjectivism/ idealism • Focus on narratives, stories, perceptions and interpretations • New understandings and worldviews as contribution 	<ul style="list-style-type: none"> • Focuses on experiences and opinions of the group of people (dominated, oppressed population etc.,) to find solutions and actions for social issues • Purpose of knowledge construction is to assist people to improve society • Knowledge is constructed from the frame of reference of the participants 	<ul style="list-style-type: none"> • Practical meaning of knowledge in specific contexts • ‘True’ theories and knowledge are those that enable successful action • Focus on problems, practices and relevance • Problem solving and informed future practice as contribution • Reconcile both subjectivism and objectivism 	<ul style="list-style-type: none"> • Adopting existing theories related to IS for developing the conceptual model and key variables • Adopting both qualitative and quantitative approaches by combining both realism and idealism aspects for finding the best practical solution for the research problem • Use of practical meaning of knowledge and practices in the selected context for answering the research problem • Adopting multiple methods to reach research objectives assuring the use of all possible sources of knowledge
Axiology	<ul style="list-style-type: none"> • Value-free research • Researcher is detached, neutral and independent of what is researched 	<ul style="list-style-type: none"> • Value-bound research • Researchers are part of what is researched 	<ul style="list-style-type: none"> • Considers research as a moral and political activity that require them to select and oblige toward a value position • Some views will be wrong while other views will be correct 	<ul style="list-style-type: none"> • Value-driven research • Research initiated and sustained by researcher’s doubts and beliefs 	<ul style="list-style-type: none"> • Using researcher’s beliefs and experiences to determine the way of doing research • Adopting different ways for reaching the research objectives • Assuming a minimum effect of bias by being independent of the data in qualitative analysis and assuring fewer interpretations by the researcher in analyzing the qualitative data

Source. Chilisa (2011); Creswell and Creswell (2018); Saunders et al. (2019)

The first assumption, **ontology**, denotes to assumptions about the nature of reality. Ontological assumptions require the researcher to consider the world as external to the researcher and/ or the world is socially constructed, through the observation of human perceptions (Karunasena, 2012). This represents two major dimensions, namely, objectivism (realism) and subjectivism (idealism) (Saunders et al., 2009). Objectivism signifies the position that social entities occur in reality as external to social actors, with methodologies that focus on testing hypotheses, while idealism is based on analysis of subjective matters. Positivism considers one or a single truth of reality (realism) and explanations are made via analysis of causal relationships between variables through use of quantitative data (Saunders et al., 2019).

Generally, the positivist researcher uses a highly structured research methodology to ensure reliability (Creswell & Creswell, 2018). Interpretivism claims idealism or multiple meanings, interpretations and realities that are socially constructed (Gill & Johnson, 2002). These authors added that, in interpretivism, explanations in the research are made through subject meanings and understanding through the generation and use of qualitative data.

As stated by Creswell (2014), pragmatism considers the notion of “what works” by mainly referring to the pragmatic theory of truth. Hence, reality is considered as a practical effect of ideas, sustained by changes in processes, experiences and practices, and knowledge is valued for allowing actions to be carried out effectively. Lohse (2017) stated that ontology is the most ignored assumption in pragmatism philosophy as it is usually considered as an epistemological and methodological stance. As explained by Saunders et al. (2009), pragmatism research accepts both the existence of one reality and multiple interpretations of reality by being subjective and objective at the same time. Hence, pragmatism is oriented with actions towards practical problem solving in the real world rather than being built on assumptions about the nature of knowledge. Pragmatism implies that reality is external and multiple, with the researcher selecting the view that best serves the research purpose. As explained by Saunders et al. (2019), pragmatists focus mainly on the research problem as the most significant element in the research design for providing realistic solutions and outcomes.

In answering the research question “how to assess the optimum water flow of industrial symbiosis?”, the researcher explored the organisational processes, experiences and practices of industrial symbiosis networks to provide a practical solution and outcomes. The researcher observed that the existing water flow of the industrial symbiosis network is suffering from various inefficiencies, with examples of its failure over the long term. Hence, the researcher focused on making a difference to existing practice in the selected industrial entities of the IS network by providing a practical solution for optimising the water flow through a robust assessment.

As disclosed in the ontology assumption, reality is thus considered in the current research as a practical consequence of ideas and experiences rather than being dependent on either a single reality or multiple realities. Maarouf (2019) stated that

reality is considered stable most of the time particularly in the selected context; however, it could change when the context changes. In such situations, pragmatism allows the researcher to use both qualitative and quantitative approaches to examine perceptions about reality in a selected context as well as testing the developed theory and related variables to obtain practical outcomes (J.W. Creswell & Creswell, 2018; Saunders et al., 2019).

As the second assumption, **epistemology** denotes to assumptions about knowledge and how the researcher obtains and accepts knowledge about the world (Saunders et al., 2019). It is concerned with what creates acceptable knowledge in a field of study (Saunders et al., 2009). Epistemologically, positivist assumptions present the traditional research practices, with these assumptions assisting true more for quantitative research than for qualitative research. These assumptions hold a deterministic view which possibly determines the effects or outcomes (Saunders et al., 2009). Epistemologically, these researchers focus on realising visible and quantifiable evidence and regularities for producing reliable and meaningful data (Saunders et al., 2019). As these authors added, the researcher looks for causal relationships in research data to generate generalisations with the use of universal rules and laws in predicting behaviours and events of the organisation. Social constructivism is usually seen as an approach to qualitative research. The purpose of social constructivist research is to make new, strong understandings and explanations of social worlds and contexts (Saunders et al., 2019). Moreover, it assumes that individuals require to understand the world where they live and work. Individuals develop subjective meanings of their experiences which are constructed by people as they involve with the world they are understanding (Creswell, 2009).

Pragmatism claims that both positivist and interpretivist assumptions question their relevance to the research. It attempts to accept both positivism and interpretivism only as relevant to the actions in the research. Hence, the facts and values, accurate and rigorous knowledge, and different contextualised experiences are harmonised together as instruments of thought and action in terms of the practical consequences in specific contexts (Saunders et al., 2019). Thus, pragmatism requires the researcher to ensure that the use of theories is valid and represents the truth. The researcher could also develop the current theory or a new theory when conducting the research in a new context or on a phenomenon. In the current research, the existing theories related to IS were adopted in developing the conceptual model for assessing the optimum water flow of industrial symbiosis.

As pragmatism reconciles both subjectivism and objectivism by creating circumstances for the researcher to be either subjective or objective, the current research combines both realism and idealism aspects to find the best practical solution for the research problem. The developed conceptual model in the research established various key variables and constraints relating to the assessment of the optimum water flow of IS. Key variables of the developed model were initially recognised through a desk study of secondary data, with these revised in the selected context. The applicability of the context-specific model was then tested by using a case study

strategy in which quantitative data collected from the selected case study were analysed by using mathematical optimisation modelling techniques, supporting both realism and idealism aspects.

In terms of the epistemology assumptions in pragmatism research, this research was focused on proposing a practical solution for the research problem through using the practical meaning of knowledge and practices in the selected context of Sri Lanka. All possible sources of knowledge in this specific context were considered when acquiring and accepting knowledge by adopting multiple methods to reach the research objectives, such as a desk study, interviews with industry experts, documents review, etc.

The third assumption, **axiology**, refers to the researcher's view relate to the role of values in research (Saunders et al., 2019). As indicated by these authors, axiology can be classified as value-free or value-bound research. Interpretivism supports the value-bound system in which the researcher is part of what is researched. Positivism supports the value-free system as the researcher is unbiased and neutral. In positivism, the choice of research is selected by objective criteria while, in interpretivism, the choice of research is considered based on human beliefs and experiences (Creswell & Creswell, 2018). Pragmatism supports a value-driven system where a pragmatist uses his/her own values and experiences in a way that serves research objectives to enhance research results. As pragmatism follows the research problem and question, the research is initiated and sustained by the researcher's beliefs and experiences. As stated by Maarouf (2019), the necessary bias principle permits the researcher to be biased only necessitating the achievement of research objectives, while avoiding unacceptable bias.

The current study supports the value-driven system as the way to conduct this research was determined by beliefs and experiences of the researcher. Hence, different ways for reaching research objectives were determined, such as a literature review, a desk study, interviews with industry experts and a case study. A minimum bias effect was achieved with the researcher's stance more towards being independent of the data in the qualitative analysis and ensuring fewer interpretations in analysing the qualitative data.

Considering the ontological, epistemological and axiological assumptions explained above, this research applied a pragmatism stance to reach the research objectives and answer the research problem. Accordingly, it is logical to adopt pragmatism epistemologically as this research accepts both positivism and interpretivism only where relevant to the research actions. This research also favours the notion of "what works" by supporting the practical consequences of reality. Hence, the researcher studied organisational processes, experiences and practices to provide a practical solution and outcomes for the research problem under the study's ontological undertaking. Finally, this research supports the value-driven system under its axiological undertaking, with the researcher biased only by the degree require to achieve the research objectives.

3.2.4 Research approach: Abductive approach in theory redevelopment

Within any selected philological worldview, it is important that the extent to which consideration has been given to theory testing or theory building matters aligns with the design of the research (Saunders et al., 2019). Saunders et al. (2019) identified three main contrasting approaches that are used in theory development, namely, deductive, inductive and abductive.

In the deductive approach, the research begins with a theory which is tested within the research strategy adopted. The deduction process initially explains the causal relationships between concepts and variables for developing testable hypotheses. The developed hypotheses are tested by collecting and analysing quantitative data. The deductive approach is mostly undertaken under the positivist research philosophy (Creswell & Creswell, 2018). The inductive approach begins collecting data to explore a phenomenon and to build a theory (conceptual framework, etc.) through subsequent analysis of qualitative data. As Creswell and Creswell (2018) stated, the inductive approach is most likely to be emphasised by the interpretivism research philosophy.

The abductive approach is used as an alternative approach instead of moving from theory to data (deductive) or data to theory (inductive), by moving back and forth combining both approaches (Suddaby, 2006, as cited in Saunders et al., 2019). Thus, the abductive approach begins with data collection to explore a phenomenon. It then follows the steps of identifying and integrating themes and patterns in an overall conceptual framework to generate a new theory or to modify an existing theory, which is subsequently tested using evidence provided by existing and new data and revised as necessary (Saunders et al., 2019). In the pragmatism stance, as the researcher develops a current theory or constructs a new theory towards ultimately and successfully answering the research problem, the use of the abductive approach is considered by researchers.

The characteristics of the research approach adopted for the theoretical reasoning applied in the current study are shown in Table 3.2 and are subsequently explained.

Table 3.2*Characteristics of the research approach*

Characteristics	Deductive	Inductive	Abductive	Approach selected in this research
Logic	<ul style="list-style-type: none"> • If the premises or propositions are true, conclusion is considered as true 	<ul style="list-style-type: none"> • Known premises are used to generate untested conclusions 	<ul style="list-style-type: none"> • Known premises are used to generate testable conclusions 	<ul style="list-style-type: none"> • Key variables and constraints of the conceptual model identified by reviewing key literature (desk study) were revised and the context specific assessment model was developed as a testable outcome
Types of data	<ul style="list-style-type: none"> • Quantitative 	<ul style="list-style-type: none"> • Qualitative 	<ul style="list-style-type: none"> • Both quantitative and qualitative 	<ul style="list-style-type: none"> • Both qualitative and quantitative data were collected; <ul style="list-style-type: none"> - Collecting qualitative data through interviews with industry experts (Phase II) - Collecting quantitative data through case study (Phase III)
Use of data	<ul style="list-style-type: none"> • To evaluate propositions or hypotheses related to an existing theory 	<ul style="list-style-type: none"> • To explore a phenomenon to identify and integrate themes and patterns into a conceptual framework 	<ul style="list-style-type: none"> • To explore a phenomenon, identify and integrate themes and patterns into a conceptual framework, test and revise through subsequent data collection and so forth 	<ul style="list-style-type: none"> • The context of Sri Lanka in order to identify context specific enhancements and modifications as the revisions of the developed conceptual model. • The applicability of the developed context specific model was tested in an industrial zone in Sri Lanka (case study)
Theory	<ul style="list-style-type: none"> • Theory testing 	<ul style="list-style-type: none"> • Theory building 	<ul style="list-style-type: none"> • Theory building or modifying (To incorporate an existing theory where necessary and accordingly built a new theory or modify the existing theory) 	<ul style="list-style-type: none"> • The conceptual model was developed based on existing theories of IS in literature. • The conceptual model was modified into a context specific model with context specific enhancements and modifications.

Methodology	<ul style="list-style-type: none"> • Highly structured methodology to ensure reliability 	<ul style="list-style-type: none"> • Variety of methods to establish different views of phenomena 	<ul style="list-style-type: none"> • Combining both qualitative and quantitative methods sequentially or concurrently 	<ul style="list-style-type: none"> • Use of sequential exploratory mixed research design combining qualitative and quantitative data collection and analysis: desk study, interviews with industry experts and case study
Sample	<ul style="list-style-type: none"> • Sample to be large or in sufficient size 	<ul style="list-style-type: none"> • A small sample is more appropriate than a large number 	<ul style="list-style-type: none"> • Depends on the method of inquiry 	<ul style="list-style-type: none"> • Sufficient size of sample was conveniently selected complying with the research methods adopted in data collection.
Generalisation	<ul style="list-style-type: none"> • From general to the specific 	<ul style="list-style-type: none"> • From specific to the general 	<ul style="list-style-type: none"> • From the interactions between the specific and the general 	<ul style="list-style-type: none"> • The proposed context specific model is robust to use in similar industry settings with confidence. The conceptual model can be applied in any context subjected to the context specific variants and constraints.

Source. Creswell and Creswell (2018); Saunders et al. (2019)

The abductive approach uses data to explore a phenomenon, identify and integrate themes and patterns into a conceptual framework, and continually test and revise the conceptual framework through subsequent data collection (Saunders et al., 2019). Therefore, this research used data to explore the phenomenon in the context of Sri Lanka to identify context-specific enhancements and modifications as revisions of the developed conceptual model. A context-specific robust model to assess the optimum water flow of industrial symbiosis was then established after the revisions were made through data analysis. Accordingly, the applicability of the developed context-specific model was tested in an industrial zone in Sri Lanka through the Phase III data collection and analysis.

Saunders et al. (2019) stated that the abductive approach directs the research towards incorporating an existing theory where necessary and, accordingly, building a new theory or modifying the existing theory, while deductive and inductive approaches support theory testing and theory generation, respectively. As this research followed the abductive approach, it identified the existing theories of industrial symbiosis in the literature to develop the conceptual model as the initial stage. The developed conceptual model was then modified into a context-specific model with context-specific enhancements and modifications.

Following the abductive approach, both qualitative and quantitative methods were adopted rather than strictly applying a highly structured methodology. This research adopted a sequential exploratory mixed research design combining qualitative and quantitative data collection and analysis, using a desk study, interviews with industry experts and a case study, thus justifying the selection of the abductive approach (refer Section 3.2.5). Furthermore, sample size was decided complying with these research methods, that is, the expert interviews and semi-structured interviews adopted in the respective data collection phases. Essentially, by following the generalisation characteristics of the abductive approach, the proposed context-specific robust model was generalised so it can be used with confidence in similar industry settings. Indeed, the conceptual model, which was developed based on the key literature can be applied in any context, subject to context-specific variants and constraints. Considering the above points, the **abductive approach** was selected in this research as the suitable research approach.

3.2.5 Research strategy: Sequential exploratory mixed research strategy

The research strategy provides specific direction for procedures in a research design (Creswell, 2009). Other researchers have called research strategies “research approaches” (Creswell, 2007; Yin, 2009) or “research methodologies” (Mertens, 1998, cited in Creswell, 2009), while Creswell (2009) identified them as strategies of inquiry. According to the onion research methodology model introduced by Saunders et al. (2019), the two main research approaches are deductive and inductive. In the deductive approach, the theory is deducted into hypotheses or research questions, with the hypotheses tested to examine causal relationships between variables. Research using

an inductive approach is likely to be particularly concerned with the context. According to previous research studies (Creswell, 2009; Yin, 2003), qualitative and quantitative research approaches are the two main schools of research design while the mixed-methods approach incorporates both qualitative and quantitative methods.

According to Creswell and Creswell (2018), both qualitative and quantitative methods can be applied together as a sequential, concurrent or transformative mixed-methods approach. Researchers can elaborate or expand on the findings of one method with the method called the “sequential mixed method”. In the “concurrent mixed method”, the researcher can collect both qualitative and quantitative data at the same time and integrate these data into interpretation of the overall results to analyse different type of questions.

The sequential explanatory mixed design allows the researcher to collect and analyse the quantitative data as the first priority. Based on the outcome, the researcher may design the qualitative phase of the research. In exploratory sequential mixed design, the research begins with qualitative data collection and analysis which is followed by quantitative data collection and analysis. In the transformative mixed research method, the researcher uses a theoretical lens containing both qualitative and quantitative data (Creswell & Creswell, 2018). The qualitative outcomes are followed by collecting and analysing the quantitative data. Tashakkori and Teddlie (1998, cited in Manu, 2012) identified another approach as the convergent parallel/simultaneous mixed design. In this approach, both quantitative and qualitative data are used in parallel during the same phase of the research design; however, analysis is conducted independently within each approach. The findings of each approach are then interpreted. Furthermore, embedded mixed design can be identified as another approach, combining the use of both quantitative and qualitative data within the traditional qualitative and quantitative design approaches (Creswell, 2007). As Creswell (2007) further explained, the research can give less priority to, or can embed, the secondary approach (either quantitative or qualitative).

Of the above-described mixed-methods designs, the **sequential exploratory mixed research strategy** was adopted in the current research for the following reasons:

- **Using both qualitative and quantitative data** - as this research aims to develop a model to assess the optimum water flow of IS, the use of both quantitative and qualitative data in subsequent stages of the research process was considered. Qualitative data were collected in stage I (Phase I and Phase II of the current research) to recognise the context-specific enhancements and modifications of the conceptual model. Stage II (Phase III) involved the evaluation of the revised model, which included collection and analysis of quantitative data, such as the flow rate of freshwater consumption, wastewater discharge and treated wastewater, water quality measurements for set parameters and life cycle cost (LCC) data. Hence, this research applied the mixed method approach appropriately merging both qualitative and quantitative approaches.

- **Involving qualitative data collection and analysis, followed by quantitative data collection and analysis** – the sequential exploratory mixed research strategy applies the qualitative data collection analysis as the first stage following the second stage of quantitative data collection and analysis. The second stage is built based on the results of the first phase. Similarly, in this research, the key findings derived through the desk study (Phase I) were integrated into the conceptual model, which then sequentially underwent the first phase of qualitative data collection and analysis (interviews with industry experts) and then the quantitative data collection and analysis (case study – Phase III). Furthermore, context-specific enhancements and modifications were derived as the results of the Phase II, which were incorporated into the conceptual model to develop the context specific robust optimum water flow assessment model for IS in Sri Lanka. The revised model was then evaluated through Phase III data collection and analysis followed by an interpretation of the overall outcomes.

Accordingly, the current research was conducted in the following three key phases:

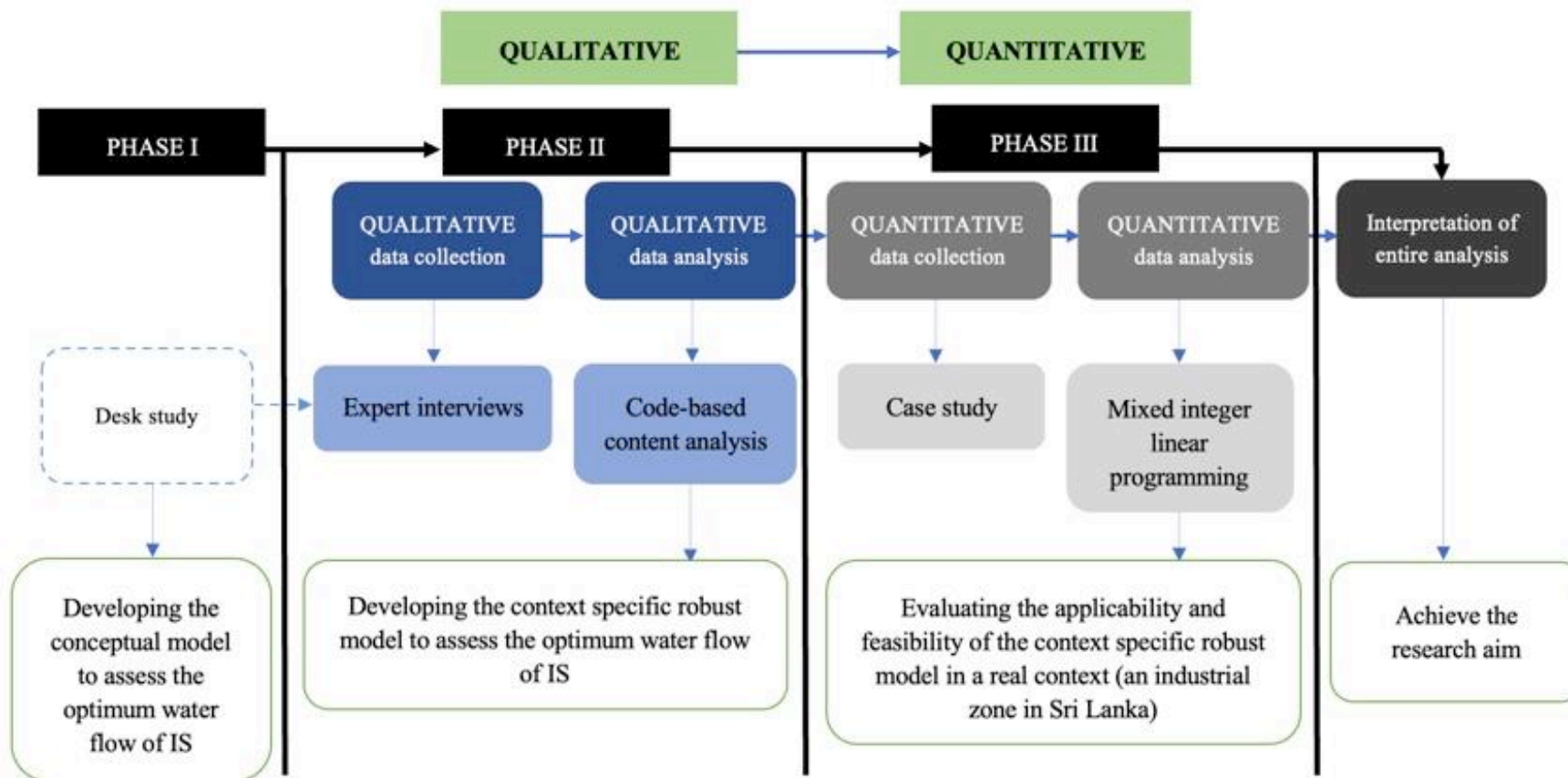
Phase I – desk study

Phase II – expert interviews

Phase III – case study

Each phase and its outcome were sequentially interconnected to achieve the research aim. The sequential exploratory mixed design of this research is shown in Figure 3.3. The figure shows the strategy, and the data collection and analysis techniques used under each phase, with these described in the following sections.

Figure 3.3
Sequential exploratory mixed design of this research



3.2.5.1 Phase I: Desk study

As stated by Prescott (2008), the desk study is a quick and easy method for collecting data from existing sources. It reduces data collection time and adds to the conclusion's accuracy as the data are collected from reliable, published sources. Furthermore, it prevents interviewee bias and allows researchers to access valuable information at little or no cost. Thus, the first phase of this research comprised a desk study to collect reliable data from published sources on IS projects.

Selection criteria of the IS projects

By adopting the following criteria, 13 global IS projects from across the world were selected for the desk study (refer to Table 4.1):

- Availability of three or more firms in the network,
- Geographical proximity of the enterprises,
- Availability of water flow synergies, and
- Availability of empirical data.

Data related to resources flow, water synergies between industries, and water inputs and outputs of IS networks were collected by referring to related journal articles published on these projects. The collected data were analysed and integrated to develop the conceptual model of the research (refer to Figure 4.12). Phase II data collection and analysis is described below.

3.2.5.2 Phase II: Interviews with industry experts

During data collection in Phase II, interviews were conducted with industry experts to fulfil the third and fourth objectives of the research (refer to Section 1.3). As the key outcome of this phase, context-specific enhancements and modifications were identified (refer to Table 5.4), which were then integrated into the conceptual model to develop a context-specific robust optimum water flow assessment model for IS in Sri Lanka.

Data collection techniques – Semi-structured interviews

Sixteen (16) semi-structured interviews were conducted with industry experts with more than five years of experience in the field of industrial water management (IWM) in Sri Lanka. The interviewees were selected through the convenience sampling technique (refer to Section 5.2 for the interviewees' profile and demographic information). According to the ethical approval granted, both face to face and online interviews were conducted by considering the existing health conditions and risk due to COVID-19 outbreak. The details of the interviewing procedure were provided to the participants and the consent of each participant was obtained by sending the plain language statement (PLS) and consent and/or withdrawal form. The time duration of each interview was approximately one hour. With the consent of experts, the interviews were audio recorded ensuring the accuracy of data.

Various measures, such as washing or sanitising hands when arrive to participate to the interview and prior to departing, following social distancing guidelines, wearing a face mask and sanitising all work surfaces & door handles etc. to avoid the risk of infection, were specially considered during the interview to ensure that there may unlikely be any risks from taking part in the interview.

During this phase, a semi-structured interview guideline was used, incorporating questions to collect data related to the strategies & issues of IWM, enablers & barriers for initiating water exchange networks and context-specific modifications & enhancements of the conceptual model (refer to Appendix - 1).

Data analysis techniques – Code-based content analysis

The collected data were analysed using the code-based content analysis technique. As stated by Guthrie (2013), content analysis can be used for analysing the collected data by codifying them into pre-defined codes to determine patterns. Hence, content analysis was used to capture imperative analysis to reduce the data and to identify concepts from the data collection evidence. QSR International's NVivo.12 (Qualitative Solutions and Research Private Limited) computer software was used to conduct the content analysis as it saves time and energy used for data classification (Dollaz et al., 2017). Further to the authors, the process of data analysis via NVivo employs six (06) key steps namely, (i) importing data, (ii) exploring data, (iii) coding (making nodes of key words), (iv) running search query for key words, (v) visualising and (vi) recording.

In the current research, 16 interview transcripts were imported into the software and explored to identify keywords. Accordingly, sub nodes were recognised under three main nodes (barriers for exchanging water among the industries, enablers for exchanging water among the industries and strategies to overcome the identified barriers), and coding structure was developed. As the next step, 'search query' was run by restricting the search to minimum three key words. The coding structure was then visualised as a list and recoded to use in data analysis.

As derived through analysis, current strategies & issues of IWM and enablers & barriers for initiating water exchange networks in Si Lanka were initially recognised. Indeed, the context-specific enhancements and modifications of the conceptual model were identified and the context-specific robust optimum water flow assessment model was developed (refer to Figure 5.7). The applicability and feasibility of the developed model were evaluated through Phase III of data collection and analysis as described below.

3.2.5.3 Phase III: Case study

According to Yin (2009), the case study approach is more appropriate for gaining an understanding of a complex issue or object and can extend experience or add strength to what is already known through previous research. A study by Stoecker (1991 as cited in Yin, 2003) highlighted that the case study as a comprehensive research strategy

comprises an all-encompassing method covering the logic of design, data collection techniques and specific approaches to data analysis. Providing detailed information is one of key advantages of case study (Yin, 2009). Case studies also assist researchers to develop a complete story by collecting data from multiple sources, such as interviews, documents, etc (Neale et. al, 2006). As Yin (2009) indicated, a primary distinction in designing case studies is the choice between single case and multiple case designs. It needs to be decided, prior to any data collection, whether a single case study or multiple cases are going to be used to address the research questions. The single case design is eminently justifiable under 05 rationales: (a) a critical test of existing theory; (b) a rare or unique circumstance; (c) a representative or typical case or when the case serves; (d) a revelatory purpose; or (e) a longitudinal purpose, while rationales for multiple case designs are derived directly through literal and theoretical replications (Yin, 2009, p.47).

Considering the above reasons, a single case study design was adopted in this research as the suitable case study design by supporting three (03) rationales as mentioned in Table 3.3.

Table 3.3

Rationale for single case study design selected in this research

Rationale	Description	Justification for adopting in the current research
(a) a critical test of existing theory	it represents a critical case and is ideal in testing a well-formulated theory	The case study was adopted to test the context specific model, which was developed based on the IS theory. A case study of an industrial zone was selected satisfying all the conditions decided on the theory (refer to Figure 4.6)
(b) a rare or unique circumstance	It represents an extreme or unique case where the conditions are rare to find.	Since water exchange was a newest concept to Sri Lanka, an industrial zone was selected embedding three industries which supports unique circumstances as specified in Figure 4.6
(d) Case serves a revelatory purpose or	It exists when researchers have an opportunity to observe and analyse a phenomenon which was not previously accessible.	Since IS is a newest concept to Sri Lanka this has not been previously investigated and implemented in IWM. This research provided useful insights for reducing freshwater consumption and wastewater generation by the industrial entities in industrial zones through optimum water exchange. This research considered investigating the existing conventional water network in industrial zone and the economic,

Rationale	Description	Justification for adopting in the current research
		environmental and social benefits that can be obtained through optimal water exchange network were also evaluated.

Source. Yin (2009)

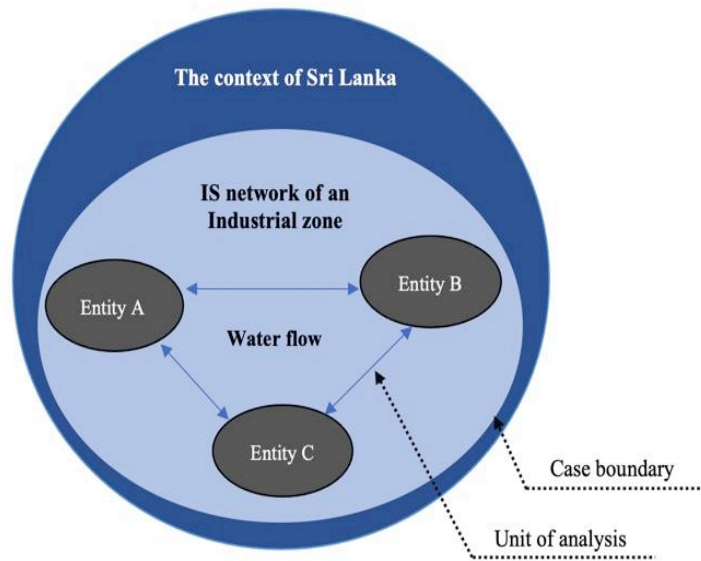
As justified in Table 3.3, a single case study design under the case study strategy was adopted to evaluate the applicability of the developed model in the context of Sri Lanka. Since a very limited number of industrial zones are in-operation in Sri Lanka, one industrial zone, located with the highly water intensive industries, was selected matching with the model requirements. Further, the evaluation of the model was limited to a single case study due to the restricted access to data during COVID-19 outbreak. By overcoming the issues pertaining to data collection due to restricted access during COVID-19 outbreak and the chances of misrepresentation of data while maximising the access needed to collect the case study evidences, IS network of an industrial zone embedding a cluster of three industrial entities was selected as the case in this research since a minimum of three entities are required to initiate a IS network as per the “3-2 heuristic” theory introduced by Chertow (2007) (refer to Section 6.3 for details of the case and industrial entities selected). After selecting a case study to be conducted within the research; the unit of analysis should be clearly identified as it is a critical factor in the case study (Tellis, 1997).

As Yin (2009) stated, identification of the “unit of analysis” or the “case” is of foremost importance to any research design, with this linked to the way in which the research problem is created. Thus, ‘water flow of industrial entities’ was considered as the unit of analysis in each industrial entity in the selected case. The data were collected as they related to freshwater consumption, wastewater generation, treated wastewater generation and the associated water cost of the three selected industrial entities under the case study of an industrial zone in Sri Lanka.

The selection of the case study and unit of analysis are shown in Figure 3.4.

Figure 3.4

Case selection and unit of analysis



The data collection and data analysis techniques used in case study are described below.

Data collection techniques – Semi-structured interviews and documents review

Six sources of evidence come under the case study approach: documents, archival records, interviews, direct observations, participant observations and physical artifacts (Yin, 2009, p.102). As Yin (2009) added, with more than one data collection technique, the reliability and validity of the data can be increased. Furthermore, this may also help in data triangulation to ensure construct validity (Harris & Brown, 2010). Considering the above points, use of more than one technique was considered. Among the above six sources of evidences proposed by Yin (2011), archival records, participant observations and physical artifacts were not considered considering the usefulness and accuracy of data in case study investigation. As stated by Yin (2009), archival records are produced for a specific purpose and a specific audience other than the case study investigation. Further, archival records often take the form of computer files and records, thus highly quantitative. As Yin (2009) further explained, participant observation is suitable for observing interpersonal behaviour and motives where physical artifacts are insightful into cultural features. Even though, direct observations technique was suitable in observing the real context, it was not selected in this research due to the COVID19 travel restrictions and health measures. Accordingly, two data collection techniques, namely, semi-structured interviews and documents review, were used to collect the data.

Semi-structured interviews

The interview is one of the most important sources of case study information. Semi-structured interviews guide conversations rather than being conducted as structured queries (Yin, 2009). As Yin (2009) added, interviews can be open-ended, focused or

structured, among which semi-structured interviews are highly used to maximise the flexibility of the interview by shaping it as per the needs of the individual interviewees.

In this research, the primary empirical data were gathered through semi-structured interviews. A semi-structured interview guideline, incorporating the questions to collect data related to water inputs and outputs, and water quality parameters, was used for Phase III data collection (refer to Appendix 2). Accordingly, to collect the data, interviews were conducted with seven industry professionals from the selected case, i.e., a sustainability executive, a mechanical engineer, a compliance manager, a facility manager, a human resource (HR) and administration manager, a deputy general manager (DGM) and a project director (refer to Table 6.3).

Similar to the ethical clearance and interview procedures adapted in expert interviews, both face to face and online interviews were conducted by considering the existing health conditions and risk due to COVID-19 outbreak. The details of the interviewing procedure were provided to the participants and the consent of each participant was obtained by sending the plain language statement (PLS) and the consent form and/or the withdrawal form. The time duration of each interview was approximately one hour. With the consent of the experts, interviews were audio recorded ensuring the accuracy of data.

Documents review

Documents play an important role in data collection when conducting case studies. Furthermore, systematic searches for relevant document are important in any data collection plan (Yin, 2009). With the current research focused on developing a model to assess the optimum water flow of industrial symbiosis, documentary evidence from the selected industrial entities, such as utility (water) bills, freshwater consumption sub-meter readings, wastewater treatment records, and environmental and water quality norms and standards were reviewed to gather the required data. However, as these documents may not always be accurate and can have outdated and biased data (Yin, 2009), documentary evidence was used along with semi-structured interviews to improve data accuracy.

Considering the reliability of data, the data collection of freshwater consumption, wastewater discharge, and primary treatment and common wastewater treatment (secondary) processes was limited to a baseline of 12 months (September 2020–August 2021), with the average monthly flow rate defined for use in calculations.

Data analysis techniques

Data collected from the case study were analysed using a mathematical programming technique. Cost data related to the whole life of the proposed and existing industrial water management (IWM) options were also analysed and compared using the life cycle cost analysis (LCCA) technique, with both described below.

Mathematical programming

In their study of water system integration, Wang and Smith (1994) applied the graphical approach when targeting maximum water reuse. However, a major drawback of the graphical approach was found by Handani et al. (2011) as the approach was ineffective in large-scale systems consisting of multiple water sources, multiple water sinks and multiple contaminants. As Handani et al. (2011) stated, the mathematical programming technique has emerged to overcome the limitations of the graphical approach. The studies by Ahmetović and Grossmann (2011) and Yang and Grossmann (2013) proposed water targeting network models with multiple contaminants based on the application of mathematical programming. Linear programming (LP), mixed integer linear programming (MILP) and mixed integer non-linear programming (MINLP) models are the mathematical programming approaches that are mostly used, as these models can easily deal with multiple contaminants, different constraints and multiple water sinks, water sources and forms of water treatment. Furthermore, the linear programming (LP) approach is a powerful tool which can find the optimal value of a linear objective function, subject to linear constraints (Handani et al., 2011). According to a study by Aviso (2014), flexible and robust optimisation are other approaches used, in which robust optimisation provides a solution which is more feasible for decision makers to use in developing optimum exchange networks.

Hence, the optimal water flow assessment model was developed in the current study as a robust optimisation model with the flexibility of using it in other contexts by making it more resilient to future system changes. The MILP approach (i.e., the Simplex coding method) was used to find the optimal value of targeted objectives as the objectives and all constraints were linear. SageMath (Open-Source mathematical Software licensed under GPL.v3) was used to develop the model.

Evaluation of environmental, social and economic feasibility

The environmental, social and economic feasibility of the proposed optimal water exchange network was expressed in comparison to the existing conventional water network. The reduction of raw water extraction and discharge of wastewater were considered in accordance with ISO 14040:2006 in analysing the environmental feasibility. To analyse the economic feasibility of existing conventional water network and proposed optimal water exchange network, the study used the LCCA (refer to Section 6.6.2 for further explanations, assumptions and calculations of LCCA).

3.2.6 Drawing conclusions and making recommendations

Based on the data analysis of each phase, conclusions were drawn and recommendations were made under each objective of the research. As targeted in each phase, the outcomes were integrated sequentially and interpreted at the end to achieve the research aim. Hence, the significance of the developed robust optimum water flow assessment model was derived and recommendations were stated to encourage the utilisation of the developed model in similar industrial settings to obtain collective economic, environmental and social benefits. Furthermore, the contributions made

towards new knowledge generation and industry enhancement were also emphasised, highlighting that the research outcomes were exceptional and innovative.

3.3 Validity of the Research

As stated by J.W. Creswell and Creswell (2018), an important aspect of data analysis in mixed methods is to undertake a series of steps to check the validity and accuracy of both quantitative data and qualitative findings. In a mixed-methods research design, validity procedures can be applied to both qualitative and quantitative phases of the study (Tashakkori & Teddlie, 1998, cited in Creswell & Creswell, 2018). Measures taken to ensure validity of the mixed-methods research comprise checks for reliability, content validity, construct validity, and internal and external validity (J.W. Creswell & Creswell, 2018). Reliability measures the stability and consistency of data, whereas internal validity considers experimentation through the use of variables. The use of multiple sources of evidence through data triangulation is considered under construct validity. External validity tests the degree to which the conclusions of the research would be applicable to other situations (Creswell, 2007; Yin, 2009).

In this study, various validity tests were conducted to ensure the validity and accuracy of the research findings. Construct validity was achieved by using multiple sources of evidence through data triangulation. Semi-structured interviews with industry professionals and the review of documents, such as utility bills, sub-meter readings, water treatment records, quality standards, environmental norms, etc., were applied as sources of evidence to provide multiple confirmation of the same situation. To ensure content validation, the developed conceptual model was refined in the selected context of Sri Lanka by conducting interviews with industry experts, with relevant context-specific enhancements and modifications subsequently made. Based on key findings derived from the literature review, a conceptual model to assess the optimum water flow of industrial symbiosis was developed for internal validation. Furthermore, applicability of the developed context-specific model was evaluated in a real industry environment by conducting a case study to ensure reliability and internal validity. In the evaluation process, each industrial plant was viewed as a 'black box' with only a single stream of water considered to enter and exit the plant. Only the input and output water flow characteristics were thus used. Therefore, information regarding the internal sub-processes of the selected industrial entities is not considered. Since the utilisation of treated wastewater for drinking purposes of the industrial entities was not practical to be considered (as per the real practices of the industries selected), freshwater consumption for the industrial and cooling purposes was only considered in assessing the optimum water flow among the industrial entities of the selected case study assuring ecological validity of the research (refer to Chapter 6 for case study findings).

3.4 Chapter Summary

This chapter described the research methodology adopted in this study. The research design framework proposed by J.W. Creswell and Creswell (2018) was adopted for determining the methodological design of this research. The research design framework was developed incorporating the logical sequence of the key elements of the research methodology applied. This research was considered as “exploratory research” as it focused on evaluating the issues in industrial water management (IWM) and in the industrial symbiosis initiation process to propose new insights for optimising the water flow between industries participating in industrial symbiosis. This research applied the pragmatism stance to achieve the research objectives and answer the research problem. Accordingly, it was logical to adopt pragmatism epistemologically as this research accepted both positivism and interpretivism only as relevant to the study’s actions. Furthermore, this research favoured the notion of “what works” by supporting the practical consequences of reality and conducting value-driven research. The abductive approach was adopted as the suitable research approach as it supports exploring a phenomenon, identifying and integrating themes and patterns into a conceptual framework, and continually testing and revising the framework through subsequent data collection. As this research combined both quantitative and qualitative data collection, a sequential exploratory mixed research strategy was adopted.

Three research strategies, that is, a desk study, interviews with industry experts and a case study were adopted for data collection and analysis in Phases I, II and III, respectively. A conceptual model to assess the optimum water flow of industrial symbiosis was developed as the outcome of Phase I, with this model refined in the selected context of Sri Lanka under Phase II to identify context-specific enhancements and modifications. In Phase II, 16 semi-structured interviews were conducted with industry experts, with the collected data analysed by using code-based content analysis. Accordingly, a context-specific robust optimum water flow assessment model for industrial symbiosis in Sri Lanka was developed as the outcome of Phase II. Applicability of the developed model was tested through a selected case study under Phase III. In the context of Sri Lanka, an industrial zone was considered as the case boundary in which the water flow of industrial entities was the unit of analysis. The collected data were analysed using the MILP approach under mathematical programming. SageMath (open-source mathematical software licensed under GPL.v3) was used for data analysis. Additionally, the economic, environmental and social feasibility of the proposed optimal water network was evaluated. The economic assessment of the proposed water exchange network was conducted using the LCCA technique. Finally, various measures were undertaken to ensure the reliability and validity of the research findings.

CHAPTER 4: DEVELOPMENT OF CONCEPTUAL MODEL AND MATHEMATICAL FORMULAE (PHASE I)

4.1 Introduction

This chapter presents the conceptual model developed for assessing the optimum water flow of industrial symbiosis based on desk study findings. The steps of the optimisation model development process are presented in Section 4.2. As the conceptual model for optimisation is the main outcome presented in this chapter, the objectives of optimisation, model constraints, key variables, model parameters and mathematical formulae are presented in the following sections.

4.2 Optimisation Model Development Process

In current practice, industrial entities or plants are consuming more freshwater for their industrial processes, which are discharging wastewater in an inefficient and linear way (Zhang et al., 2011). This has created numerous environmental and health impacts due to the escalating extraction and use of freshwater and the discharge of wastewater to the surface and ground water bodies. As a solution, industries can exchange treated wastewater to replace the utilisation of freshwater (Becker et al., 2019). However, wastewater is not optimally reused. Hence, this research is focused on developing a model to assess the optimum water flow of IS.

At the outset, it is important to establish an optimisation model development process. Hence, the current study introduced an optimisation model development process including the following four (04) key steps as illustrated in Figure 4.1.

Step 1 - Data compilation and initial processing (refer Section 4.2.2)

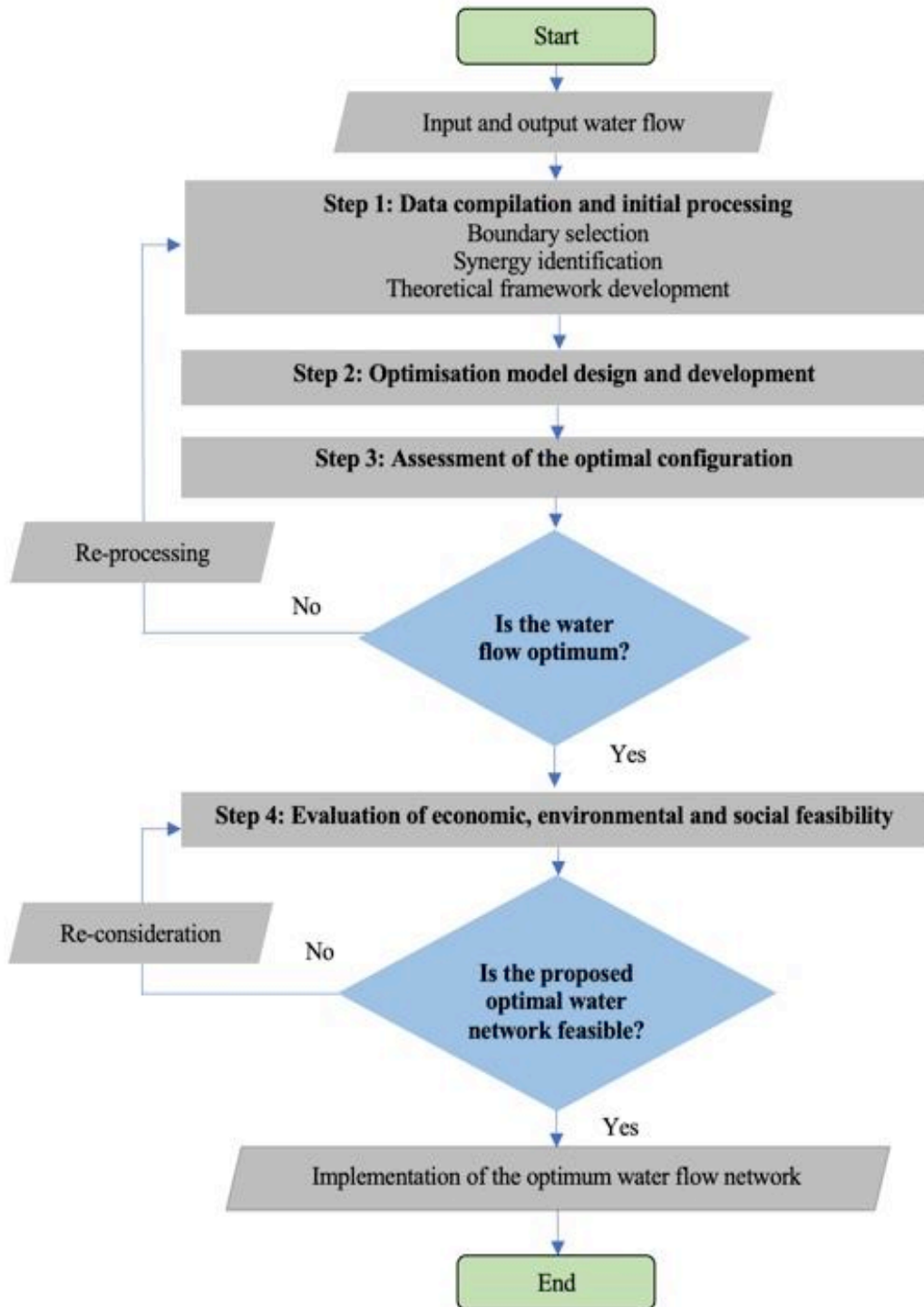
Step 2 - Optimisation model design and development (refer Section 4.2.3)

Step 3 - Assessment of the optimal configuration (refer Section 4.2.4)

Step 4 - Evaluation of economic, environmental and social feasibility (refer Section 4.2.5)

Each item in the optimisation model development process flow chart is explained in subsequent sections in this chapter.

Figure 4.1
Optimisation model development process flow chart



4.2.1 Input and output water flow

The water inputs and outputs of IS networks were first determined through desk study. Thirteen (13) published IS projects were chosen considering the research scope and availability of data. As aimed, the reliable data on the resource flow of IS projects were collected from the published sources. Hence, data were collected from the journal

articles, which have been published relating to the selected projects during the period of 1989 to 2019 as stated in Table 4.1.

Table 4.1

Selection of published IS projects for desk study

Reference	Global IS Projects	Selection Criteria			
		Three or more number of firms	Proximity of the enterprises	Availability of water flow	Availability of data
[1]	Kalundborg IS Project, Denmark	X	X	X	X
[2]	Gujiao Eco-Industrial Park, China	X	X	-	-
[3]	Shandong Lubei IS Project, China	X	X	-	-
[4]	Choctaw Eco-Industrial Park, USA	X	X	X	X
[5]	Dunkirk IS Project, France	X	X	-	-
[6]	Guitang Group IS Project, China	X	X	-	-
[7]	Kwinana Industrial Area, Australia	X	X	X	X
[8]	Gladstone Industrial Area, Australia	X	X	-	-
[9]	Barceloneta IS Project, Puerto Rico	X	X	-	-
[10]	Qijiang Industrial Park, China	X	X	X	X
[11]	Tianjin IS Project, China	X	X	-	-
[12]	Ulsan Eco-industrial Park, South Korea	X	X	X	-
[13]	Songmudao Chemical Industrial Park, China	X	X	X	X
References: [1] Chertow, 2007; [2] Song et al., 2018; [3] Zhang & Chai, 2019; [4] Carr, 1998; [5] Morals et al., 2019; [6] Zhu et al., 2007; [7] Van Beers et al., 2007; [8] Van Beers et al., 2007; [9] Lee, 2015; [10] Li et al., 2017; [11] Yu et al., 2014; [12] Park et al., 2019; [13] Zhang et al., 2017					

Out of 13 IS projects, five (05) projects which are supporting the criteria given in Table 4.1 were specifically selected for analysing the water flow of IS. The 05 selected IS projects include (a) Kalundborg IS Project, Denmark, (b) Choctaw Eco-Industrial Park, USA, (c) Kwinana Industrial Area, Australia, (d) Qijiang Industrial Park, China, and (e) Songmudao Chemical Industrial Park, China. These five projects were selected based on the fulfilment of all four criteria. The identified IS projects were reviewed to identify the resources flow of IS, its' transformation over the years and water flow of IS. The review was based on the key research publications describing the water flow of IS. The distribution of the selected articles is stated in Table 4.2.

Table 4.2*Articles availability of the selected cases*

IS project	Source of Reference
Kalundborg IS Project, Denmark	Ehrenfeld and Gertler, 1997; Jacobson, 2006; Chertow 2007; Domenech and Davies, 2011; Zhang, et al., 2016; Branson, 2016; Valentine, 2016; Zhang and Chai, 2019
Choctaw Eco-Industrial Park, USA	Carr, 1998
Kwinana Industrial Area, Australia	Van Beers et al., 2007
Qijiang Industrial Park, China	Li et al., 2017
Songmudao Chemical Industrial Park, China	Zhang et al., 2017

As key literature findings derived through the review, the inputs and outputs of the water flow of IS were identified in each project and detailed below.

Water flow network of Kalundborg IS Project, Denmark

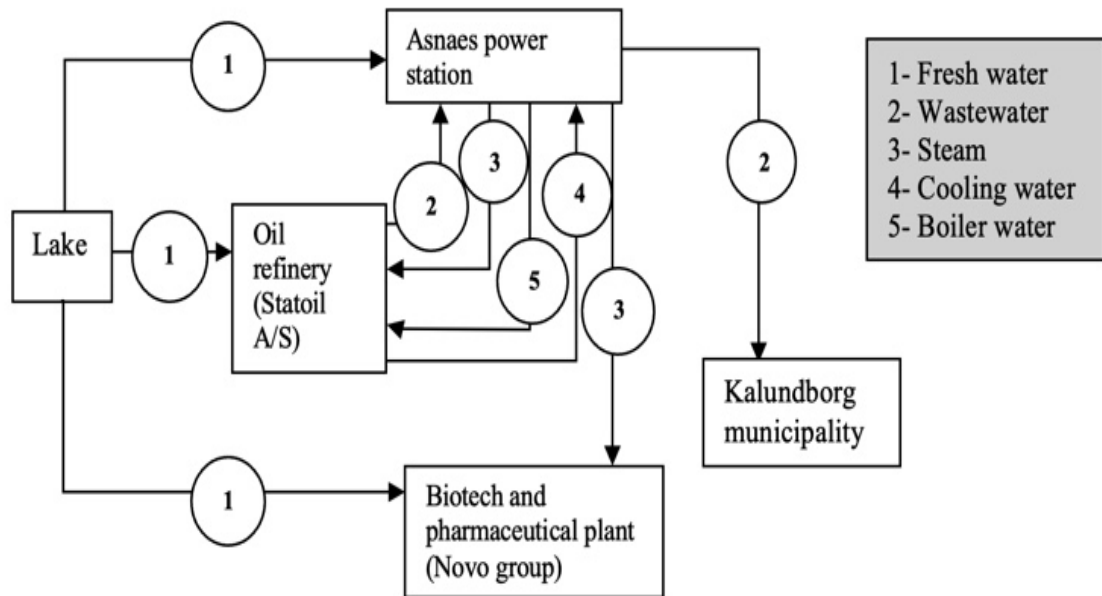
Kalundborg is considered to be the most definitive model of an industrial ecology network (Chertow, 2000; Jacobsen, 2006). This first model of IS was realised in the eco-industrial park at Kalundborg, Denmark (Chertow, 2000). Furthermore, it is an operative industrial ecology model, which comprises a complex web of material, energy and water exchanges, in which 11 physical linkages can be found. The IS as operating in Kalundborg has generated significant environmental and economic gains through the reduction of waste within the process. Domenech and Davies (2011) found in their study that the environmental benefits include ground, surface and wastewater savings as well as reduction of carbon emissions. The authors reported that, the annual savings for the whole network is US\$ 15 million. Furthermore, it has generated over US\$ 310 million of accumulated savings over the years.

In this industrial park project in Denmark, individual by-product exchanges have been gradually extended to a complex web of symbioses in which the local municipality has collaborated with five co-located primary partners in Kalundborg (Jacobsen, 2006). The companies involved in IS comprise an oil refinery (Statoil A/S), power station (Asnaes), gypsum board facility (Gyproc Nordic East), biotech and pharmaceutical plant (Novo Group) and a soil remediation company (Soilrem A/S), all of which have collaborated with the municipality of Kalundborg to share materials, energy, water and by-products to generate a high level of environmental and economic efficiency (Chertow & Ehrenfeld, 2002; Jacobsen, 2006; Chertow, 2007). Furthermore, some other actors, such as a fishery farm, farmers and recycling companies act as recipients of other resources in Kalundborg IS Project.

As the focus of the current study is on water related IS exchanges, the water flow network of Kalundborg's IS was reviewed. Accordingly, the flows of freshwater, wastewater and water related by-products (i.e., treated water, steam and sludge) were considered. The water flow related inputs and outputs of the main actors in the network are presented in Figure 4.2.

Figure 4.2

Water flow network of Kalundborg IS Project, Denmark



According to studies in literature, the Kalundborg municipality operates a waste management project for generating waste heat and steam. Hence, the water flow of the Kalundborg IS network mainly comprises freshwater, wastewater, cooling water and steam.

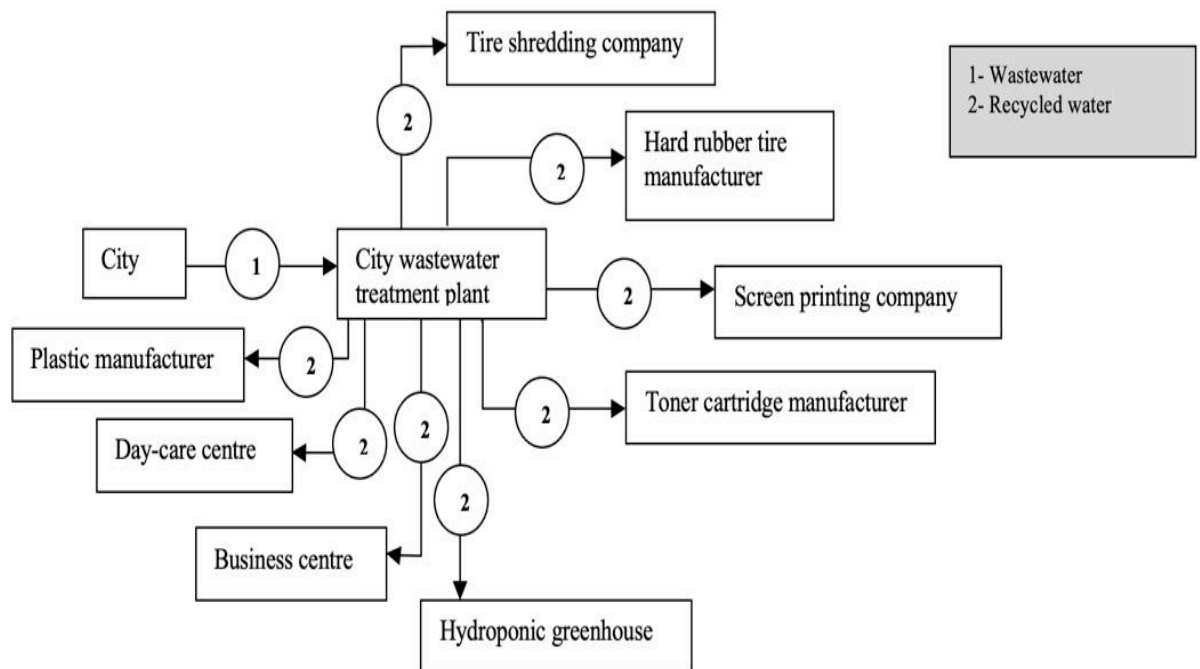
Water flow network of Choctaw Eco-Industrial Park, USA

The Choctaw Eco-Industrial Park is located in Oklahoma City, USA and was initiated with the idea of recycling tyres through pyrolysis processing to generate valuable and reusable products, such as steel, gas, heat, extender process oil, to name a few. Over the years, tyre and FRT (the processor) have initiated the IS partnership in the Eco-industrial park promoting both tyre recycling and the reuse of treated wastewater to fulfil the non-potable water needs (Carr, 1998). The IS partnership at Choctaw includes 11 organisations: a wastewater treatment plant, Safe Tire Disposal Crop, Federal Recycling Technologies Inc, a plastics manufacturer, a screen-printing company, a toner cartridge manufacturer, a hard rubber tyre manufacturer, a carbon processor, a hydroponic greenhouse, a business centre and a day-care centre.

The water flow related inputs and outputs of firms participating in Choctaw's IS are as presented in Figure 4.3. The collaboration between these industries involves a complex flow of materials inputs and outputs.

Figure 4.3

Water flow network of Choctaw Eco-Industrial Park, USA



Among the resources flows, the water flow mainly consists of wastewater and treated water. Treated water from the city wastewater plant is distributed to other firms in the park and is the main input for most of them, that is, the tire shredding company, the hard rubber tyre manufacturer, the screen-printing company, the toner cartridge manufacturer, the plastic manufacturer, the hydroponic greenhouse, the business centre and the day-care centre. Hence, the water flow of Choctaw EIP mainly comprises wastewater and treated water exchanges that need to be considered in optimising the water flow network.

Water flow network of Kwinana Industrial Area, Australia

The Kwinana industrial area is dominated by the heavy processing industry. It is the largest and most diverse industrial area in Western Australia, accommodating major processing industries and is located 40 kilometres from the capital city of Perth. The total economic input of the industrial area is about A\$4.3 billion per year (van Beers et al., 2007). Within the industrial area, the industrial symbiosis network comprises 48 synergistic exchanges. These involve 16 partners: an industrial chemical producer, a coal-fired power station, a gas-fired power station, an industrial chemical and fertiliser producer, an oil refinery, a co-generation plant A, an industrial gas producer A, an alkali plant, an industrial gas producer B, an iron plant, a titanium dioxide producer, an alumina refinery, a water supply and treatment company, a wastewater treatment plant, a liquid petroleum gas (LPG) distributor, and an LPG producer and a co-generation plant B, all of which are exchanging utilities including water. The water

flow inputs and outputs of the industrial symbiosis partners at Kwinana are presented in Table 4.3.

Table 4.3

Water inputs and outputs of Kwinana Industrial Area, Australia

Participating industries	Water flow	
	Input flow	Output flow
Industrial chemical producer	-	Wastewater
Coal fired power station	-	Demineralised water
Gas fired power station	Demineralised water	-
Oil refinery	Sea cooling water Wastewater Recycled water Steam	-
Co-generation plant A	Recycled water	Wastewater Steam
Industrial gas producer A	Steam	-
Alkali plant	Steam Potable water	Wastewater
Industrial gas producer B	-	-
Iron plant	Recycled water	Steam
Titanium Dioxide producer	Wastewater Recycled water Steam	Steam Potable water Process water
Alumina refinery	Recycled water	-
Water supply and treatment company	Wastewater	Recycled water
Wastewater treatment plant	Wastewater	Recycled water
LPG distributor	-	-
LPG producer	-	-
Co-generation plant B	Potable water Process water	Wastewater Steam

As shown in Table 4.3, various water inputs and outputs can be seen in the Kwinana industrial area. Wastewater collected at the wastewater treatment plant is treated and distributed to other industries as recycled water through the water supply and treatment plant. The major wastewater generators in the industrial area are the industrial chemical producer, the co-generation plant A, the alkali plant and the co-generation plant B. The industrial chemical and fertiliser producer and the titanium dioxide producer use wastewater in their processes and distribute steam to other selected industries. Accordingly, recycled water, wastewater, steam, potable water and process water are the major water flows of industrial symbiosis in the Kwinana industrial area.

Water flow network of Qijiang Industrial Park, China

Qijian is an industrial park, located in Chongqing, China, in what is mainly a coal-producing area. Aluminium products are the main products of the industrial park: through their production processes, the main by-products generated are gypsum,

ammonium sulphate, gypsum flue gas, fertiliser, coal ash, concrete blocks and aluminium scrap. The industrial park consists of a sewage treatment plant which is linked to all firms in the network. The industrial symbiosis network of the Qijiang Industrial Park comprises 10 co-located industrial firms: a carbon plant, a fertiliser plant, a building materials company A, a building materials company B, a building materials company C, the lime slurry of a flue gas desulphurisation plant, a power plant, an exhaust heat boiler plant, a deep processing complex and a sewage treatment plant, all of which exchange materials, energy and water.

Table 2.5 shows the water flow inputs and outputs of the Qijiang Industrial Park. As the major actor, the sewage treatment plant collects wastewater (including sewage) from other industries and distributes the recycled water mainly to the lime slurry of the flue gas desulphurisation plant, the power plant and the deep processing complex in the industrial park. Among other resources flows, the water flow of Qijiang Industrial Park includes wastewater and recycled water.

Table 4.4

Water inputs and outputs of Qijiang Industrial Park, China

Participating industries	Water flow	
	Input flow	Output flow
Carbon plant	-	-
Fertiliser Plant	-	Wastewater
Building Material company A	-	Wastewater (with sewage)
Building Material company B	-	Wastewater (with sewage)
Building Material company C	-	Wastewater (with sewage)
Lime slurry of flue gas desulphurisation plant	Recycled water	-
Power plant	Recycled water	Wastewater
Exhaust heat boiler plant	-	-
Deep processing complex	Recycled water	Wastewater (with sewage)
Sewage/wastewater treatment plant	Wastewater	Recycled water

Water flow network of Songmudao Chemical Industrial Park, China

The Songmudao Chemical Industrial Park is located in Dalian, China, and is a large-scale chemical processing complex. The individual chemical firms have been relocated to the Songmudao Chemical Industrial Park as a result of urban development. The industrial park combines these enterprises to bring about the sharing of resources, thus facilitating industrial platform and technological development. The industrial symbiosis network of Songmudao consists of various enterprises which are mostly related to chemical processing. The seven industries involved in exchanging resources

comprise a fertiliser producer, a co-generation power plant, a soda plant, an ammonia plant, an ammonium nitrate plant, a cement plant and a wastewater treatment plant. The network was initiated to exchange materials, energy and water-related synergies. The water-related inputs and outputs of the Songmudao Chemical Industrial Park are shown in Table 4.5.

Table 4.5

Water inputs and outputs of Songmudao Chemical Industrial Park, China

Participating industries	Water flow	
	Input flow	Output flow
Fertiliser producer	-	-
Co-generation power plant	Steam condensate	Soft water Steam Desalted water Wastewater
Soda plant	Soft water Steam Steam condensate Cooling water	
Ammonia plant	Steam	Wastewater Steam condensate Cooling water
Ammonium Nitrate plant	Steam Desalted water	Steam condensate Wastewater
Cement plant	-	-
Wastewater treatment plant	Wastewater	-

As shown in Table 4.5, wastewater collected from industries, such as the co-generation power plant, the ammonia plant and the ammonium nitrate plant is the major input for the wastewater treatment plant. The low-, medium- and high-grade steam is distributed among industries for use in chemical processing. Accordingly, the water flow of the Songmudao Chemical Industrial Park comprises wastewater, steam, cooling water, desalted water and steam condensate.

Summary of water inputs and outputs of selected IS networks

The summary of typical water inputs and outputs of these five industrial symbiosis networks is shown in Table 4.6. Within the industrial park or the cluster selected, the two major industrial actors are the processing firm (manufacturing organisation/plant) and the wastewater treatment unit. Cooling water, process water, demineralised water, soft water, steam and steam condensate are mainly generated through the production process of firms co-located in the industrial park. The municipality generally handles the wastewater treatment of the industrial network; thus, it is a major contributor in the water flow. In most cases, wastewater from the processing firms is linked to wastewater treatment by the municipality.

The utilisation of freshwater from reservoirs and the city mains is also visible. According to a study by van Beers et al. (2007), water flow between industrial firms is considered as a utility synergy flow of industrial symbiosis. As per Domenech and Davies (2011), the Kalundborg Industrial Symbiosis Project includes three types of flows, namely, materials, energy and utilities. The authors indicated that the flow of freshwater, wastewater and recycled water are considered under the utility flow. Furthermore, industries generate production process-oriented water outflows which can be directly or indirectly used by other industries. According to a study by Chertow (2007), treated wastewater is one of the major resources exchanged between industries. The author indicated that the wastewater generated by industries is an input to a water recycling company: after being recycled, the water then flows to other industries as treated water.

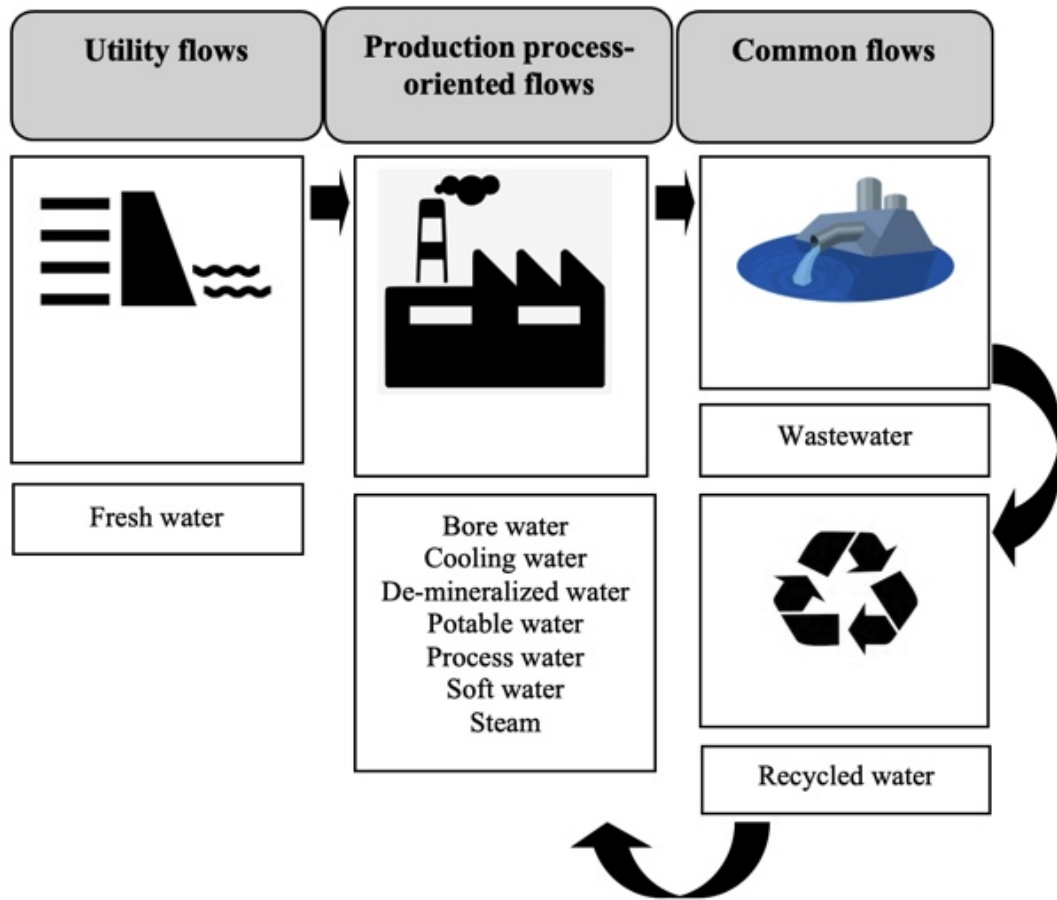
Table 4.6*Typical water inputs and outputs of IS networks*

IS project	Water Inputs										Water Outputs									
	Fresh water	Wastewater	Steam	Recycled water	Demineralised water	Cooling water	Potable water	Process water	Soft water	Desalted water	Steam	Wastewater	Cooling water	Recycled water	Demineralised water	Bore water	Potable water	Process water	Soft water	Desalted water
Kalundborg IS Project, Denmark	×	×	×								×	×	×							
Choctaw Eco-Industrial Park, USA		×		×										×						
Kwinana Industrial Area, Australia		×	×	×	×	×	×	×			×	×		×	×	×	×			
Qijiang Industrial Park, China		×		×								×	×							
Songmudao Chemical Industrial Park, China		×	×			×			×	×	×	×	×						×	×

Figure 4.4 illustrates the water inputs and outputs derived through the above analysis.

Figure 4.4

General water inputs and outputs

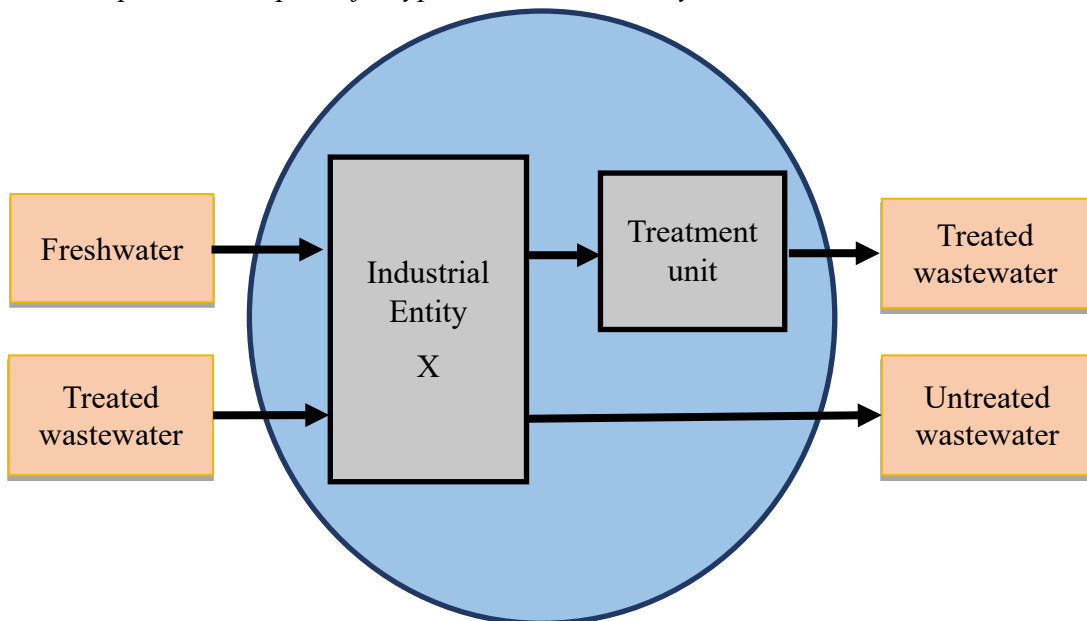


As shown in Figure 4.4, water inputs and outputs of IS networks are known as ‘utility flows’, ‘production process-oriented flows’ and ‘common flows.’ Since wastewater and recycled or treated wastewater are common to industries in all selected IS networks, it has been derived in this research as ‘common flows.’

The water inputs and outputs of each industrial entity are fed into the process flow to continue the following four key steps. Figure 4.5 illustrates the water inputs and outputs of a typical industrial entity namely, freshwater input, treated wastewater input, treated wastewater output and untreated wastewater output.

Figure 4.5

Water inputs and outputs of a typical industrial entity



The water input and output data entered into the process are managed by using the steps described below.

4.2.2 Step 1 - Data compilation and initial processing

Step 1 of the optimisation development process is to compile the collected water input and output data through initial processing. This comprises three (03) sub activities: (i) boundary selection, (ii) synergy identification and (iii) theoretical framework development as described below.

4.2.2.1 Boundary selection - Selection of industrial entities based on the theory of IS

The theory of IS refers to:

“the engagement of traditionally separated and geographically proximate industrial entities to achieve collaborative benefits through the physical exchange of resources including materials, energy, water, by-products, services and infrastructure” (Chertow, 2000, p. 12).

As stated by Chertow (2007, p.14),

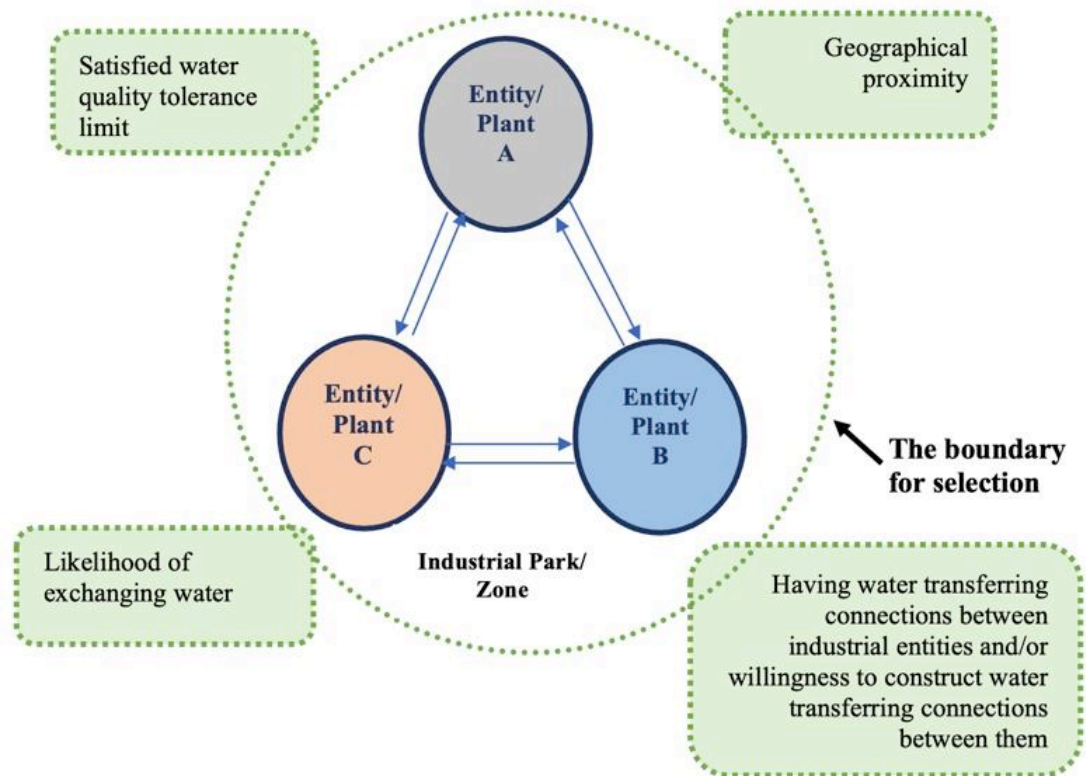
“at least three different entities must be involved in exchanging at least two different resources to counter it as a basic type of IS. By involving three entities, none of which is primarily engaged in a recycling-oriented business, where the 3-2 heuristic begins to recognise the complex relationships rather than the linear one-way exchanges”.

Collaborative sharing and the circular nature between firms in industrial estates may enhance the collective economic and environmental benefits. Specifically, industries with close proximity and those that have a willingness to engage are mainly considered when initiating symbiotic relationships. In this sense, industrial sites/parks have been recognised as ideal environments to initiate the IS clusters. For example, the first IS cluster was fully realised in the EIP at Kalundborg, Denmark. Choctaw Eco-Industrial Park, USA, Qijiang Industrial Park, China, and Songmudao Chemical Industrial Park, China are the other examples for IS based eco-industrial clusters that have been initiated. It is evident in many studies that the industrial park is a perfect spatial platform in which to facilitate waste and by-product exchanges between neighbouring industrial firms.

In accordance with the above point, the current study considered a cluster of three ‘traditionally separated’ industrial entities, located in the same industrial park/zone to initiate the water network. The selection of industrial entities was undertaken subject to the following criteria, as shown in Figure 4.6:

- Industries within the same industrial park with geographical proximity,
- Industrial entities which demonstrate the likelihood of exchanging wastewater,
- Industrial entities with water transferring connections between them, and/or industrial entities with a willingness to invest for constructing the water transferring connections with other industries and,
- The industries satisfying the upper tolerance limit of water quality

Figure 4.6
Selection of industrial entities



4.2.2.2 Synergy identification of industrial entities

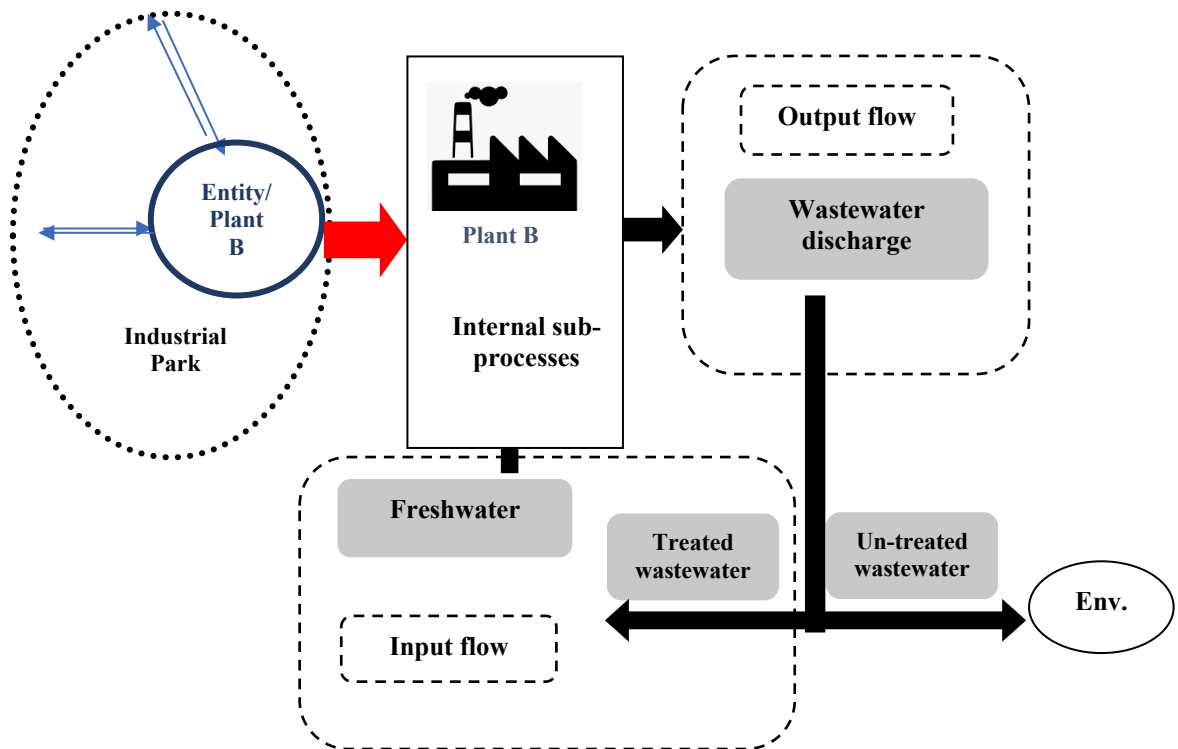
Each industrial plant is viewed as a ‘black box’ with only a single stream of water considered to enter and exit the plant. Therefore, information regarding the internal sub-processes of the selected industrial entities is not considered.

As stated by Aviso et al. (2010), the sharing of information between the participating industries in industrial parks is a critical concern due to confidentiality issues. Tan et al. (2011) stated that all participant information is not transparent in developing exchange networks. These authors added that industrial entities must therefore be considered as ‘black boxes’ in which detailed information about their internal processes is not revealed and only the input and output resources flow characteristics are used in common. For example, Singh and Lou (2006) successfully utilised the same approach to design an exchange network that considered regeneration units in eco-industrial parks (EIPs).

Hence, water input flows and water output flows of each entity are only considered where the information about the internal processes are not revealed, as shown in Figure 4.7.

Figure 4.7

A typical water input and output flows of an industrial entity

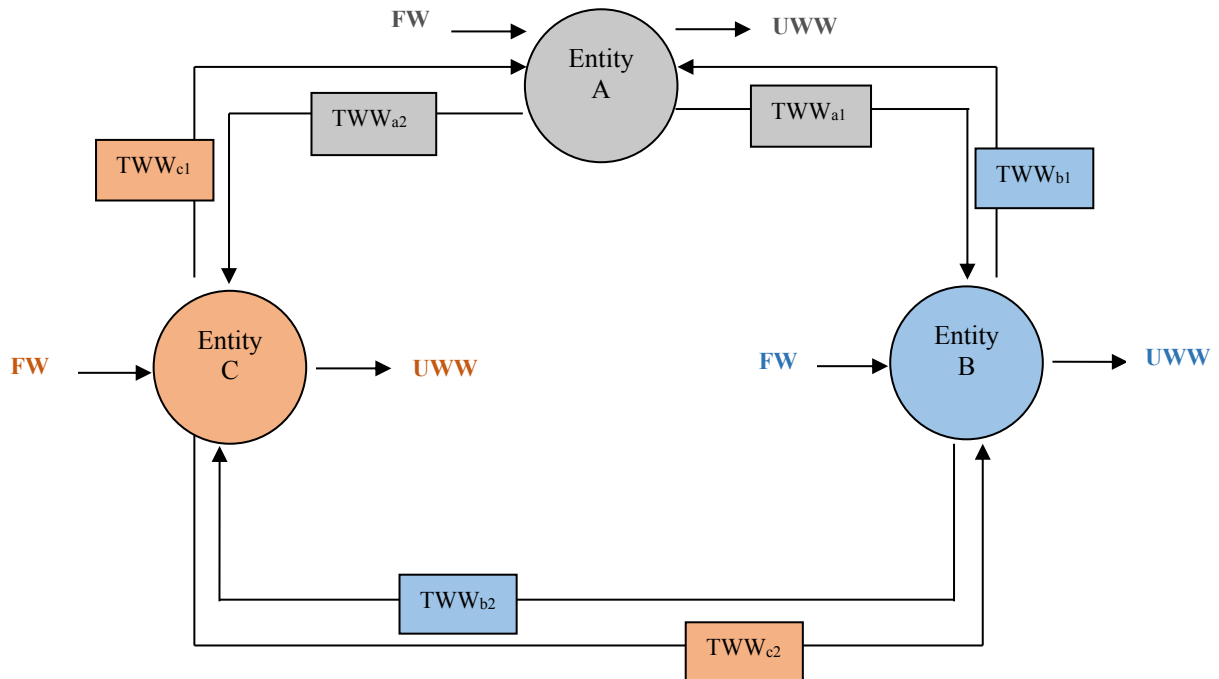


As shown in Figure 4.7, freshwater and treated wastewater are considered as water input flows while wastewater is considered as water output flows from the selected industrial entity.

In relation to the water flow, all possible water synergies between the selected industrial entities in the cluster are presented in Figure 4.8.

As depicted in Figure 4.8, the input and output flows of water; freshwater inputs, treated wastewater inputs and un-treated wastewater outputs, are considered in determining the water synergies between the participating industrial entities.

Figure 4.8
Water synergies between participating industrial entities



Legend:	TWW_{a2} = TWW from Entity A to Entity C
FW = Freshwater	TWW_{b1} = TWW from Entity B to Entity A
UWW = Untreated wastewater	TWW_{b2} = TWW from Entity B to Entity C
TWW = Treated wastewater	TWW_{c1} = TWW from Entity C to Entity A
TWW_{a1} = TWW from Entity A to Entity B	TWW_{c2} = TWW from Entity C to Entity B

Water can be exchanged between the participating industrial entities A, B and C in various ways. Freshwater (FW), utilised from an external water source, is the main input for all three entities, with untreated wastewater (UWW) being discharged from each entity.

As hypothesised, treated wastewater (TWW) can be exchanged between each entity, providing possible synergies. For example, TWW_{a1} and TWW_{a2} of Plant A are flowing to Plants B and C, respectively, or vice versa. The optimum solution is determined by considering the probability of the occurrence of all such possible water synergies.

As the major concern of the current research is to develop an optimisation model for minimising freshwater utilisation, the water source–water sink relationship of the water exchange network is considered. As stated by Aviso (2014), each water-generating industrial entity is considered as a ‘water source’, while each water-using industrial entity is considered as a ‘water sink’.

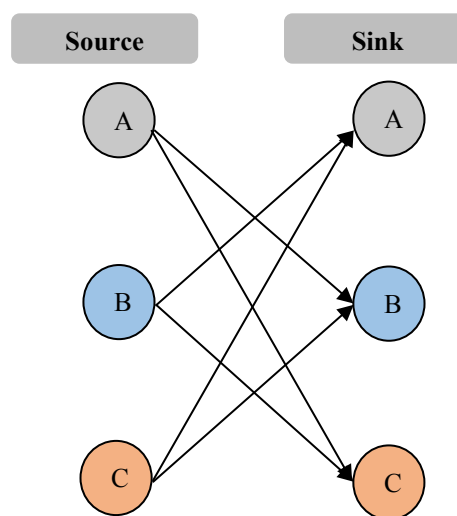
As participating industrial entities in an industrial park have the probability of obtaining various synergies, different approaches have been proposed to aid in the systematic planning of resource exchange networks. A study conducted by Tan et al.

(2011) proposed the use of a source–sink framework to optimise energy exchange systems, with this mathematically equivalent to the synthesis of single component resource conservation networks. Furthermore, this can be solved by considering various constraints with the use of linear programming techniques (Aviso et al., 2011). Similarly, Aviso (2014) utilised source–sink modelling in his study that proposed a water network for a hypothetical industrial cluster with the overall objective of achieving economic viability.

All possible source–sink relationships between industrial entities A, B and C are shown in Figure 4.9.

Figure 4.9

Source-sink relationships between industrial entities A, B and C

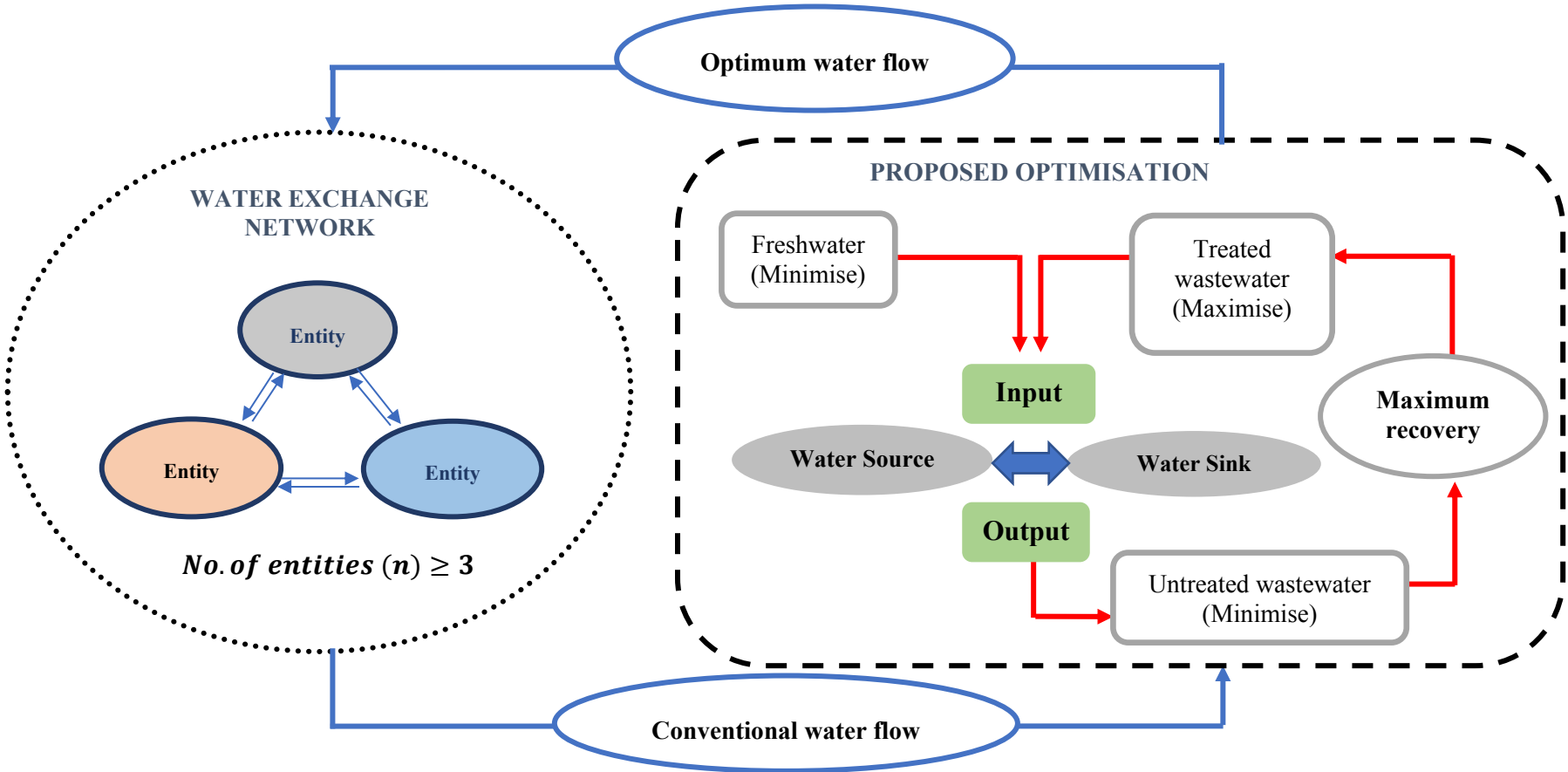


As shown in Figure 4.9, each entity, which is generating and supplying water to other plant/plants can be considered as a water source. Each entity, which is receiving water from other plants can be considered as a water sink. Therefore, the selected cluster of industrial entities is characterised by ‘ n ’ = the number of wastewater-generating industrial entities (water sources) and ‘ n ’ = the number of water-using industrial entities (water sinks). Based on the above considerations, the theoretical framework is next presented.

4.2.2.3 Theoretical framework of the research

Figure 4.10 presents the theoretical framework developed for the proposed optimisation. The framework indicates the importance of designing optimum water exchange networks in order to reduce their inefficiencies. The relationships between water sinks and water sources in the water exchange network are considered as a base from which to develop the proposed optimisation model. The optimum water exchange network solution between the participating industrial entities is finally determined to reduce the total freshwater (FW) consumption in the selected park, which results in minimum wastewater (WW) discharge.

Figure 4.10
Theoretical framework



4.2.3 Step 2 - Optimisation model design and development

Step 2 of the process is devoted to presenting the optimisation model which is developed to assess the optimum water flow of industrial symbiosis. Hence, the systematic method used for developing the model, the objectives of optimisation, constraints and key variables are described in the following sections.

4.2.3.1 Proposed systematic method for optimisation model design

Various graphical and mathematical modelling approaches have been adopted for modelling optimum resource exchange networks. Wang and Smith (1994) applied the graphical approach in their study of water system integration that targeted maximum water reuse. However, a major drawback of the graphical approach was found by Handani et al. (2011) as the approach was ineffective for use in large-scale systems consisting of multiple water sources, water sinks and contaminants. Hou et al. (2014) and Ahmetović et al. (2015) also verified the ineffectiveness of pinch analysis for use in water networks with multiple contaminants and multiple freshwater sources. As Handani et al. (2011) stated, the mathematical programming technique has emerged to overcome the limitations of the graphical approach.

The studies by Ahmetović and Grossmann (2011) and Yang and Grossmann (2013) proposed water targeting network models with multiple contaminants based on mathematical programming. The main mathematical programming approaches used are linear programming (LP), mixed integer linear programming (MILP) and mixed integer non-linear programming (MINLP) models which can easily deal with multiple contaminants, different constraints and multiple water sinks, sources and water treatments. Furthermore, the linear programming (LP) approach, as a powerful tool, can find the optimal value of a linear objective function, subject to linear constraints (Handani et al., 2011).

According to a study by Aviso (2014), flexible and robust optimisation are other approaches used, in which robust optimisation provides a more feasible solution for decision makers to use in developing optimum exchange networks. The same approach has been utilised by various researchers in the similar field of designing industrial networks. For example, Tan et al. (2011) proposed an optimal allocation of energy sources to related energy sinks by using robust optimisation rather than a flexible model, adding that flexible networks could involve variations due to seasonal and daily changes of the process.

Considering the above points, the optimal water flow assessment model in the current study was developed using the mixed integer linear programming (MILP) approach (the Simplex coding method) to find the optimal value of the targeted objective as the objective and all constraints were linear. The model was developing using SageMath (open-source mathematical software licensed under GPL.v3).

4.2.3.2 Objective of optimisation

In the existing literature, the main objectives for optimisation problems are related to the economic and environmental objectives of water networks (Boix et al., 2015; Tiu & Cruz, 2017). Economic objectives in industrial symbiosis networks have been the most developed and studied objectives in optimisation studies (Kurup, 2007). Most optimisation models in the previous literature have considered the cost reduction of water treatment and transportation between industrial plants (Aviso, 2010; Tiu & Cruz, 2017). Another study by Rubio-Castro et al. (2012) proposed an optimisation model for minimising the capital and operating costs of constructing piping connections and treatment facilities for wastewater. However, environmental indicators in industrial symbiosis networks have not been as well developed as economic indicators. Fewer studies were found that considered environmental indicators as objectives for optimising the water flow. As examples for the optimisation of environmental objectives, Tiu and Cruz (2017) conducted a study developing an optimisation model for water flow in EIPs by means of water quality. Nobel and Allen (2000) studied the use of geographic information systems (GISs) for industrial water reuse modelling, while Aviso et al. (2011) studied input–output modelling of water supply chains in industrial parks. Therefore, the current study recognised the absence of a model for optimising the water flow of industrial symbiosis through maximum wastewater recovery.

Furthermore, in the field of mathematical optimisation, many contributions have been made toward both single and multi-objective formulations of problems (Montastruc et al., 2013; Mahrach et al., 2020). For example, Tiu and Cruz (2017) developed an optimisation model by simultaneously considering economic and environmental objectives.

As indicated in the above-mentioned prior research, the objective functions of the capital and operating costs of wastewater treatment as well as the reduction of environmental impact by EIPs have been solved separately by normalising them as single and separate objectives using the goal programming method. Optimisation models have focused on EIPs in terms of minimisation of capital and operating costs of treatment facilities and minimisation of the quantity of water consumed (Aviso et al., 2010; Aviso, 2014). Hence, among the single and multi-objective optimisation in mathematical programming, the current research used single objective optimisation and only considered environmental indicators. As research was lacking on environmental indicators of IS networks for optimising water networks in comparison to studies on economic indicators, the objective of the optimisation proposed in this research related only to environmental indicators.

Accordingly, the objective of the proposed optimisation was to reduce freshwater consumption in the industrial zone/ industrial symbiosis network by reusing treated wastewater through its maximum recovery, which may result in reducing wastewater discharged to the environment. Hence, this research intended to develop a model to assess the optimum water flow between participating industrial entities, resulting in

minimum freshwater consumption and wastewater discharge through maximum recovery.

4.2.3.3 Constraints for optimisation

In the optimisation literature, various constraints can be found which have been considered when designing optimum exchange networks. Tiu and Cruz (2017) developed a MILP model by considering water quality, subject to various constraints, such as the input–output water balance, quality and topological constraints. A model developed by Aviso (2014) was subject to material balances and quality constraints, with the input and output water balance ensuring that each industrial entity would only accept as much water as it demanded and would only release as much water as was available. The average consumption of freshwater inputs and wastewater outputs of each entity are considered in quantifying the available water supply and demand within the network. Furthermore, this assumed that each industrial entity had already integrated recycling or pre-treatment within its facility, thus resulting in single inlet and single outlet streams. The quality constraint considers the maximum allowable rate of contaminant both in freshwater and treated wastewater. Quality at the water sink ensures that each industrial plant only accepts input water from water sources if the water satisfies the maximum contaminant limit (Tiu & Cruz, 2017). As reviewed in literature, the quality of freshwater and wastewater discharge by each individual industry is measured as per the available water quality regulations (WHO, 1993; ZDHC, 2019, CEA, 2019). The available water quality regulations adopted in industries were considered to determining the maximum allowable rate of contaminant of each participating industrial entity of the IS network.

The availability of pipe connections between industrial plants is also considered in developing optimum exchange networks. To be specific, no water transfers occur when no connections exist. Hence, the current research assumed that connections were available between participating industrial plants or industrial entities showed a willingness to invest for water transferring connections when developing the optimum water exchange network.

4.2.3.4 Key variables of the model

Three key variables are considered in developing the optimisation model: (a) freshwater utilised by water sink, (b) wastewater generated by water source, and (c) treated wastewater from source to sink. These three variables are further elaborated below.

(a) Freshwater utilised by water sink

As per the findings derived from the desk study of global IS cases, freshwater is supplied to the industries from external water sources, which mainly includes lakes and the city water supply (Zhang et al., 2016). Freshwater utilised by the water sink can be calculated as shown in Eq. 1.

$$\begin{aligned}
 &\text{Freshwater utilised by water sink} && \dots\dots \text{(Eq. 1)} \\
 &= \text{Freshwater from surface water sources (lakes, etc.)} \\
 &+ \text{Freshwater from city water supply}
 \end{aligned}$$

(b) Wastewater generated by water source

As derived from the desk study findings, wastewater outputs of industrial entities in IS networks include wastewater collected from households at the city level, wastewater with sewerage and wastewater from manufacturing processes (industry effluent) (Domenech & Davies, 2011; Zhang et al., 2016).

Wastewater generated by the water source can be calculated by using Eq. 2.

$$\begin{aligned}
 &\text{Wastewater generated by water source} && \dots\dots \text{(Eq. 2)} \\
 &= \text{Wastewater collected from households at city level} \\
 &+ \text{Wastewater with sewerage} + \text{Industry effluent}
 \end{aligned}$$

(c) Treated wastewater from water source to water sink

According to the desk study findings, industries obtain treated wastewater from other industries in two different ways, directly and indirectly. The water sink obtains treated wastewater directly from other water sources and indirectly through centralised wastewater treatment. In the indirect method, the water source sends the wastewater through a centralised wastewater treatment process and shares it with other industries (Carr, 1998; van Beers et al., 2007).

According to Ahmetović and Grossmann (2011), water loss may occur during wastewater treatment due to evaporation and removal of concentrated contaminants. As further stated by these authors, within the process water network, the removed mass load of contaminants from wastewater treatment are usually too small when compared to wastewater flow rates; thus, in these cases, it can be assumed that the inlet and outlet wastewater flows of wastewater treatment units are the same. However, considerable water loss may occur during water transmission due to water leakage, deteriorated pipes and water connections, etc. (Eguavoen & Youkhana, 2008; Perera et al., 2018). Water loss is typically calculated as the difference between the amount of water consumed and the amount of water produced (Eguavoen & Youkhana, 2008). Hence, the water loss during wastewater treatment is considered as negligible. Furthermore, water loss during distribution is also not considered, as treated wastewater is transmitted within the same geographical boundary of the industrial park, where no long-distance transmission exists. Accordingly, treated wastewater flow transferred from water source to water sink can be calculated as shown in Eq. 3.

$$\begin{aligned}
 &\text{Treated wastewater from water source to water sink} && \dots \text{ (Eq. 3)} \\
 &= \text{Treated water direct supply} \\
 &+ \text{Indirect supply through central treatment}
 \end{aligned}$$

4.2.3.5 Parameters of the model

The model parameters comprise: (a) number of water sources and water sinks, and (b) number and types of water quality parameters, as described below.

(a) Number of water sources and water sinks

According to the “3-2 heuristic” criterion introduced by Chertow (2000), at least three different entities must be involved in exchanging at least two different resources for the model to be counted as a basic type of IS. Accordingly, the water source–water sink relationship between three industrial entities is considered as the threshold.

(b) Number and types of water quality

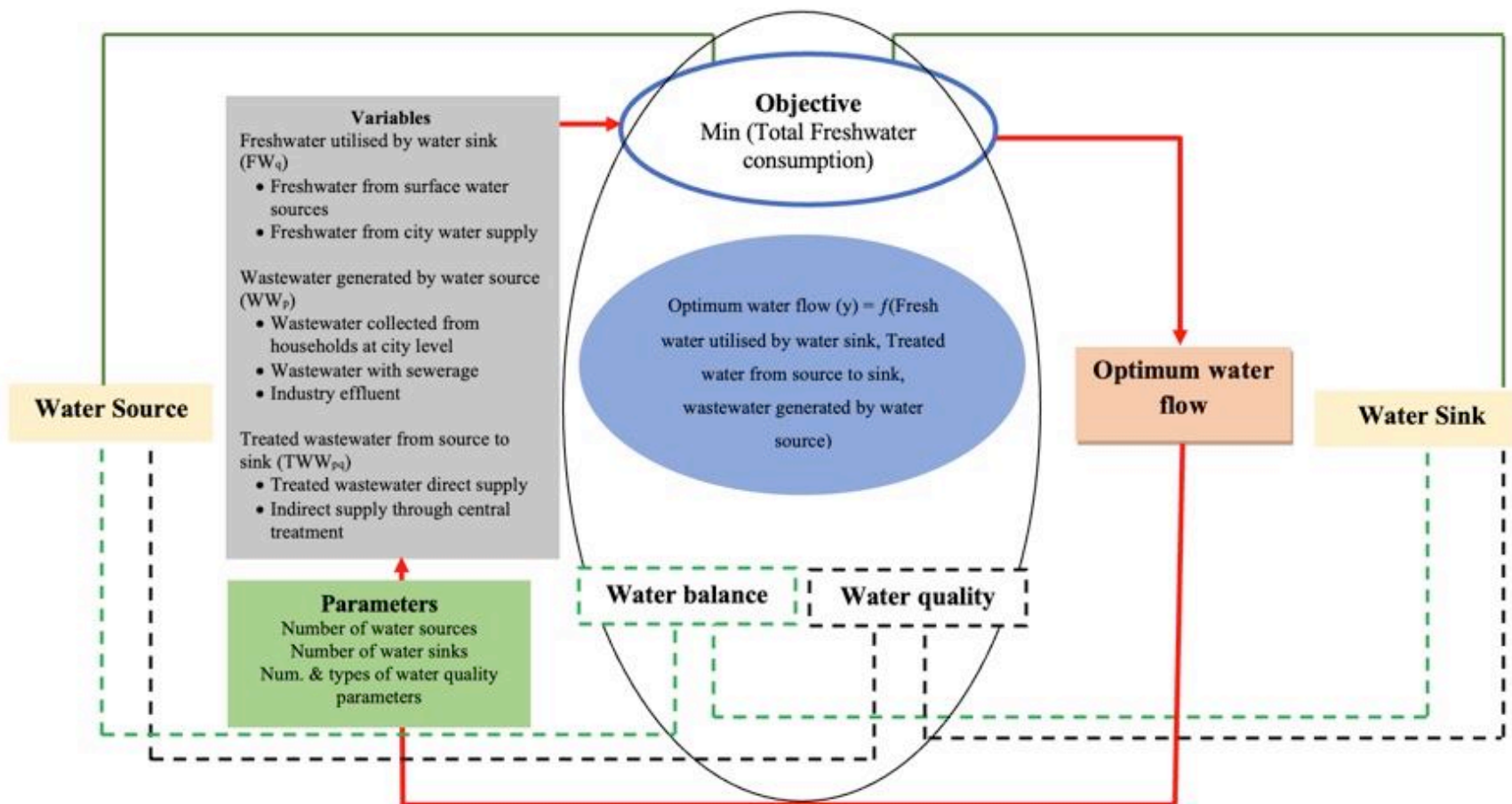
Many studies can be found in the literature on the optimisation of water networks in industrial symbiosis related to water quality. Aviso (2014) developed the optimisation model by considering the multiple quality contaminants of water comprising three parameters, namely, Total Organic Carbon (TOC), Total Suspended Solid (TSS) and Total Dissolved Solids (TDS). The optimisation model developed by Handani et al. (2011) also used the multiple quality contaminants in their model in which Total Suspended Solid (TSS), Total Dissolved Solids (TDS), Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD) and hardness considered by setting the maximum tolerance limits. However, the selection of contaminants was based on the specific industrial entities that participated in the water network in the selected context (Aviso, 2014). Considering the above points, multiple quality contaminant concentrations were considered in the current research model by setting the maximum allowable quality limits. Therefore, it was assumed that all contaminant concentrations of each water sink and water source were fixed to their maximum values. However, selection of the number and types of quality contaminants remained to be decided upon in the selected context.

4.2.3.6 Conceptual model for assessing the optimum water flow of industrial symbiosis

Incorporating the above identified methods, objectives, constraints, variables and parameters, the conceptual model for assessing the optimum water flow of IS was developed as presented in Figure 4.11.

Figure 4.11

The conceptual model for assessing the optimum water flow of IS (before mathematical formulae development)



As shown in Figure 4.11, the proposed model is designed as a generic linear relationship between water source and water sink, which can be applied in scenarios with similar industrial characteristics. The objective of optimisation is limited to minimisation of freshwater utilisation in the industrial zone through maximum recovery of wastewater. The developed model comprises three key variables, namely, freshwater utilised by the water sink, treated wastewater from the water source to water sink and wastewater generated by the water source. Hence, the optimal value is presented as a function of these three key variables. The number of water sources and water sinks, and the number and types of water quality parameters are the model parameters. The optimal value is restricted to two main constraints, namely, water balance and water quality.

In relation to the established conceptual model, mathematical formulae were developed as described below.

4.2.3.7 Mathematical formulae development of the optimisation model

The optimum water network was assessed through the objective of minimising total freshwater consumption of the selected industrial cluster, subject to material balances and quality constraints and based on the characteristics of the water sources and water sinks. With the use of mathematical modelling, the optimisation model was developed with three key mathematical formulations: (i) objective function; (ii) water source and sink balance (water demand and supply); and (iii) quality constraint (maximum allowable concentration of contaminants).

The taxonomies of the model indices, parameters, variables and constraints are shown in Table 4.7.

Table 4.7

Nomenclatures

Indices	
p	index for water source
q	index for water sink
m	index for water quality parameter
FW	index for freshwater
WW	index for wastewater generated
TWW	index for treated wastewater
Parameters	
N_p	num. of water sources
N_q	num. of water sinks
N_m	num. of water quality parameters
Decision variables	
FW_q	flowrate of freshwater utilised by water sink q
WW_p	flowrate of wastewater generated from water source p
TWW_{pq}	flowrate of treated wastewater from source p to sink q
Constraints	
D_q	demand flow rate at water sink

S_p	available flowrate at water source
C_{pm}	quality measurement of parameter m in water source p
C_{qm}	quality measurement of parameter m in water sink q
C_{fm}	quality measurement of parameter m in available freshwater

Problem statement

Three participating industrial entities (plants) located in the same industrial park in close proximity consume freshwater for their industrial processes and discharge wastewater to the environment with no or minimum recovery. It is planned that the total freshwater (FW) consumption (quantity and cost) in the selected zone be minimised by developing an optimum water flow between the participating industrial entities, which results in minimum wastewater (WW) generation. Each industrial entity is considered as a ‘black box’, with no information provided regarding its internal sub-processes and only a single stream entering and exiting each entity.

Objective function

The overall objective is to minimise the freshwater consumption of water sinks (q) of the selected IS network through maximum wastewater recovery, which results in minimum wastewater generation. The objective function is given in Eq. 4.

$$\text{Min} \sum_{q=1}^{Nq} FW_q \quad \dots\dots \text{(Eq. 4)}$$

The objective function is subject to the water balance at both the water source and water sink, with quality constraints explained below.

Water balance at sink

In the given scenario, ‘ q ’ represents the water sink. The demand of water sink ‘ D_q ’ is fulfilled by TWW acquired from the water source to water sink ‘ TWW_{pq} ’ and by freshwater ‘ FW_q ’, which is supplied by an external source without exceeding the maximum allowable level of water quality. For each sink q , the freshwater supply (FW_q) from the external source and the supply of TWW from source p (TWW_{pq}) must be equal to the required water demand at the water sink (D_q).

The water balance for each sink q is given in Eq. 5.

$$FW_q + \sum_{p=1}^{Np} TWW_{pq} = D_q \quad \forall q \quad \dots\dots \text{(Eq. 5)}$$

Water balance at source

In the given scenario, 'p' represents the water source. Each water source is characterised by the available water flowrate (S_p) and quality 'm' of its available TWW. For each source p, the generated wastewater (WW_p) and treated wastewater from source p to sink q (TWW_{pq}) must be equivalent to the available water flow.

The water balance for each source p is specified in Eq. 6.

$$WW_p + \sum_{q=1}^{Nq} TWW_{pq} = S_p \quad \forall p \quad \dots\dots \text{(Eq. 6)}$$

Quality constraints at sink

It is important to consider the quality of freshwater and treated wastewater as the input flow into water sink. Therefore, the N_m (number of selected quality parameters m) is considered at each water sink. It is assumed that all contaminant concentration of each sink and source is fixed to their maximum values. Furthermore, the quality of freshwater and wastewater are considered separately as it is impracticable to determine these together. The concentrations of contaminants at each sink referring to the quality of treated wastewater and quality of freshwater are given in Eq. 7 and Eq. 8 respectively.

Quality of treated wastewater

$$\sum_{p=1}^{Np} TWW_{pq} \times C_{pm} \leq (Dq - FWq) \times C_{qm} \quad \forall q, m \quad \dots\dots \text{(Eq. 7)}$$

Quality of freshwater

$$FWq \times C_{fm} \leq (Dq - TWW_{pq}) \times C_{qm} \quad \forall q, m \quad \dots\dots \text{(Eq. 8)}$$

In Equations 7 and 8, N_p represents the total number of water sources, TWW_{pq} refers to the flowrate of treated wastewater from source p to sink q; C_{pm} refers to the quality measurement of parameter m in source p, FW_q represents the freshwater utilised by sink q and C_{fm} denotes the quality measurement of parameter m in available freshwater. D_q represents the demand flow rate of water sink q; whereas C_{qm} refers to the quality measurement of parameter m in water sink q.

An additional constraint was introduced to ensure the single inflow and outflow of TWW from one entity to another considering the following reasons:

- According to the 3-2 heuristic criteria and IS theory proposed by Chertow (2000), scope of this model was limited to the complex source and sink relationships among industrial entities. As per the theory, each entity exchanges TWW with another participating industrial entity through 06 source-sink relationships (refer to Figure 4.9) beyond their own reuse. Hence, this model considers symbiotic exchanges between participating industries by assuming that each entity in the network will go through already integrated treatment or recycling facility within the manufacturing process and willing to exchange TWW (with or without own reuse due to organisational procedures and quality standards, etc.), which resulted in single inflow and outflow of water from the industrial entity.
- As proposed by Tan et al. (2011), industrial entities were considered as ‘black boxes’ in which the detailed information about its internal processes were not revealed and only the input and output water flow characteristics were used in assessing the optimum water flow.
- TWW discharged from each entity is used by another entity when the quality requirement is being satisfied in case the quality of TWW is not satisfactorily met by the same industry to be used within the manufacturing process.

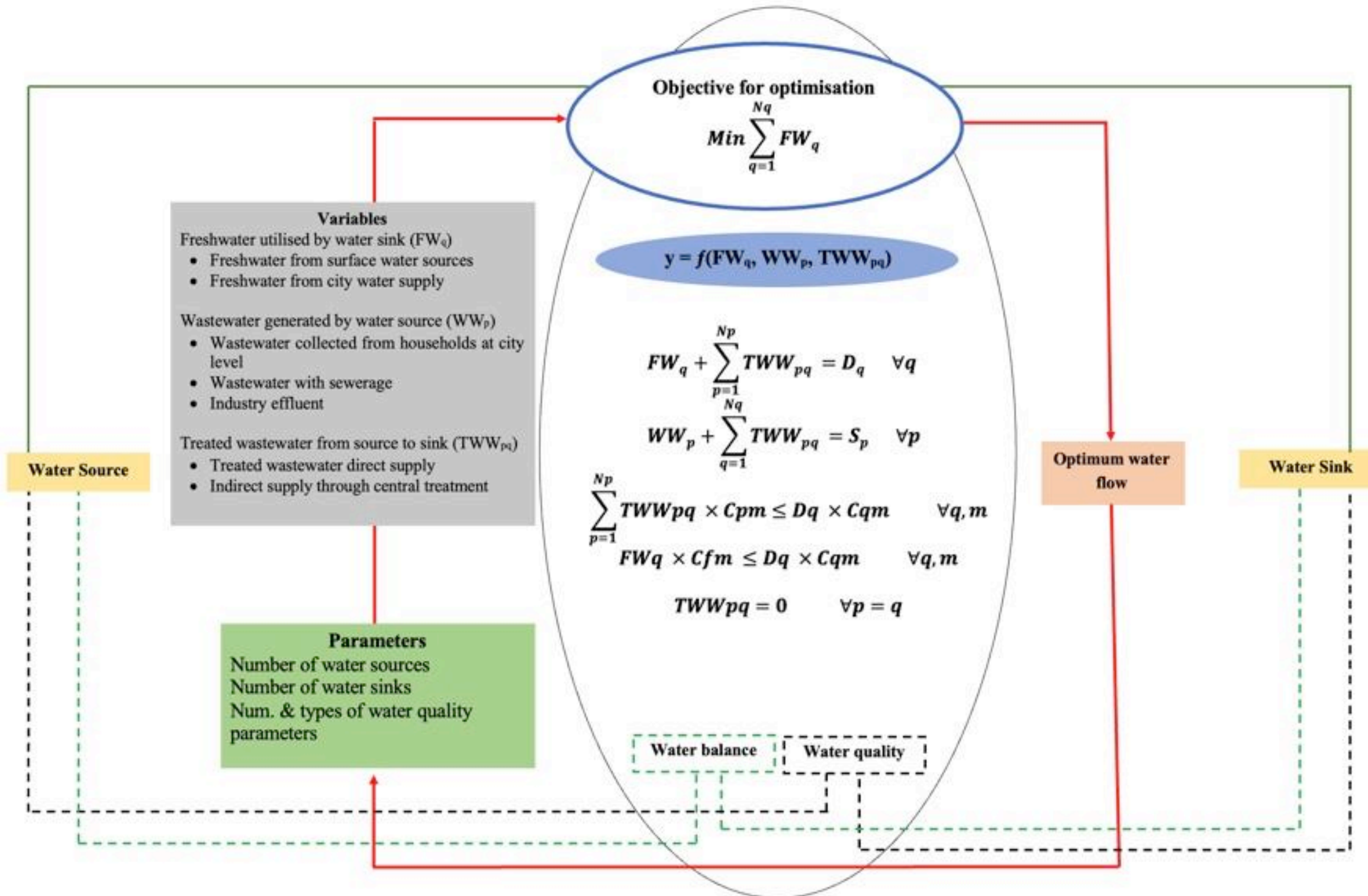
The additional constraint is given in Eq. 9.

$$TWW_{pq} = 0 \quad \forall p = q \quad \dots\dots (Eq.9)$$

Accordingly, the conceptual model was revised by incorporating the mathematical formulae developed. The revised conceptual model is presented in Figure 4.12.

Figure 4.12

The conceptual model for assessing the optimum water flow of IS (after mathematical formulae development)



4.2.4 Step 3 - Assessment of the optimal configuration

Step 3 of the process is dedicated to explaining the considerations relating to the assessment of the optimal configuration. The developed model is applied in this stage by feeding real water input and output data to obtain the optimal solution. The details on data extraction for assessment and the selection of the optimal configuration are described below.

4.2.4.1 Data extraction for assessment

The input and output data, which can be used in assessing the optimal water flow are given in Table 4.8.

Table 4.8

Input and output data extraction

Input/ output data	Means of measurement
Freshwater utilised by water sink - quantity	Input flowrate (m ³ /day)
Freshwater utilised by water sink - quality level	Quality measurement (mg/L)
Treated wastewater from source to sink - quantity	Input flowrate (m ³ /day)
Treated wastewater from source to sink – quality level	Quality measurement (mg/L)
Wastewater generated by water source (untreated + treated) - quantity	Output flowrate (m ³ /day)
Wastewater generated by water source (untreated + treated) – quality level	Quality measurement (mg/L)

The collected data are fed to the software to obtain the optimal solution with the use of MILP approach (Simplex Coding Method). SageMath (open-source mathematical software licensed under GPL.v3) is used to develop the model.

4.2.4.2 Selection of the optimal configuration

The decision about the optimum solution in support of the objective of minimising total freshwater consumption in the industrial zone is next considered. Through using the MILP approach, the optimal value of the targeted objective can be obtained as the objective and all constraints are linear. The optimum water flow between each industrial entity can be designed by achieving the objective of minimising total freshwater consumption in the industrial zone. Furthermore, as per the objective of optimisation being considered, the reduction of freshwater consumption in the optimal water network can also be obtained. If the optimal value cannot be obtained or the water flow is not optimal, “re-processing” takes place by again proceeding to Step 1 of the optimisation development process (refer to Figure 4.1).

The optimal water flow, designed as the result of the optimisation being carried out, is then evaluated to ensure its relevance to the selected context, as described below.

4.2.5 Step 4 - Evaluation of the economic, environmental and social feasibility

As treated wastewater provides an alternative water source to reduce industrial water demand, initiating industrial symbiosis-based water exchange networks between industries is an ideal platform on which to reuse and reshare treated wastewater. Hence, the proposed model is conveniently used to pre-evaluate and design optimum water networks between these industries, which are located within the same geographical boundary.

Pre-evaluation can also be used to provide a feasibility assessment of the planned water synergies before their implementation within the selected industrial setting. Hence, in Step 4 of the optimisation development process, the economic, environmental and social feasibility of the developed optimal solution is evaluated.

The economic feasibility assessment can be conducted by using the life cycle cost analysis (LCCA) method which considers all projected significant and relevant cost flows over the period of analysis as they relate to investment in the proposed solution. Sensitivity analysis can also be conducted to review the financial benefits under different conditions to foresee how the economic benefit could vary.

Environmental feasibility of the proposed optimal solution is assessed based on the reduction of environmental impact in terms of water. According to ISO14040:2006, the reduction of raw water extraction and discharge of wastewater are the two key criteria considered in life cycle analysis (LCA) under environmental feasibility.

The generation of social benefits and contributions to enhance socio-economic development by participating industries through the proposed optimal solution can be considered as social feasibility. As industrial symbiosis is targeted to achieve collective advantages, the economic, social and environmental benefits can be considered at both network level and the individual entity level. If the expected benefits cannot be achieved or the proposed optimal solution is not feasible in terms of economic, environmental and social viability, “re-consideration” of the economic, social and environmental priorities of each industrial entity takes place, continuing again from Step 4 of the optimisation model development process (refer to Figure 4.1).

4.3 Chapter Summary

This chapter described the conceptual model developed for assessing the optimum water flow of industrial symbiosis and the related mathematical formulae. The optimisation model development process flow chart was initially presented consisting of four key steps. The objectives of optimisation, model constraints, key variables, model parameters and objective functions were also defined. The conceptual model was designed as a generic linear relationship between water source and water sink industries. The model functions and formulae were developed to address the optimisation problem. The chapter also described the considerations made of the assessment and selection of the optimal configuration as well as the evaluation of economic, environmental and social feasibility.

CHAPTER 5: DEVELOPMENT OF A CONTEXT-SPECIFIC MODEL (PHASE II)

5.1 Introduction

This chapter presents Phase II data collection carried out by conducting interviews with industry experts in the field of water management in Sri Lanka, data analysis and key findings derived through content analysis. Phase II was conducted to fulfil the third and fourth objectives: (i) Objective 3 - to investigate the existing methods & issues of industrial water management and enablers & barriers to initiate water exchange networks in Sri Lanka and (ii) Objective 4 – to develop a context-specific robust optimum water flow assessment model for industrial symbiosis in Sri Lanka (Objective 4). The key findings derived through content analysis are presented in two major sections, namely, Section 5.4 – Research findings: industrial water exchange in Sri Lanka and Section 5.5 – Research findings: development of a context-specific robust model to assess the optimum water flow of IS in Sri Lanka.

5.2 The Profile of Interviewees and Demographic Information

In the Phase II data collection, 16 experts with more than five years of experience in the field of industrial water management (IWM) in Sri Lanka were selected as suitable interviewees through the convenience sampling technique. The profile of interviewees is presented in Table 5.1.

Table 5.1

Profile of interviewees

Interviewee code	Designation	Field of specialisation	Years of experience
E1	Project Director	Wastewater and water treatment	20 years
E2	Researcher	Civil engineering and water management	15 years
E3	Deputy General Manager - Sewerage	Sanitary engineering	13 years
E4	Project Consultant	Waste management	10 years
E5	Manager – Compliance and Sustainability	Facilities management and sustainability	9 years
E6	Facility Manager	Facilities management	6 years
E7	Executive - Compliance	Facilities management and sustainability	5 years
E8	Assistant Manager - Compliance	Sustainability	5 years

Interviewee code	Designation	Field of specialisation	Years of experience
E9	Executive Director	Civil engineering and wastewater	30 years
E10	Senior Expert - Wastewater	Environmental science	10 years
E11	Expert - Wastewater	Wastewater treatment	8 years
E12	Mechanical Engineer	Wastewater treatment	10 years
E13	Senior Expert - Resource Efficient and Cleaner Production	Water resources management	10 years
E14	Assistant Manager - Environmental Sustainability	Environmental sustainability and facilities management	8 years
E15	Director	Civil engineering and sustainability	20 years
E16	Mechanical Engineer	Wastewater treatment	8 years

Figures 5.1 and 5.2 present the interviewees' demographic information with the purpose of providing an overview of their expertise and experience in the industrial water management field. Furthermore, this generates confidence and credibility in the research findings.

Figure 5.1

Years of experience

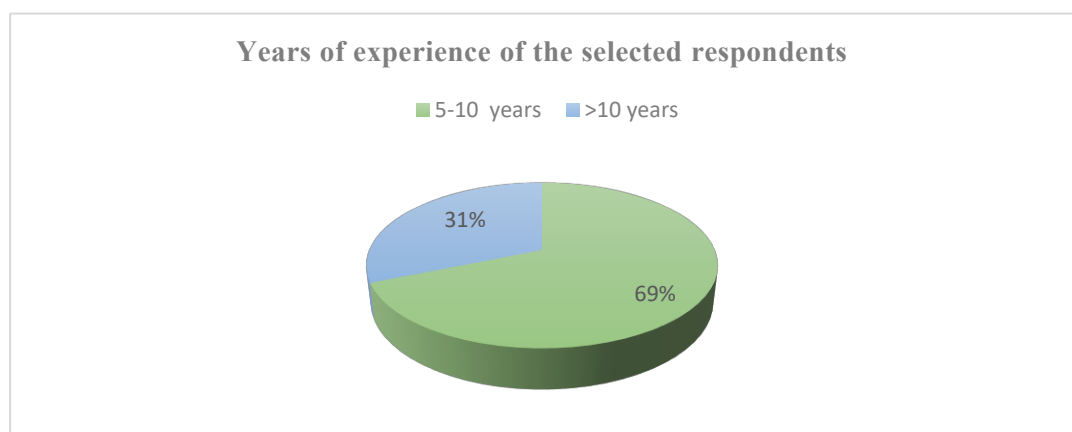
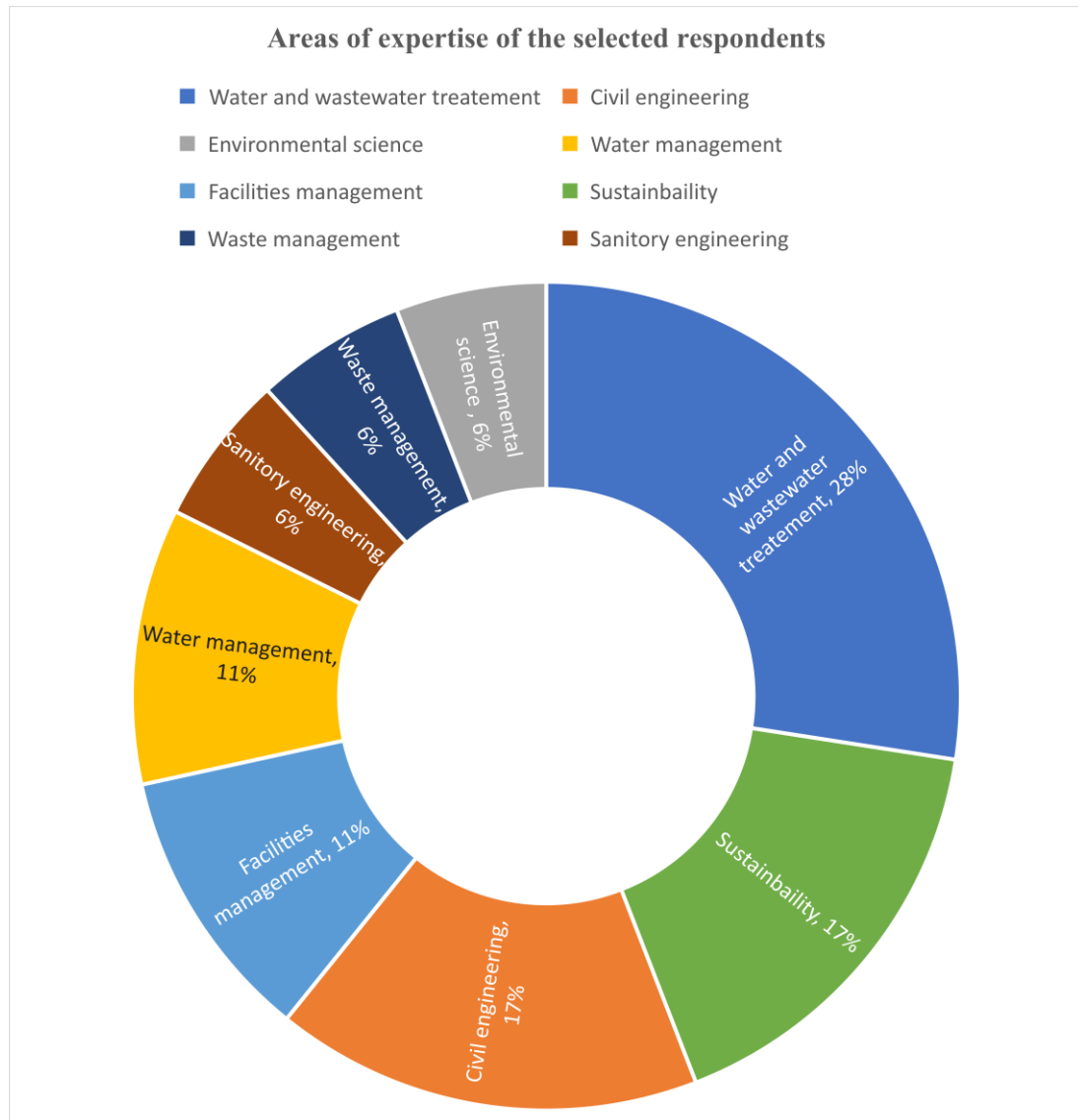


Figure 5.1 shows the years of experience of the selected interviewees in the field of industrial water management and relevant fields. As shown in Figure 5.1, 31% of interviewees had more than 10 years of experience while 69% had experience of between 5 to 10 years.

Figure 5.2 illustrates the areas of expertise of the selected interviewees in relation to industrial water management.

Figure 5.2
Areas of expertise



As shown in Figure 5.2, of the 16 selected interviewees, the highest proportion (28%) were familiarised with water and wastewater treatment. Sustainability and Civil Engineering were the equal second highest areas of expertise (17%) while Water Management and Facilities Management at 11% were the third highest area of expertise of the selected interviewees. The expertise areas of Waste Management, Environmental Science and Sanitary Engineering each comprised 6%. It is evident that the selected interviewees were in position to contribute for Phase II interviews by providing the requested information on industrial water management in Sri Lanka.

5.3 Data Collection and Analysis

Phase II data collection was carried out by conducting interviews with industry experts in the field of industrial water management in Sri Lanka. A semi-structured interview guideline, incorporating the questions to collect data related to the strategies & issues of IWM, enablers & barriers for initiating water exchange networks and context-specific modifications & enhancements of the conceptual model, was used during this phase (refer to Appendix - 1). The collected data related to the industrial water exchange in Sri Lanka were analysed by using the content analysis technique. Content analysis was used to capture imperative analysis in order to reduce data and identify concepts from the data collecting evidences. Since the purpose of Phase II analysis was to identify the strategies & issues of IWM and enablers & barriers for initiating water exchange networks, which were pre-coded into the coding structure and ‘search query’ was run by restricting the search to minimum three key words. The analysis was done manually in line with the identified codes, by reducing the impact of possible data losses. The QSR International’s NVivo.12 (Qualitative Solutions and Research Private Limited) computer software was used to conduct the content analysis. As the next stage of data analysis, the context-specific assessment model was developed and tested by using SageMath (open-source mathematical software licensed under GPL.v3).

Phase II research findings are discussed below under two sub headings, i.e., Industrial water exchange in Sri Lanka (Section 5.4) and Development of a context specific robust model to assess the optimum water flow of IS in Sri Lanka (Section 5.5).

5.4 Research Findings - Industrial Water Exchange in Sri Lanka

The demand for freshwater in industrial processes is ever increasing, while direct discharge of industrial wastewater into bodies of surface water and groundwater has created severe environmental and health issues in Sri Lanka. This section describes the findings related to methods (refer to Section 5.4.1) and issues (refer to Section 5.4.2) of industrial water management in Sri Lanka as well as the enablers for and barriers to initiating water exchange networks in Sri Lanka (refer to Section 5.4.3) based on the data collected through expert interviews.

5.4.1 Existing methods of industrial water management

During the expert interviews, the below questions were raised.

- What are the current strategies, policies and procedures applied for industrial water management in Sri Lanka?
- What are the current strategies, policies and procedures applied internally for wastewater management in industries?
- What are the existing national policies for industrial water management in Sri Lanka and their impact on industries?

Various international and national strategies and guidelines that have been implemented for industrial water and wastewater management in Sri Lanka, such as WHO's guidelines for Drinking-Water Quality, SLSI drinking water quality standards, ambient water quality standards and Water Quality Index by the Central Environmental Authority (CEA), Wastewater discharging standards by the CEA and BOI environmental norms etc., (WHO, 1993; BOI, 2011; CEA, 2019) were first identified through a comprehensive literature review (refer Section 2.6). The literature review findings were further refined and expanded through expert interviews during the Phase II of data collection. Based on the empirical findings derived through analysis, the current strategies, policies and procedures adapted to manage water and wastewater in industries were identified as discussed below.

The control made over the industries by introducing national policies and regulatory framework was one of main strategies used in industrial water management. As stated by the Project Consultant (E4):

“There were some policy attempts during previous years for the water resources and their conservation and management, such as the National Water Supply and Drainage Board (NWSDB) Act, Irrigation Act and National Environmental Act by the Central Environmental Authority (CEA), etc. Further, there is an approved National Drinking Water Policy of the Ministry of City Planning and Water Supply, which is intended to provide a framework for the water supply sector to provide safe water supply to the people of Sri Lanka”.

As further stated by the Senior Expert - Resource Efficient and Cleaner Production (E13):

“There is an Act called the Water resources Board Act No.29 of 1964 and Ground Water Extraction Gazette No:2010/23. The industries that are planning to have tube wells or dug wells for agriculture, commercial and industrial purposes, they must get an approval and a written permission from the Water Resources Board. Prior to starting drilling of tube wells, the industry must get registered”.

As described by several interviewed experts, including the Researcher (E2), Executive – Compliance (E7) and Facility Manager (E6), national/ international level industry effluent discharge standards, industry/ institutional level guidelines for water and industry level testing and monitoring of water quality are other strategies adopted.

As the Researcher (E2) stated:

“There are effluent discharge standards introduced by the CEA. Industries must follow it and maintain the quality before they release to relevant water bodies. They are also practicing certain monitoring mechanisms as well”.

Facility Manager (E6) stated:

“Board of Investment (BOI) approved company, we are following the BOI environmental guidelines. We have agreed to test and maintain the all

required quality parameters when discharging treated wastewater for inlands and for central treatment”.

As stated by Deputy General Manager – Sewerage (E3) stated, other strategies used to manage industrial water include sorting and separation of the different type of wastewater, applying water efficiency measures, setting organisational level sustainability targets, investments targeting environmental return and conducting training and awareness programs.

Deputy General Manager – Sewerage (E3) mentioned that as:

“We have asked the industries to separate the different types of wastewater from different industrial processes. They have to do a specific pre-treatment to the wastewater with effluents to take it to the domestic wastewater quality level and then they can send it for common biological treatment”.

Indeed, strategies also include adopting cost effective new technologies, industry specific pre-treatment to reduce the micro pollutants of industry effluent and providing common treatment facilities, as explained by Assistant Manager – Environment Sustainability (E14).

As the Assistant Manager - Environmental Sustainability (E14) indicated:

“In terms of water reduction, we have implemented several strategies, sensors, visual monitoring and sub metering. For example, we have internal standards for water fittings... we set targets for water reduction annually... Specially, for wastewater from the production process containing dye and other chemicals, we have lots of water initiatives to reduce water consumption. So, we have done process improvement in the dye cycle as it requires more water in each step”.

Some industries are reusing wastewater without pre-treatment for non-potable water use within the same premises while others are considering direct dumping of treated wastewater to city mains and sea outfall. One government concern is to locate similar industries within one industrial zone or park, which may enhance the efficiency of managing both solid and liquid waste.

Key findings from the analysis related to current strategies of industrial water management are summarised in Table 5.2.

Table 5.2

Summary of the methods of industrial water management in Sri Lanka

Methods		Responses by industry experts															
		E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14	E15	E16
1	Introducing national policies and regulatory framework for governing industries	X		X	X				X			X		X			X

Methods		Responses by industry experts															
		E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14	E15	E16
2	Following international level industry effluent discharge standards by industries	X	X		X			X	X	X	X			X	X	X	X
3	Adopting cost effective new technologies for wastewater treatment	X												X	X		
4	Conducting industry level testing and monitoring of water quality		X				X							X	X		
5	Providing industry specific pre-treatment to reduce micro pollutants in industry effluent			X				X	X					X	X	X	
6	Sorting and separating different types of wastewater			X				X						X	X		
7	Providing common treatment facilities within industrial parks			X				X	X					X	X	X	
8	Initiating industry/ institutional level guidelines for water management					X	X	X	X	X				X	X		
9	Industry level agreements for water management					X		X							X		
10	Reusing wastewater without pre-treatment					X	X				X			X	X		
11	Applying water efficiency measures					X							X	X	X		
12	Setting organisational level sustainability targets for managing water														X		
13	Locating similar industries within one industrial zone or park									X							
14	Direct pumping of treated wastewater to seawater outfall and city mains									X			X				
15	Initiating investments targeting environmental return														X		X
16	Conducting training and awareness programs													X	X		

In summary, national policies and a national regulatory framework for governing industries, industry effluent discharge standards for water management and locating similar industries within one industrial zone or park were identified as national-level strategies. It is noticeable that industry-level strategies were more towards improving water efficiency while reusing domestic wastewater (without pre-treatment) within individual industry premises. These strategies included industry/institutional-level guidelines for water management, industry-level agreements for water management, reuse of wastewater without pre-treatment, applying water efficiency measures, setting organisational-level sustainability targets, investments targeting environmental return and conducting training and awareness programs. Consideration was given at both national level and institutional level to maintaining the quality of treated wastewater by providing common and industry-oriented treatment facilities; however, reuse of treated wastewater had not been considered.

Therefore, adopting improved water management strategies at institutional, national and international levels was recognised as a timely need, which may effectively lower freshwater demand for industrial purposes, while reducing wastewater discharge to the environment through maximum wastewater recovery.

The concept of industrial symbiosis was recognised as an ideal concept which could be considered for the above purpose (refer to Section 2.2.4). IS facilitates the engagement of co-located industries to exchange wastewater in a circular way without discharging it to the environment, while obtaining a collective economic and environmental return. However, as revealed through analysis, these strategies are less practised in Sri Lankan industry. Various issues of industrial water management (IWM) were therefore recognised by the interviewed experts.

5.4.2 Existing issues of industrial water management

Data in relation to IWM issues were collected and analysed, based on responses to the following questions:

- What are the issues in obtaining and utilising freshwater in industries?
- What are the issues in current practice related to industrial water management (IWM)?
- What are the issues in current practice related to wastewater treatment and disposal in industries?

As derived from the study's analysis, industries are one of the major consumers of freshwater as well as major polluters of water bodies. The pollution of bodies of surface water and groundwater due to industrial activities has created severe health and sanitation issues in Sri Lanka. Accordingly, 19 IWM issues in Sri Lanka were derived through analysis, as summarised in Table 5.3.

Table 5.3*Summary of the issues of industrial water management in Sri Lanka*

Issues		Responses by industry experts															
		E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14	E15	E16
1	Unavailability of a national water policy for governing water extraction and use	X		X	X												
2	Unawareness of industries about modern water treatment technologies	X										X	X				
3	Less economic value for water due to outdated tariff	X															
4	Difficulty in achieving required water quality through treatment by industries	X		X				X		X							
5	Impact of improper industrial pre-treatment on the water quality of central treatment	X		X													
6	Operational inefficiencies in central treatment, such as less water supply inputs, inefficient daily collection of wastewater, etc.	X		X				X									
7	Unavailability of company level budgeting and funding for water management	X									X						
8	Ignorance by industries for following national and international guidelines and standards	X			X						X	X	X	X			X

Issues		Responses by industry experts															
		E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14	E15	E16
9	Heavy extraction of raw water for industrial needs		X														
10	Difficulties faced in discharging wastewater concentration, such as proper location, expected quality etc.		X							X							
11	Unavailability of a contingency plan for facing sudden failures of wastewater discharging and treatment facilities		X			X		X	X								
12	Unavailability of a formal or adequate water allocation system within the country		X	X	X									X			
13	Use of freshwater bodies and sea outfall as industrial effluent discharging points				X					X	X			X			X
14	Surface and ground water pollution due to illegal effluent discharge by industries					X	X				X			X			
15	High cost of wastewater treatment									X	X						
16	Insufficient capacity of existing treatment facilities							X		X							
17	Lack of monitoring on industries in water management											X					
18	Less use of alternative water sources														X		
19	Cultural and poor attitude of industries towards the reuse of water															X	

As stated by several interviewed experts, ignorance by industries for following national and international guidelines and standards can be identified as one main IWM issue in Sri Lanka. It is mentioned by Deputy General Manager - Sewerage (E3) as:

Even though we have introduced certain standards and policies both at national and zone level, the main issue that we have faced is a less consideration given by individual industries for discharging wastewater as per the set standards”.

The unavailability of an explicit national water policy can be identified as one main IWM issue in Sri Lanka. Furthermore, owing to the lack of such a policy, industries have been led towards heavy extraction and misuse of raw water for industrial purposes.

It is stated by the Project Consultant (E4) as:

“Up to now there is no explicit water policy on water uses, such as industrial, recreational, environmental or hydropower. Further, there is no formal or adequate water allocation system in the country”.

The less consideration is given on using the alternative water sources to fulfil industrial needs is identified as another issue. The lower economical value of water due to outdated tariff is another issue as stated by the Project Director (E1):

“NWSDB [National Water Supply and Drainage Board] provides water to industries [at] around 70 LKR [Sri Lankan rupees] to 1m³. That is the charge for water. We are spending around 150 LKR per 1m³ [in] production itself and around 200 LKR per 1m³ as the pumping cost. However, the tariff has not been revised after 2014”.

The use of freshwater bodies and sea outfall as discharge points for industrial effluent and surface water and ground water pollution due to illegal effluent discharge were also identified as other issues in industrial water management. It is further proved by the Project Consultant (E4) as:

“... in practice, how many industries are operating near riverbanks? Kelani riverbank is a very good example. A few of industries are obtaining EPL annually while other industries are discharging wastewater directly to the river. So, as I think, freshwater bodies or the sea outfall should not be considered as discharge points for industrial effluent. There should be sound strategies to reduce the pollution”.

Furthermore, inappropriate site location of high-water consuming industries and the unavailability of a formal or adequate water allocation system within the country are other major issues related to IWM in Sri Lanka (E3, E2).

The Deputy General Manager - Sewerage (E3) proved that as:

“Siting of industries has become a big issue for us. For example, there are different types of industries, such as type A and type B category. Type A is a high polluting category. We must have a Cabinet decision if type A industries are located upstream of our drinking water sources due to micro pollutants.

However, some type A industries are already located upstream. We cannot relocate them, but we have asked them to relocate their industries in five years' time preferably in a suitable location”.

As the Researcher (E2) stated:

“Some industries are using both ground water and freshwater supply for their industrial purposes... it will result in lowering of the ground water table in surrounding areas. However, they are not considering about alternative water sources, such as onsite treated wastewater and offsite water sources”.

The unavailability of company-level budgeting and funding for water management was recognised as an institutional level issue. It is stated by the Project Director (E1) as:

“Organisations do not consider wastewater as their own responsibility. So, they do not have a company budget for wastewater treatment and discharge. Also, industries do not have a good attitude in investing money for wastewater treatment even though they spend more money for other organisational tasks”.

The Senior Expert - Resource Efficient and Cleaner Production (E13) supported that as:

“There are many issues due to improper location of some industries near rivers and in upstream. There are 7,000 factories located on the banks of the river. Out of that, only 3,000 factories have obtained certain environmental approvals. About 4,000 factories on the riverbanks are operating without having proper environmental approvals”.

Thus, other IWM issues include, industries not following national guidelines and standards, and improper pre-treatment by industries. Furthermore, the operational inefficiencies in central treatment, discharging issues of wastewater concentration, unavailability of a contingency plan for facing sudden failures of wastewater discharging facilities, and the high cost and insufficient capacity of existing treatment facilities have created a severe burden on industrial water management.

As the Executive Director (E9) further stated:

“The main issue is wastewater treatment. Existing capacity is not sufficient and so, it is too expensive to go for expansions. Discharging treated wastewater has made problems for drinking water. Even though we treated to some certain standard, there is a cumulative effect”.

A critical issue identified was achieving and maintaining the quality of water. Industries are facing difficulties in maintaining the required quality of wastewater with existing treatment technologies (E7, E1). However, unawareness of industries about modern technologies as well as cultural and poor attitudes of industries has hindered the use of efficient and modern treatment technologies.

The Executive - Compliance (E7) stated that as:

“Maintaining the required quality of wastewater is an issue with existing treatment facilities. Sometimes, the common plant does not accept the water as it does not have the required quality. ... we are facing issues when central treatment faces sudden failures”.

The Project Director (E1) also indicated that:

“I think in the Sri Lankan context, people are not aware about the treatment technologies available in the world. It is a big gap. Even experts in wastewater management field have no concern on getting an experience in treatment technologies available in other countries... European countries are using technologies to treat 100% of wastewater and they have a culture of treating and reusing treated wastewater. But in the Sri Lankan context, we could not find that culture”.

Most identified issues related to the lack of wastewater treatment technologies, and the operational inefficiencies of wastewater treatment as well as the difficulty of and ignorance about maintaining the quality of treated wastewater. Furthermore, all treated wastewater, which is discharged in a linear way has created a severe burden on freshwater availability.

Therefore, it is important to develop a method to reuse industrial wastewater among industrial entities to reduce freshwater consumption and wastewater discharge by industries in Sri Lanka. The concept of IS is recognised as an ideal model for initiating the water exchange networks in Sri Lanka as it aims to improve the business and environmental performance of industries through resource efficiency improvements. As stated by the Deputy General Manager - Sewerage (E3) and the Project Director (E4), Free Trade Zones (FTZs) or Export Processing Zones (EPZs) in Sri Lanka offer great potential for such closed-loop industrial systems. Further, Project Director (E4) stated that both new developments as well as existing or obsolete industrial sites can be transformed into an eco-industrial nature. Hence, the co-located industries in EPZs could become industrial clusters by moving them towards a new stage of environmental upgrading, becoming an eco-industrial park. Accordingly, the existing environmental degradation of EPZs due to elevated freshwater utilisation can be overcome through proposed water exchange.

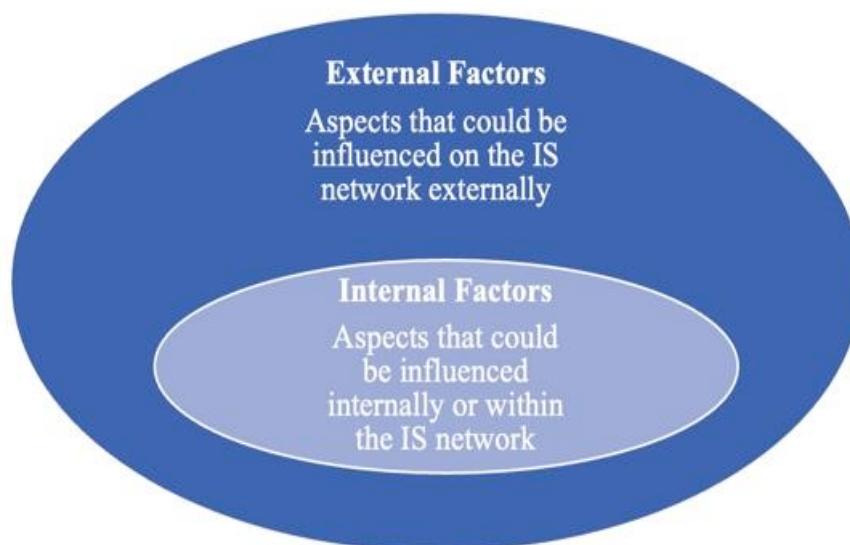
Since industrial symbiosis is a new concept to Sri Lanka, the enablers for and barriers to initiating water exchange networks in Sri Lanka were identified in the current study through Phase II data analysis. These findings are presented in the next section.

5.4.3 Enablers and barriers to initiate water exchange networks in Sri Lanka

As key findings revealed through analysis, various enablers and barriers for initiating water exchange networks between industries in Sri Lanka were identified under two major categories, that is internal and external factors, as specified in Figure 5.3.

Figure 5.3

Key categories of enablers and barriers (author defined)



The identified enablers for initiating water exchange networks are described below.

5.4.3.1 Enablers for initiating water exchange networks in Sri Lanka

As derived through analysis, 7 enablers were identified as shown in Figure 5.4.

Figure 5.4

Enablers for exchanging water among the industries in Sri Lanka

Name	Files	Refer...
> ● Barriers for exchanging water among the industries	0	0
∨ ● Potentials for exchanging water among the industries	0	0
● Existing infrastructure and facilities	3	3
● Existing national policies for water management	4	4
● Industries governing under one ownership	3	3
● Industries located within the same geographical proximity	6	6
● Industry level water management initiatives	6	6
● Technologies available to use for water treatment	4	5
● Willingness of industries to engage in water exchange initiatives	7	7

According to the analysis, the willingness of industries to engage in water exchange initiatives was identified as having a significant potential in Sri Lanka by adopting the IS concept. Furthermore, the motivation of industries to invest in water management initiatives by considering the environmental return is a significant way forward, which could be further promoted through government incentives and assistance.

This was indicated by the Deputy General Manager - Sewerage (E3) as:

“If industries are willing to use the treated wastewater for their industrial needs, we can supply it with a reduced price lower than the pipe borne water”.

The existing national environmental policies and regulations for environmental management, including water management that are motivating industries towards reuse of water were a good sign toward reducing industrial demand for freshwater.

As stated by the Project Director (E1):

“In the near future, we may refine the existing policy to protect the catchment areas and ground water. Then industries cannot discharge water to the environment, and they must find their own way to reuse it. Empowering the policies to motivate the industries is the requirement...”.

The Deputy General Manager -Sewerage (E3) also mentioned that:

“There is a regulatory requirement in the country for industry specific pre-treatment of wastewater prior to discharging it to inland waterbodies. However, it has also been limited by new environmental and climate change adaptation policies and regulations enacted to protect the marine and groundwater tables and to reduce several health issues including chronic kidney disease (CKD), etc., Also, many new policies will be coming into practice in the near future for promoting the industries to reuse wastewater, which may reduce the unnecessary extraction of freshwater and the linear discharge of industry effluent”.

As mentioned by the Researcher (E2), existing infrastructure and facilities including common treatment and pipe networks as well as the technologies available to use for pre-treatment and central treatment of industrial effluent within the industrial parks are having a good potential to initiate water exchange networks between industries where it can be further improved through government and institutional financial support.

As reinforced by the Expert - Wastewater (E11):

“We have treatment facilities, pipe networks etc. within the zone. So, we can use the existing facilities to initiate this kind of a system to reduce the direct discharge of wastewater”.

Further, industrial zone is an ideal environment to initiate the water exchanges where it is convenient to identify the possible synergies between industries, which have been located within the same geographical proximity.

It is highlighted by the Deputy General Manager - Sewerage (E3) as:

“Since we have all required facilities and infrastructure within one geographical location, industrial zones are ideal for initiating water and other resource exchange networks. Specifically, factories are located close to each other, which may reduce the cost for transporting water and for laying pipe networks”.

The selection of industries, all of which are governed under one ownership, is another potential for initiating water exchange networks between industries.

As the Assistant Manager - Environmental Sustainability (E14) stated:

“I think we can even start this concept within our factories under one ownership. It will be the best way to begin this new strategy as it is manageable with the same ownership of industries”.

In summary, industries located within the same geographical proximity, the willingness of industries to engage in water exchange, industry level water management initiatives and industries governing under one ownership, existing national policies for water management, technology available to use for water treatment and existing infrastructure & facilities were encountered as key enablers for initiating water exchange networks in Sri Lanka.

5.4.3.2 Barriers to initiating water exchange networks in Sri Lanka

As initiating IS-based water exchange networks is new to Sri Lanka, the country is facing various barriers in initiating water exchange networks between industries. As derived from the analysis, 12 barriers to initiating water exchange networks in Sri Lanka were recognised, as shown in Figure 5.5.

Figure 5.5

Barriers for exchanging water among the industries in Sri Lanka

Name	Files	Refer...
Barriers for exchanging water among the industries	0	0
Cultural impact of the industrial organisations towards water reuse	2	2
Difficulty in synchronising synergies from different types of industries	4	4
Expected water quality for industrial needs	9	11
Isolated industries situated in different geographical boundaries	1	1
Lack of expertise and awareness	5	7
lack of government incentives and financial assistance for industries	3	3
Lack of legal provisions for reuse of water	3	3
Less investment on water management by the industries	4	5
Less reusable quantity of water available for the exchange	2	2
Non-operational infrastructure	3	4
Outdated technologies use in water treatment	9	10
Unavailability of proper discharging strategies for reject water	3	3

As shown in Figure 5.5, the interviewed experts highlighted lack of expected water quality as a major aspect that needs to be considered in implementing water exchange between industries.

This was stated by the Executive Director (E9) as:

“Industries expect water with potable water quality standards for their industrial processes. This is because colour and odour are very sensitive as they can affect the quality of products. So, water quality is a critical factor for exchanging water among the industries to use for their production purposes”

This was further explained by the Assistant Manager - Environmental Sustainability (E14) as:

Fabric dyeing is a critical aspect in our textile manufacturing process. If the quality of water is less or if we cannot obtain the expected water quality, it can interfere with fabric dye and could cause colour changes to result.

Furthermore, the non-operational existing infrastructure is another barrier as stated by the Mechanical Engineer (E12):

“Even though we can initiate this with the existing infrastructure, it can be an issue in the long term as the Sri Lankan industrial parks are still suffering from outdated technology and non-operational infrastructure including the pipe network”.

Moreover, industries are suffering from outdated technologies used in water treatment and the lack of expertise in and awareness of initiating new water management initiatives, especially the concept of IS.

This was proved by the Assistant Manager-Compliance (E8) as:

“First, industries should be aware about these modern concepts... otherwise, they will use the older strategies and technologies even in the future. Therefore, outdated technology is a major barrier. It is required to have new technology in treating wastewater that will help to reduce the cost of treatment. Also, they do not have expertise and knowledge regarding this novel concept, so lack of expertise is another matter. It is important to obtain the expertise in this field even by observing similar projects in other countries”.

The latter point was emphasised by the Senior Expert - Wastewater (E10) as:

“... industries are not aware about the concept as well as they could not continue their synergies, because they don't have experts to do any prior evaluations and analysis”.

Also, the Project Director (E1) indicated that:

“Industries do not have a proper attitude to investing money for wastewater treatment even though they spend more money for some other tasks of the organisation. Definitely they can go for reusing water, but they are not doing it because they can obtain water at a very low rate”.

Consequently, the poor attitude and low interest of industries toward engagement in water management initiatives and the cultural impact of the organisation regarding the reuse of wastewater were identified as other barriers. As stated by the interviewed

experts in the field, many industries expect an economic return rather than considering the environmental return; thus, they invest less in water management projects.

This was mentioned by the Project Consultant (E4) as:

“Only very few industries have this reusing culture. Others just think about the economic gain only. The industries do not prefer to invest in those initiatives if you cannot show them the financial return. So, it is a very difficult task to initiate these kinds of programs in Sri Lanka. As I think, those initiatives should come from the policy level. Then the industries must follow those provisions; otherwise, it is illegal. Industries are afraid to pay fines and of the cancellation of their industrial activities, so they will effectively engage”.

In addition, both the Senior Expert - Wastewater (E10) and the Assistant Manager - Environmental Sustainability (E14) reported that the lack of government incentives and financial assistance for industries has hindered industries’ willingness to engage in water management initiatives.

As stated by the Senior Expert - Wastewater (E10):

“Earlier we had a workshop for industrial professionals to introduce this concept. They showed a willingness to engage in this. However, the programme was not continued since no funding was taking place. Even if the government can give a financial assistance for those who are willing to engage in water management initiatives, that would be really good. It is lacking in the present context”.

Furthermore, other barriers that could affect the water exchange network were identified as the unavailability of appropriate discharging strategies for reject water generated from industrial water treatment projects and a lower reusable quantity of water available for exchange.

This was stated by the Deputy General Manager – Sewerage (E3) as:

“The issue will be managing the reject water. When doing the Reverse Osmosis (RO) treatment, 40-50% is reject water. You cannot just discharge it to the environment as it contains more pollutants”.

Furthermore, the difficulties in initiating water network between the isolated industries situated in different locations and the difficulties face in synchronising water synergies from different types of industrial entities were identified as some other barriers for exchanging water between industries.

This was mentioned by the Assistant Manager - Environmental Sustainability (E14) as:

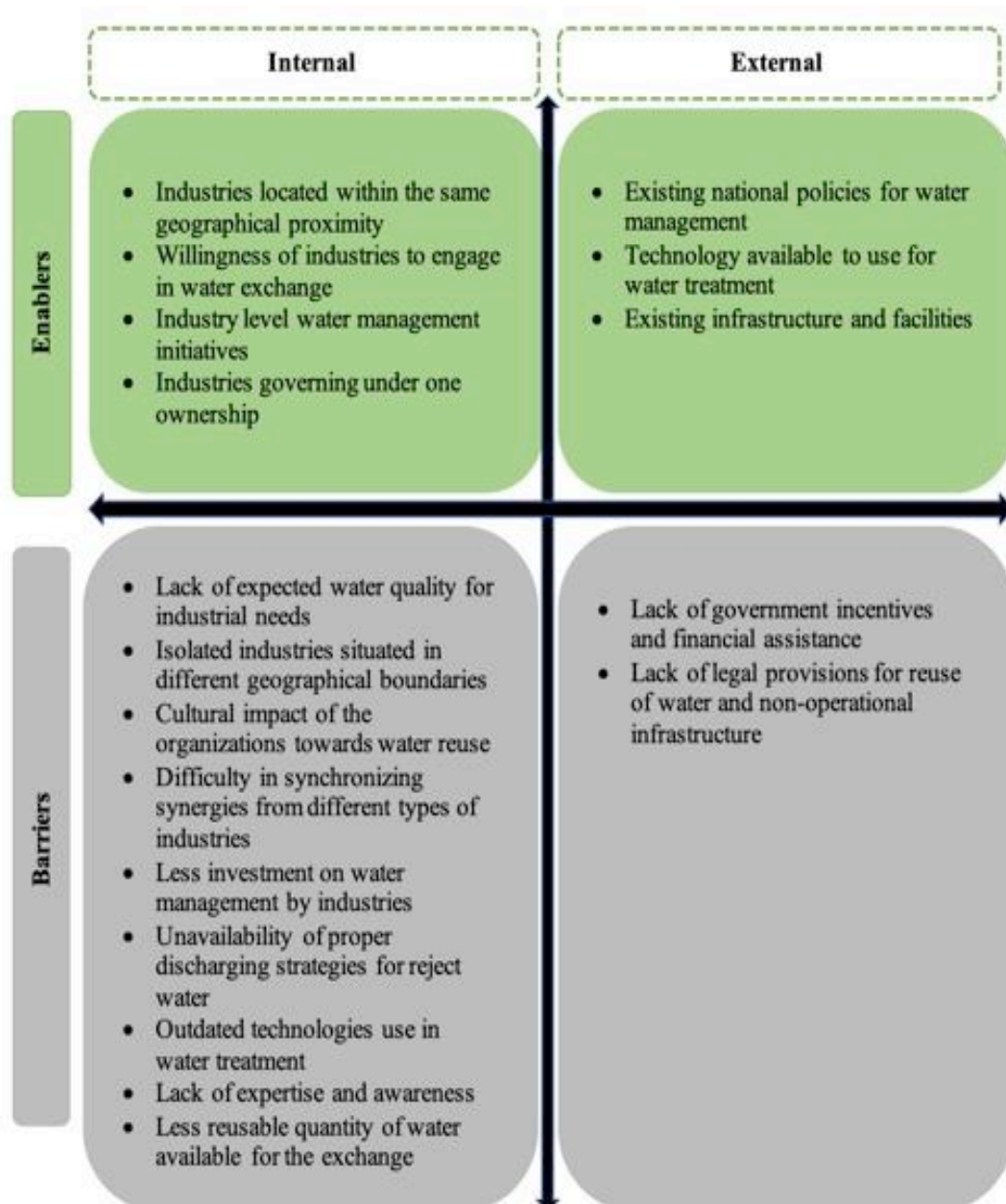
“There is a huge possibility to implement this strategy in industrial parks because the factories are closely located. If the factories are in isolation, reuse is possible only within the same premises”.

Among identified barriers, the lack of expected water quality for industrial needs, outdated technologies used in industrial water management and the lack of expertise and awareness were identified as major barriers that need to be considered in initiating water exchange networks between industries.

Accordingly, the identified enablers and barriers were synthesised under two main codes namely, “internal” and “external” as shown in Figure 5.6.

Figure 5.6

Enablers and barriers for initiating water exchange networks



As shown in Figure 5.6, internal enablers that are supporting the process of initiating water exchange networks in Sri Lanka were identified as industries located within the same geographical proximity, the willingness of industries to engage in water

exchange, industry level water management initiatives and industries governing under one ownership, while external enablers were identified as existing national policies for water management, technology available to use for water treatment and existing infrastructure & facilities were encountered as external enablers that need to be considered in assuring the collective engagement of industries in IS.

Internal barriers that need to be urgently addressed in the process of initiating water exchange networks in Sri Lanka were identified as the lack of expected water quality for industrial needs, isolated industries situated in different geographical boundaries, cultural impact of the organisations towards water reuse, difficulty in synchronising synergies from different types of industries, less investment on water management by industries, unavailability of proper discharging strategies for reject water, outdated technologies use in water treatment, lack of expertise and awareness and less reusable quantity of water available for the exchange. The external barriers were lack of government incentives & financial assistance, lack of legal provisions for reuse of water and non-operational infrastructure.

The identified enablers can be further enriched while taking actions for overcoming the identified barriers for initiating treated wastewater exchange networks in Sri Lanka. As it encourages maximum contribution of all capable industries located within EPZs, this research considered developing a model to assess optimum water flow of IS in Sri Lanka as a way forward for obtaining optimum socio-economic and environmental benefits through eco-industrial development.

5.5 Research Findings - Development of a Context-Specific Robust Model to Assess the Optimum Water Flow of IS in Sri Lanka

As a key outcome derived through the Phase II data collection and analysis, the current study developed a context-specific robust model to assess the optimum water flow of IS in Sri Lanka. The key variables of the developed conceptual model were refined specifically for the selected context.

Hence, the data collected from the interviewed industry experts in Sri Lanka in relation to the following questions, were analysed to identify the specific requirements and enhancements of the optimum water flow assessment model especially in the context of Sri Lanka.

- How do industries obtain freshwater (water sources)?
- How do industries measure the current freshwater consumption from the above sources?
- What are the existing techniques used by the industries to measure and record the discharge and reuse of wastewater?
- What are the water quality parameters currently applied by industries for (i) the use of freshwater, (ii) the use of treated wastewater; and (iii) wastewater discharge?

The context-specific enhancements of the developed model are described below.

5.5.1 Context-specific model requirements and enhancements of the conceptual model

The conceptual model developed in Chapter 4 was further evaluated and the key variables and parameters of the model were refined during the Phase II to identify context-specific model requirements and enhancements. The identified model requirements and enhancements are summarised in Table 5.4.

Table 5.4

Comparison of the model requirements and enhancements: Conceptual vs context specific models

Model functions	Optimum water flow assessment model (conceptual)		Optimum water flow assessment model (context specific)
Variables	Freshwater utilised by water sink	• Freshwater from surface water sources (lakes)	• N/A
		• Freshwater from city water supply	• Freshwater from city water supply
			• Freshwater from groundwater sources (tube wells)
	Treated wastewater from water source to water sink	• Treated wastewater direct supply (mostly untreated)	• N/A
		• Indirect supply through central treatment (water loss during wastewater treatment and transmission is negligible)	• Treated wastewater supply through central treatment (5% of water loss with the removal of sludge is considered)
	Wastewater generated by water source	• Wastewater collected from households at city level (city wastewater)	• N/A
		• Wastewater with sewerage	• Wastewater with sewerage
• Industry effluent		• Industry effluent	
		• Domestic wastewater (kitchen water, etc.)	
Constraints	Water quality	• Multiple quality parameters by setting the maximum allowable quality limits	• Multiple quality parameters by setting the maximum allowable quality limits
	Water balance at sink		Water balance at sink
	Water balance at source		Water balance at source
	Each entity in the network may go through pre-treatment thus resulting in single inlet and outlet streams.		Each entity in the network may go through central treatment thus resulting in single inlet and outlet streams.
Parameters	Number of water sources and sinks		Number of water sources and sinks
	Number of quality contaminants		Number of water quality parameters
	Types of quality contaminants	<ul style="list-style-type: none"> • TOC • COD • TDS • BOD • Hardness 	<ul style="list-style-type: none"> • BOD • COD • TSS

Notes. BOD = biological oxygen demand; COD = chemical oxygen demand; TDS = total dissolved solids; TOC = total organic carbon; TSS = total suspended solids

The requirements and enhancements of the context specific model shown in Table are described in detail below.

5.5.2 Key variables of the context-specific model

The key variables of the conceptual model namely, freshwater utilised by water sink, wastewater generated by water source and treated wastewater from water source to water sink are further refined based on the status of industry applications in Sri Lanka.

Freshwater utilised by water sink (modified)

In the conceptual model (refer to Section 4.2.3.7), ‘freshwater utilised by water sink’ is calculated by two factors: ‘freshwater from surface water sources (lakes, etc.)’ and ‘freshwater from city water mains.’

As per the findings from Phase II data analysis, in Sri Lanka, freshwater is supplied to industries by many sources. As stated by the Executive Director (E9) and the Deputy General Manager – Sewerage (E3), industries in ETZs of Sri Lanka obtain freshwater mainly from two sources: ground water sources (tube wells) and the city water supply. Hence, freshwater utilised by the water sink (Eq. 1) is amended in the context specific model as shown in Eq. 10.

$$\begin{aligned} & \textit{Freshwater utilised by water sink (modified)} && \dots\dots \text{(Eq. 10)} \\ & = \textit{Freshwater from ground water sources (tube wells, etc.)} \\ & + \textit{Freshwater from city water supply} \end{aligned}$$

Wastewater generated by water source (modified)

In the proposed conceptual model (refer to Section 4.2.3.7), the calculation of ‘wastewater generated by water source’ is equal to the sum of ‘city wastewater’, ‘wastewater with sewerage’ and ‘wastewater from manufacturing processes (industry effluent)’.

According to the empirical findings of the Phase I data analysis, industries in Sri Lanka generate wastewater mainly from three major sources.

As specified by the Manager – Compliance and Sustainability (E5), domestic wastewater generated (wastewater from household activities such as wastewater from kitchen, cafeterias and washing, etc.) is a main source that generates wastewater within industrial premises. Assistant Manager - Environmental Sustainability (E14) stated that industry effluent and wastewater with sewerage are other major sources that generate wastewater. Accordingly, ‘wastewater generated by water source’ equation shown in Eq. 2 is amended in the context-specific model as shown below in Eq. 11.

$$\begin{aligned} & \textit{Wastewater generated by water source (modified)} && \dots\dots \text{(Eq. 11)} \\ & = \textit{Domestic wastewater (wastewater from kitchen, etc.)} \\ & + \textit{Wastewater with sewerage} + \textit{Industry effluent} \end{aligned}$$

In calculating the flow rate of wastewater generation by water source, it is assumed that the wastewater generation is 80% from the total freshwater consumption of the industry, as per the industry norms established by the Board of Investment of Sri Lanka (BOI, 2011).

Treated wastewater from water source to water sink (modified)

In the conceptual model presented in Section 4.2.3.7, ‘treated wastewater from water source to water sink’ is calculated by using the factors: ‘treated wastewater direct supply from industries’ and ‘indirect supply through central treatment’ (Eq. 3).

According to the findings derived from the Phase II data analysis, industries are not currently engaged in treated wastewater sharing initiatives, with wastewater being treated for discharge to the recommended downstream water bodies and to the sea outfall at a 1:8 dilution (Deputy General Manager – Sewerage - E3). As stated by the Manager – Compliance and Sustainability (E5), industry effluent is screened through pre-treatment to remove solid particles and then sent it for common wastewater treatment (CWWT), while domestic wastewater and wastewater with sewerage are directly pumped for central treatment which undertakes the appropriate treatment complying with national level wastewater discharge standards. Considering existing industry practices, the loss of water due to evaporation during wastewater treatment is considered negligible in the current process as of the mass removal of contaminants concentration. However, as specified in Section IV of the particular specification published by NSWDB (n.d.), the maximum water loss from the water treatment plant through removal of sludge was 5% of the treated water output. Hence, 5% of water loss with the removal of sludge was considered and deducted from the outlet flow rates of treated wastewater as shown in Eq. 12. The wastewater treated by each industry (water sources) through CWWT is considered for sharing with other industries (water sinks) matching this with the water demand.

Accordingly, the treated wastewater that can be transferred from water source to water sink is assumed and calculated by using Eq. 12 by modifying the Eq. 3.

$$\begin{aligned}
 & \textit{Treated wastewater from source to sink (modified)} \quad \dots\dots \text{(Eq. 12)} \\
 & = \textit{Treated wastewater supply through CWWT} \\
 & - \textit{5\% water loss}
 \end{aligned}$$

5.5.3 Parameters of the context-specific model

The key parameters of the proposed conceptual model (refer to Section 4.2.3.7), that is, water sources and water sinks, and number and types of water quality parameters, were also refined as per the context-specific industry applications.

Number of water sources and water sinks

As with the conceptual model developed, the number of water source and sink industrial entities are considered as per the theory proposed by Chertow (2000).

Satisfying the criteria given in conceptual model for selecting industrial entities for water exchange networks (refer to Figure 4.6), a minimum of three (03) industrial entities in an industrial zone in Sri Lanka are selected as shown in Table 5.5.

Table 5.5

Selection of water sources and water sinks in Sri Lankan context

Criteria	Description
Geographical proximity	Industrial entities located within the same export processing zone (EPZ) were selected.
Likelihood of exchanging water	Industrial entities, which showed a likelihood of exchanging wastewater were considered.
Satisfied water quality tolerance limit	Industries satisfying the water quality tolerance limits introduced by CEA (upper limit) were selected.
Availability of water transferring connections between industrial entities	The selected industries who are willing to invest for setting the water transferring connections with other industries were selected since no water could be transferred if no connections existed.

Number and types of water quality parameters

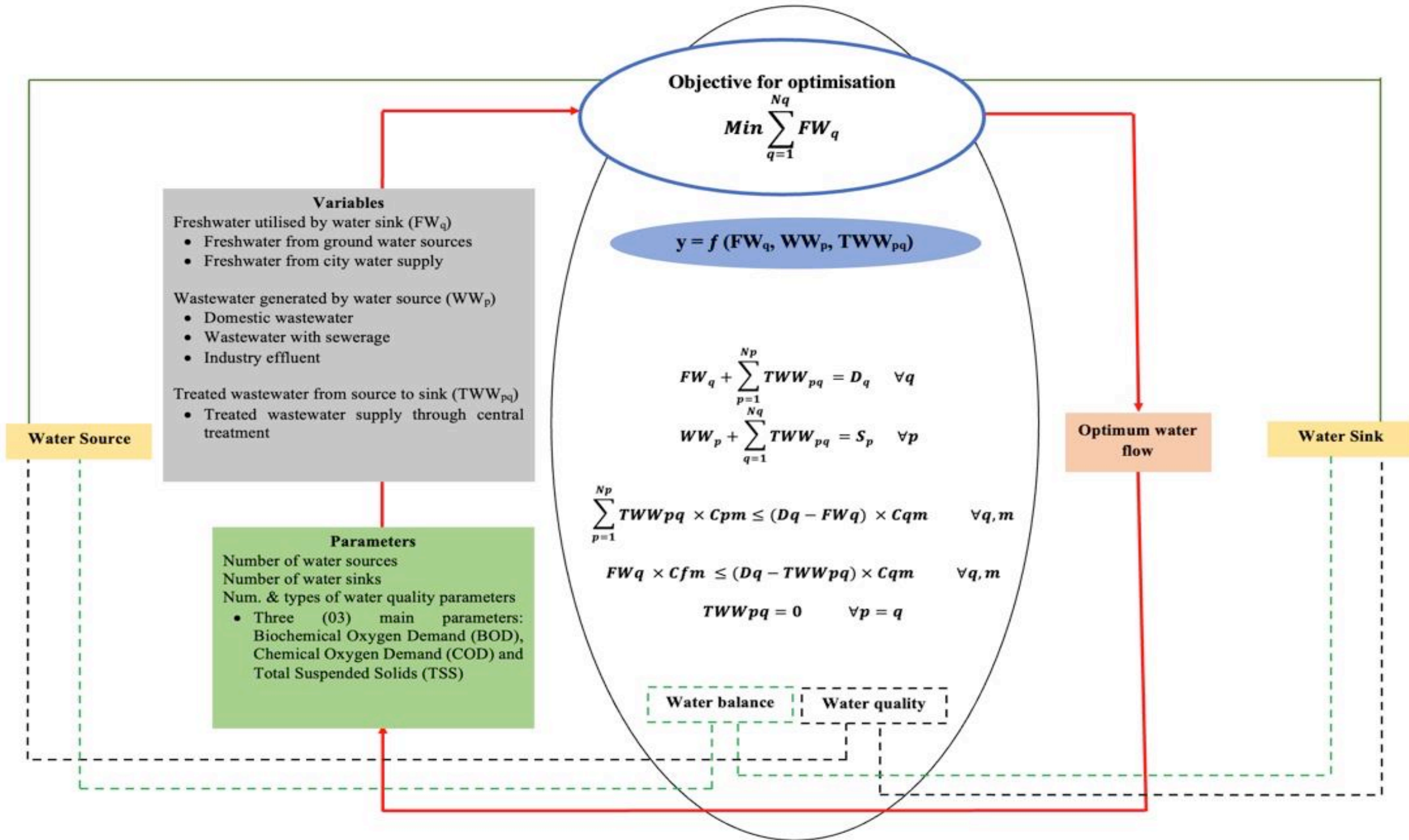
In the context specific model, the number and types of water quality parameters were selected by referring to the national environmental regulations and norms enacted by National Environmental Act, Water Resources Board Act, No. 29 of 1964, the Gazette of the Democratic Socialist Republic of Sri Lanka, the Ambient Water Quality Standard and Water Index by the Central Environmental Authority (CEA) and Board of Investment (BOI) of Sri Lanka.

As drinking water quality standard has become a requisite for supplying water for industries in Sri Lanka (BOI, 2011), this is considered as the maximum allowable quality limit for fresh water inputs from water sources to water sinks. Further, water quality of treated wastewater inputs will also be considered as per the industrial entity requirements. Furthermore, by considering the present monitoring procedure of industries and regulatory requirements enforced by CEA, as well as the industry's expected water quality requirements, the quality parameter of the context-specific model was limited to three (03) main parameters: biochemical oxygen demand (BOD), chemical oxygen demand (COD) and total suspended solid (TSS) of water.

5.5.4 Context-specific model development and testing

Based on the context-specific requirements and enhancements defined, the context-specific robust optimum water flow assessment model for industrial symbiosis in Sri Lanka was developed as presented in Figure 5.7.

Figure 5.7
Context-specific model to assess the optimum water flow of industrial symbiosis in Sri Lanka



As shown in Figure 5.7, mathematical formulae of the conceptual model remained without changing them while variables of the context-specific model were refined. Furthermore, model parameters were set to the selected context of Sri Lanka. Accordingly, SageMath (open-source mathematical software licensed under GPL.v3) was used to develop the model and relevant coding. The MILP approach was used for finding the optimal value of the targeted objective. A successful test run was achieved by feeding hypothetical data (refer to Appendix - 3). The applicability and feasibility of the context specific model was then evaluated through the Phase III data collection and analysis, which is presented in Chapter 6.

5.6 Chapter Summary

This chapter presented the Phase II data analysis and the key findings derived through content analysis. Phase II is related to the interviews conducted with industry experts in the field of industrial water management (IWM) in Sri Lanka. The key findings from content analysis comprised recognition of current issues and strategies of IWM in Sri Lanka. Major IWM issues identified included difficulty in achieving required water quality and use of freshwater bodies & sea outfall as industrial effluent discharging points. Current strategies of IWM in Sri Lanka included introducing national policies and a national regulatory framework for governing industries, industries following international level industry effluent discharge standards by industries, providing industry specific pre-treatment to reduce the micro pollutants of industry effluent, providing common treatment facilities within industrial parks and initiating industry/ institutional level guidelines for water management. Furthermore, internal and external enablers and barriers to initiating water exchange between industries in Sri Lanka were also recognised. A key outcome derived from analysis was determination of the context-specific requirements and enhancements of the model variables and parameters. The context-specific model to assess the optimum water flow of IS in Sri Lanka was finally developed and tested by using SageMath computer software with the use of hypothetical data. The next chapter presents the key findings derived through the Phase III case study data analysis focusing on the application of the developed model to an industrial zone in Sri Lanka.

CHAPTER 6: EVALUATION OF THE APPLICABILITY AND FEASIBILITY OF THE CONTEXT SPECIFIC MODEL (PHASE III)

6.1 Introduction

This chapter presents the research findings of Phase III data collection and analysis, which was conducted to evaluate the applicability of the developed context-specific robust optimum water flow assessment model in an industrial zone in Sri Lanka. The procedures and methods adapted in model evaluation and case study selection and their justification are initially described. The analysis and findings related to the evaluation of applicability and feasibility of the developed model are then presented by following the key steps of the general procedure of initiating IS networks. Accordingly, a life cycle cost analysis (LCCA) was undertaken by providing evidence of the long-term economic benefits of the optimal water exchange network, which was initiated and evaluated in the selected context. Environmental and social benefits were determined through analysis, thus assisting the decision-making process of the participating industries. The chapter concludes with an explanation of the model's uniqueness and generalisability.

6.2 Procedure Adapted in Model Evaluation

Phase III of this study involved evaluating the applicability of the developed context-specific robust optimum water flow assessment model (refer to Figure 5.7). The case study was selected as the most suitable approach for applying the developed model in an IS concept adopted environment. Hence, IS network of an export processing zone (EPZ) in Sri Lanka was selected as a suitable case study to evaluate the applicability and feasibility of the developed model. Then, the possible water synergies between industrial entities were planned. Accordingly, the developed context specific model was used to a pre-evaluate the proposed water exchange network in order to assess the optimum water flow, as described in following sections respectively.

6.3 Industrial Symbiosis Network of an Export Processing Zone in Sri Lanka: The Case Study

The selected export processing zone (EPZ) is located in Western Province. It has a total land area of 450.95 acres of which 259.52 acres have been allocated to the industrial area. The EPZ employs around 25,661 workers and hosts 57 enterprises mainly in the apparel, rubber manufacturing, electronics, granite and marble, security printing, and water sports goods manufacturing sectors. The zone has been recognised as Sri Lanka's only industrial estate designed to accommodate high polluting-type industries. Specifically, of the 52 industries located in Block A, 14 are wastewater generating industries. The daily consumption of water by these industries is 20,000m³,

as supplied by the NWSDB. Daily wastewater discharge is at 16,000m³. The EPZ is facilitated by a common wastewater treatment (CWWT) system within the premises, which consists of two systems namely flowthrough type mechanical aerated lagoon and oxidation ditch. The treatment process has been operated since year 1996 as a biological wastewater treatment process, which carries out the steps of screening, grit removal, aerated lagoon, oxidation ditch, settling tank and sand drying bed. The capacity of the CWWT is 10,000m³ per day. All industries including the three selected industrial entities discharge their sewage to the CWWT plant for treatment. The industries treat their effluent to pre-standard levels as specified by the BOI and the CEA (BOI, 2011) through a preliminary treatment prior discharge into CWWT. The preliminary treatment process includes screening, equalisation, a rapid mixing tank, a slow mixing tank, a clarifier, a sludge tank and a belt press. The wastewater treated in CWWT is finally discharged to a river through a canal. Sludge of around 10 tons monthly, which is generated from the zone after common treatment is disposed of at the dump yard within the zone after dewatering and sun drying.

Various environmental complaints have arisen within the area due to heavy raw water consumption by industries and improper discharge of industrial wastewater from the industrial zone. Specifically, the surrounding drinking water treatment facilities have been severely compromised and environmentally sensitive wetlands as well as ground water have been polluted due to improper industrial wastewater discharge. Furthermore, industries located in the EPZ are very closer to a river into which treated wastewater is discharged. This has created a severe environmental issue as around 47% of the population in Pradeshiya Sabha area depend on pipe-borne water which is obtained from the river. The above reasons emphasise the urgent need to initiate an appropriate industrial wastewater management system within the zone to reduce both freshwater consumption and direct discharge of industrial wastewater to environmentally sensitive areas.

Industrial entities to be selected for the water exchange network were defined based on the theory of industrial symbiosis. Industrial sectors with a high level of freshwater consumption and wastewater discharge were considered. The selection criteria developed in relation to the context of Sri Lanka (refer to Table 5.5) were considered in deciding upon the suitable industrial entities for the selected case study, as specified in Table 6.1.

Table 6.1

Criteria adopted in selecting industrial entities in the selected case study

Criteria	Description of the case study selected
Geographical proximity	As the industrial entities are located within the same geographical location, the export processing zone (EPZ) was selected.

Criteria	Description of the case study selected
Likelihood of exchanging water	Industrial entities consuming a large amount of water for industrial purposes and having a linear wastewater discharge, that showed a likelihood and willingness to exchange wastewater were selected. Possible synergies among the identified industrial entities were recognised to develop the water exchange network.
Satisfied water quality tolerance limit	Industries satisfying the upper limit of BOD, COD and TSS of freshwater and treated wastewater were selected. Additionally, pH and colour of water were also considered in the CWWT, ensuring fewer effects of treated wastewater on industrial processes.
Availability of water transferring connections between industrial entities	Industries with the willingness to invest for constructing water transferring connections with other industries were selected since no water can be transferred if no connections existed. Thus, treated wastewater transferring connections from individual industrial entities through the CWWT were established.

Accordingly, three industrial entities satisfying the above criteria were finally selected for data collection. The industry type and the key processes of the selected industrial entities are shown in Table 6.2.

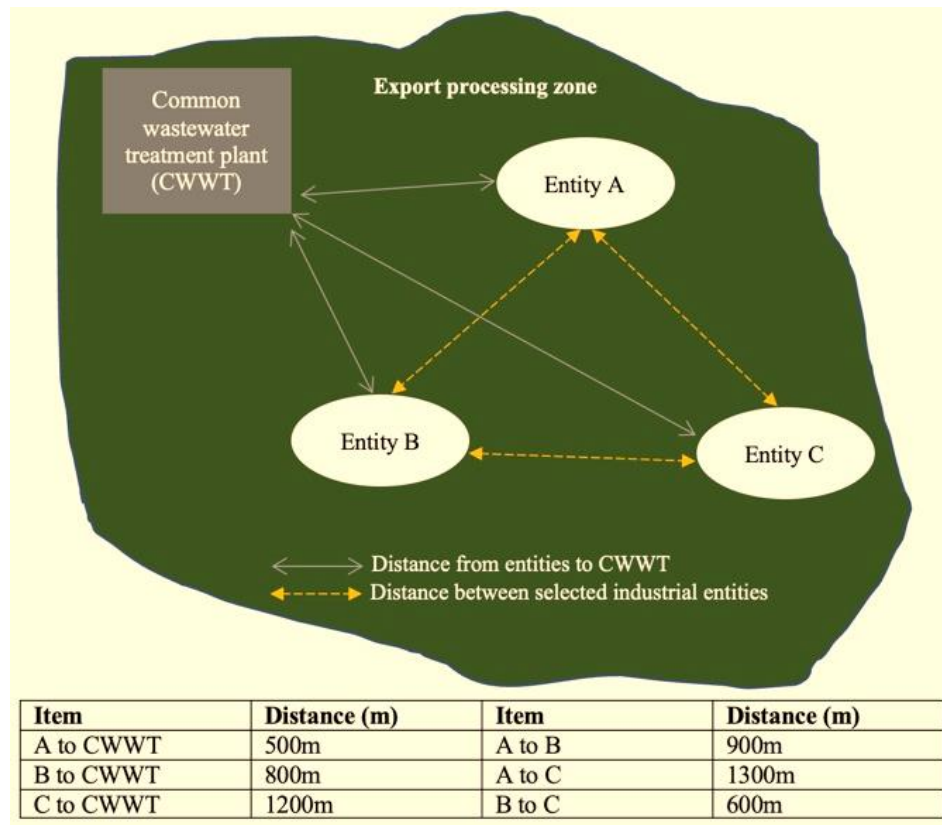
Table 6.2

Details of selected industrial entities

Industrial entity	Type of industry	Key processes
A	Elastic manufacturer	Pre-treatment, wet processing, finishing and manufacturing
B	Textile dyeing and washing plant	Dyeing and washing
C	Rubber toy manufacturer	Concept and design, washing of rubber, moulding, baking and painting

The geographical plan showing the selected industrial entities and the common wastewater treatment plant within the zone is presented in Figure 6.1.

Figure 6.1
Geographical plan of the selected case study



The selected industrial entities are located with geographical proximity within the EPZ boundary. The distance between each industrial entity as well as between industrial entities and the CWWT are not exceed 1.5km.

The current industrial water management (IWM) phenomenon of the industrial entities in the selected industrial zone is firstly analysed as the base case for developing the optimisation problem that needs to be solved by using context-specific robust optimum water flow assessment model.

The data related to freshwater consumption, wastewater discharge, primary treatment and the common wastewater treatment (secondary) processes were collected from the baseline of last 12 months (September 2020 - August 2021) and the average monthly flow rate was defined to use in calculations. Mixed integer linear programming approach (Simplex coding method) was used to solve the optimisation problem by finding the optimal value of the targeted objective. The model was developed and tested by using SageMath (open-source mathematical software licensed under GPL.v3).

During the case studies, the data were collected from the interviewed industry professionals in each industrial entity. The profile of interviewees is stated in Table 6.3.

Table 6.3

Profile of interviewees

Industrial entity in the selected case study	Interviewee code	Designation
Industrial Entity A	A1	Executive – Sustainability
	A2	Mechanical Engineer
Industrial Entity B	B1	Manager – Compliance
Industrial Entity C	C1	Facilities Manager
	C2	Manager - Human Resources & Administration
Central Treatment	T1	DGM – Sewerage
	T2	Project Director

First and foremost, the current industrial water management scenario in each industrial entity is analysed prior to adopting the industrial symbiosis-based water exchange network formulation as described below.

6.4 Analysis of the Current Status of the Selected Case Study

The identified industries consume freshwater for their industrial purposes and discharge industry effluent, domestic effluent and sewage into inland surface water bodies through the CWWT plant. The current status of each industrial entity is analysed and presented under two broader headings: (i) freshwater consumption and (ii) wastewater generation, treatment & discharge. Freshwater consumption and wastewater discharge of each entity are calculated as per the revised equations (Eq. 10 and Eq. 11) stated under Section 5.5.2.

6.4.1 Current status - Industrial Entity A

Industrial Entity A is a leading elastic manufacturer in Sri Lanka as well as a major supplier and exporter of covered elastomeric yarn and textile coating to the global market. It operates in a 60,000 square feet factory within the selected industrial zone. The operation of the facility has been expanded internationally. Entity A’s production process includes weaving, knitting and braiding, dyeing and printing, finishing and yarn covering. The factory mainly carries out the wet processing of fabric from which dyeing and printing discharge a considerable amount of industry effluent. Various sustainability and innovative production initiatives, together with the latest technologies, such as innovative elastic designs, colouration with natural dyes and

mordants, specialty dyeing and finishing, etc., have been introduced at the factory level to reduce the wastewater discharge.

6.4.1.1 Freshwater consumption

Specific to industrial water management, industrial Entity A obtains water from the municipal/city water mains supplied by the NWSDB, at around 37,876.5m³/month. The factory consumes freshwater mainly for domestic purposes, industrial uses (production process) and cooling as presented in Table 6.4.

Table 6.4

Freshwater consumption – Industrial Entity A

Freshwater consumption purposes	Consumption (m ³ /month)	Percentage
Domestic use	3,974.42	<p>A pie chart illustrating the distribution of freshwater consumption for Industrial Entity A. The largest portion is Industrial use at 79%, followed by Domestic use at 11%, Cooling at 8%, and Other at 2%.</p>
Cooling	3,179.53	
Industrial use	29,893.29	
Other	829.26	
Total consumption	37,876.50	

Among the other uses, industrial (production) process consumes 29,893.29m³ of freshwater monthly which is the highest consumer of water in Entity A, representing 79% of its total freshwater consumption. The average of 3,974.42 m³/month (11%) and 3,179.53 m³/month (8%) of freshwater are consumed respectively for domestic purposes and cooling respectively.

Therefore, it is evident that Entity A has a high demand for freshwater for industrial and production processes with its current practice.

6.4.1.2 Wastewater generation, treatment and discharge

Wastewater generation in Industrial Entity A includes domestic wastewater, sewage and industry effluent. As the factory mainly carries out wet processing of fabric, including dyeing and printing, it discharges a large amount of industry effluent. The monthly average of wastewater generation of Entity A is shown in Table 6.5.

Table 6.5*Wastewater generation – Industrial Entity A*

Wastewater generating sources	Wastewater m ³ /month	Percentage
Domestic wastewater	3,179.53	<p>A pie chart illustrating the distribution of wastewater generation for Industrial Entity A. The chart is divided into three segments: a large grey segment representing Industry effluent at 86%, a blue segment representing Domestic wastewater at 12%, and a small orange segment representing Wastewater with sewage at 2%. Labels with leader lines point to each segment.</p>
Wastewater with sewage	466.25	
Industrial effluent	23,312.25	
Total generation of WW	26,958.03	

The monthly average total wastewater generation of Entity A is 26,958.03 m³/month. The monthly average generation of industry effluent is 23,312.25 m³/month, which represents 86% of its total wastewater generation. Entity A also generates 3,179.5 m³/month of domestic wastewater from the factory's domestic uses, such as the kitchen, restaurant and cleaning, etc. The generation of sewage is 466.25 m³/month, which is only 2% of the total wastewater generation.

Compared to other types of wastewater, industry effluent generated by Entity A is eight times greater than its domestic wastewater generation, thus requiring special attention in reducing its generation and improper discharge.

In Entity A's current practice, domestic wastewater and sewage are discharged directly into the CWWT plant located within the industrial zone for treatment. As specified under the CEA and the BOI guidelines, industry effluent is treated to pre-standard levels (BOI, 2011) through preliminary treatment prior to discharge to the CWWT plant. The treated effluent, domestic wastewater and sewage then go through a secondary treatment in the CWWT plant. The total amount of treated wastewater is finally discharged into a river through a canal with no reuse taking place.

6.4.2 Current status - Industrial Entity B

Industrial Entity B is Sri Lanka's only washing and dyeing plant capable of handling all types of fabrications within its single facility and is a leading service provider in garment finishing. Entity B is the most popular wet processing partner who is serving the washing and dyeing requirements of companies in the apparel industry in Sri

Lanka, as well as presently catering to some of the world’s leading textile brands. The types of washing by Entity B include garment washing, heavy garment washing, enzyme washing, stone washing and acid washing, etc. The plant also undertakes fabric dyeing including pigment dyeing, reactive dyeing, direct dyeing, tie dyeing, over dyeing and spray dyeing. The current capacity of the wet processing plant is 950,000 pieces per month, with reactive and pigment dyeing capacity at 250,000 pieces per month.

Entity B has more than 20 years of industry experience specialising in denim fabric washing and dyeing in which, they have utilised eco-friendly and technologically advanced practices. The washing and dyeing processes are also maintained at the highest environmental standards through proper monitoring and quality control. Various in-house strategies have been initiated for energy and water conservation with the goal of reducing water consumption and wastage. For example, some of Entity B’s sustainability-oriented initiatives include the use of T-Hues and natural dye made from tea waste, maintaining chemical compliance under the ZDHC framework and initiating water-based corporate social responsibility.

6.4.2.1 Freshwater consumption

Industrial Entity B obtains water from the municipal/ city water supply by through the NWSDB. The factory’s monthly average total freshwater consumption of 24,360m³/month is consumed mainly for domestic purposes, industrial uses (production process) and cooling as shown in Table 6.6.

Table 6.6

Freshwater consumption – Industrial Entity B

Freshwater consumption purposes	Consumption (m ³ /month)	Percentage
Domestic use	3,144.83	<p>A pie chart illustrating the distribution of freshwater consumption. The largest slice is Industrial use at 83%, followed by Domestic use at 13%, Other at 3%, and Cooling at 1%.</p>
Cooling	239.25	
Industrial use	20,187.93	
Other	787.98	
Total consumption	24,360.00	

As shown in Table 6.6, Entity B consumes 20,187.93m³ of freshwater for industrial purposes monthly, which is 83% of its total freshwater consumption. The second highest freshwater consumption of the factory is domestic uses (3,144.83 m³/month), which is 13% of the total freshwater consumption.

Entity B’s high demand for freshwater is evident in its current practice with freshwater utilised in the washing and dyeing process.

6.4.2.2 Wastewater generation, treatment and discharge

Entity B mainly generates domestic wastewater, wastewater with sewage and industry effluent. As Entity B consumes a considerably high level of freshwater for wet processing and garment washing processes, it generates and discharges a greater amount of industry effluent than domestic water and sewage as shown in Table 6.7.

Table 6.7

Wastewater generation – Industrial Entity B

Wastewater generating sources	Wastewater m ³ /month	Percentage
Domestic wastewater	177.27	<p>A pie chart illustrating the distribution of wastewater generation. The largest slice is grey, representing 'Industry effluent' at 97%. A small orange slice represents 'Wastewater with sewage' at 2%, and a very thin blue slice represents 'Domestic wastewater' at 1%.</p>
Wastewater with sewage	330.41	
Industrial effluent	16,520.55	
Total generation of WW	17,028.23	

The monthly average total wastewater generation of Entity B is 17,028.23m³. As shown in Table 6.7, the monthly average generation of industry effluent is 16,520.55m³, which is 97% of its total wastewater generation. Furthermore, Entity B generates 177.27m³ of domestic wastewater and 330.41m³ of wastewater with sewage monthly, which together are only 3% of its total wastewater generation. Compared to the other types of wastewater generated, the generation of industry effluent is much

higher, thus, urgent attention is required to reduce environmental effects from the direct disposal of wastewater.

In Entity B's current practice, domestic wastewater and sewage are discharged directly into the CWWT plant located within the industrial zone for treatment. Industry effluent is treated to pre-standard levels (BOI, 2011) through preliminary treatment prior to discharge to the CWWT plant. The sludge is then dewatered and provided to a fertiliser producer outside the premises. The treated effluent, domestic wastewater and sewage then undergo a secondary treatment in the CWWT plant. The total amount of treated wastewater is finally discharged into a river through a canal.

6.4.3 Current status - Industrial Entity C

Industrial Entity C is an export-oriented manufacturer of soft toys and infant garments and a specialist in organic and natural rubber toys. It is one of the primary exporters in Sri Lanka distributing toys to over 48 countries. The factory uses natural rubber to produce its natural rubber products range rather than using synthetic rubber. Furthermore, it undertakes production by adhering to strong standards and an oversight process ensuring safe working conditions for employees, ethical labour practices and environmental stewardship.

Entity C's industrial process includes concept and design, washing of rubber, moulding, baking and painting. The monthly average production is from 250,000–275,000 soft toys and 60,000–75,000 rubber toys. The company has undergone many operational changes in production and packaging to make its processes more sustainable, such as the use of biodegradable bags, natural rubber, recycled materials, non-toxic vegetable dyes, etc.

6.4.3.1 Freshwater consumption

Industrial Entity C also obtains potable water from the water mains with this supplied by the NWSDB. The monthly average freshwater consumption of Entity C is 2,130.09 m³. Entity C consumes 1,640.84 m³ for industrial processes monthly, which is 77% of its total freshwater consumption. Freshwater consumption for domestic uses is at 311.75 m³/month (15%), with no water utilised for cooling, as shown in Table 6.8.

Table 6.8*Freshwater consumption – Industrial Entity C*

Freshwater consumption purposes	Consumption (m³/month)	Percentage
Domestic use	311.75	<p>A pie chart illustrating the distribution of freshwater consumption for Industrial Entity C. The chart is divided into four segments: a large grey segment for 'Industrial use' at 77%, a blue segment for 'Domestic use' at 15%, a yellow segment for 'Other' at 8%, and a very thin segment for 'Cooling' at 0%.</p>
Cooling	0	
Industrial use	1640.84	
Other	177.5	
Total consumption	2,130.09	

In comparison to Entity C's other uses of freshwater, its industry process consumes a considerably higher amount of water, at a level five times greater than its freshwater demand for domestic needs.

6.4.3.2 Wastewater generation, treatment and discharge

Entity C's monthly average of total wastewater generation is 1,826.81 m³ of which industry effluent has the highest level of generation (1,312.67 m³). The monthly averages of domestic wastewater and wastewater with sewage generation are respectively 297.38 m³ and 216.76 m³, as shown in Table 6.9.

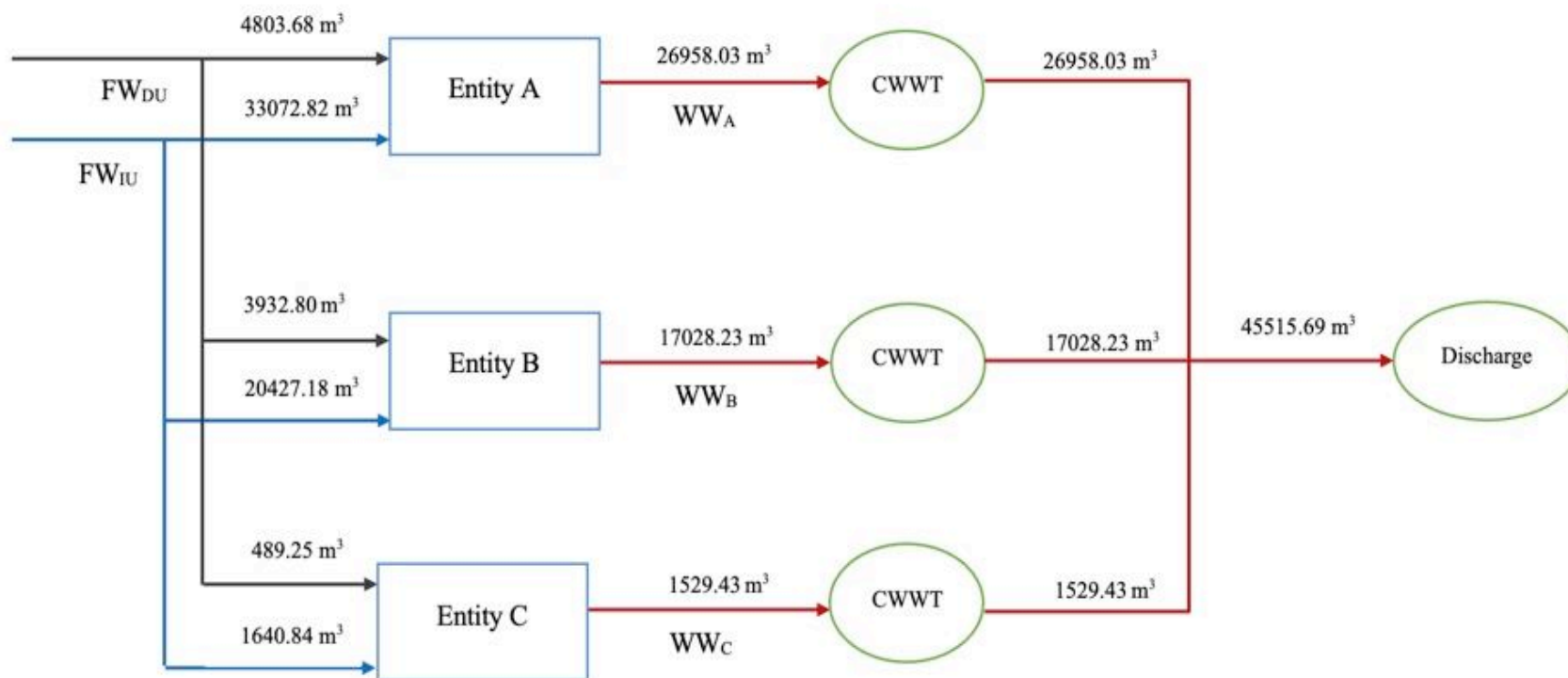
Table 6.9*Wastewater generation – Industrial Entity C*

Wastewater generating sources	Wastewater m ³ /month	Percentage
Domestic wastewater	297.38	<p>A pie chart illustrating the percentage distribution of wastewater generation. The largest slice is grey, representing 'Industry effluent' at 72%. A blue slice represents 'Domestic wastewater' at 16%, and an orange slice represents 'Wastewater with sewage' at 12%.</p>
Wastewater with sewage	216.76	
Industrial effluent	1,312.67	
Total generation of WW	1,826.81	

The generated effluent is pre-treated to required standards and sent to the CWWT plant, which is located within the industrial zone. In the current practice, wastewater with sewage and domestic wastewater are directly discharged into the CWWT plant without preliminary treatment. However, inhouse water-saving strategies have been implemented including using domestic wastewater for the factory's internal non-potable water requirements, such as toilet flushing, gardening, etc. Similar to the other industries, the treated effluent, domestic wastewater and sewage then undergo a secondary treatment in the CWWT plant. The total amount of treated wastewater is finally discharged into a river through a canal.

In consideration of the above points, the conventional water network of the selected case study is shown in Figure 6.2.

Figure 6.2
Conventional water network of the selected case study



FW_{DU}	Freshwater for domestic use	WW_A	Wastewater discharge – Entity A	WW_C	Wastewater discharge – Entity C
FW_{IU}	Freshwater for industrial use	WW_B	Wastewater discharge – Entity B	CWWT	Common wastewater treatment

Figure 6.2 elaborates the monthly average of freshwater inflows to the three selected entities and wastewater outflows through the CWWT plant through to the final discharge to inland surface water bodies. The water quality standards (tolerance limits) required for drinking water and industrial wastewater discharge into inland surface water bodies are shown in Table 6.10, specifying the selected water quality parameters.

Table 6.10

Water quality standards for drinking water and wastewater discharge

Item	Water Quality Standards (Maximum tolerance limit)			
	BOD (mg/l)	COD (mg/l)	TSS (mg/l)	pH
For drinking water/ freshwater	5	10	500	6.5-9.0
For industrial wastewater discharge to CWWT	200	600	500	6.0-8.5
For industrial wastewater discharge into inland surface water bodies	30	250	50	6.0-8.5

Source. Sri Lanka Standards [SLS] for potable water (1983); BOI (2011)

The selected industrial entities consume freshwater supplied by the NSWDB mainly for domestic and industrial purposes. Freshwater is obtained and used for domestic and industrial needs as it ensures drinking water quality. With respect to the three selected industrial entities, the monthly average total freshwater consumption is 64,366.58m³. Wastewater generated by each entity is discharged to the CWWT plant after being pre-treated to the required standards.

An average of 45,515.69m³ of wastewater, satisfying the required water quality tolerance limits, inflows to the CWWT plant monthly. In the CWWT plant, all industrial wastewater (domestic wastewater, sewage and industrial effluent) undergoes its secondary (biological) treatment to fulfil the water quality tolerance limits required to discharge treated industrial wastewater into inland surface water bodies. After its secondary (biological) treatment in the CWWT, all treated wastewater (43,239.90 m³/month) is released to inland surface water bodies without being reuse in the process.

The conventional water network of the selected case study is considered as the base case from which to initiate an optimum water exchange network between selected industrial entities in export processing zone (EPZ) in Sri Lanka. The applicability of the developed context-specific robust optimum water flow assessment model to the selected case study is evaluated accordingly.

6.5 Initiation of Optimum Water Exchange Network between Selected Industrial Entities

As described above, a conventional water network is utilised in the selected case study. As the network has a linear flow, industries consume freshwater for domestic and industrial purposes and discharge wastewater to inland surface water bodies after

preliminary and secondary wastewater treatment. In considering the environmental issues generated due to improper discharge of industrial wastewater into inland surface water bodies, initiation of a water exchange network between industrial entities has been considered.

The key phases of IS initiation process (modified) comprising planning of IS, barrier removal & negotiation, pre-evaluation & optimisation modelling, implementation and evaluation & follow up, (refer to Figure 2.11) were considered in initiating the water exchange network between selected industrial entities as described below.

6.5.1 Planning of industrial symbiosis and identification of water synergies

By considering the present status of the selected case study, the optimum use of treated wastewater obtained through maximum wastewater recovery (wastewater treatment) was considered for minimising freshwater consumption by the selected industrial entities. The reuse of treated wastewater was limited to only industrial uses (industrial and cooling purposes) by each entity, following consideration of a high demand for freshwater for industrial uses in each selected entity. Hence, it was considered that the domestic needs of each entity were fulfilled through the city water (NWSDB) supply whereas the reuse of TWW was considered for reducing freshwater consumption for industrial and cooling needs. The average consumption of freshwater and production of wastewater during the period of September 2020 – August 2021 was considered in calculating the availability of water/ limiting water data for water sources and water sinks (refer Section 6.5.2). The expected water quality requirements of each industry were considered in exchanging TWW (refer to Table 6.10).

Accordingly, the industrial and cooling water requirements of each industrial entity were recognised as stated in Table 6.11.

Table 6.11

Industrial and cooling water requirement of each industrial entity

Industrial entity	Industrial and cooling water requirement (m³/month)
A	33,072.82
B	20,427.18
C	1,640.84

As specified in Table 6.11, the industrial and cooling water requirement of Entity A is 33,072.82 m³. Entity B requires 20,427.18 m³ of water for industrial and cooling needs, whereas the requirement for Entity C is equal to 1,640.84 m³.

To fulfil the industrial and cooling water requirement of each industrial entity, industrial wastewater generated by each entity, after having undergone its preliminary and secondary treatments, was considered for exchange between the three selected industrial entities. The amount of treated wastewater of each industrial entity is

calculated based on the revised Eq. 12 of the context specific model of this research (refer to Section 5.5.2).

Refer to Figure 6.2, the available TWW supply (Total WW discharge from all three entities to the CWWT plant) is 43,239.90m³/month. The wastewater treated by each industry (water sources) through the CWWT plant is considered to share with other industries (water sinks) matching with their water demand.

However, as specified in Section IV of the particular specification published by NSWDB (n.d.), the maximum water loss from the water treatment plant through removal of sludge was 5% of the treated water output. Hence, 5% of water loss with the removal of sludge was considered and deducted from the outlet flow rates of TWW. The availability of TWW of each entity after the CWWT is shown in Table 6.12.

Table 6.12

Availability of treated wastewater supply of each entity after preliminary and secondary treatment

Industrial entity	WW discharge/ inflow to CWWT (m³/month)	Availability of treated wastewater supply/ outflow from CWWT (5% water loss adjusted) (m³/month)
A	26,958.03	25,610.12
B	17,028.23	16,176.82
C	1,529.43	1,452.96

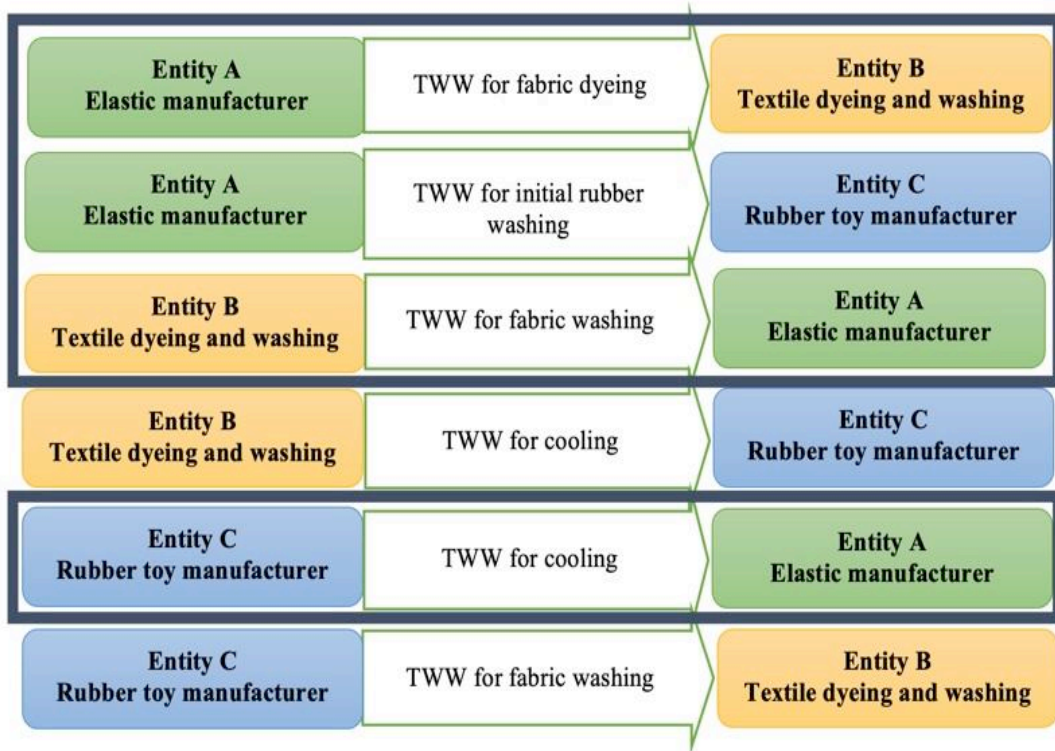
Industrial Entity A discharges a monthly average of 26,958.03 m³ of wastewater, which comprises domestic wastewater, sewage and industrial effluent, in the current scenario. The total monthly average wastewater discharge of Entity B, comprising domestic wastewater, sewage and industrial effluent, is equal to 17,028.23 m³. Entity C discharges 1,529.43 m³ of wastewater monthly, which comprises sewage and industry effluent only, with domestic wastewater used for internal non-potable water requirements of the factory, such as toilet flushing, gardening, etc.

6.5.1.1 Possible water synergies between industrial entities

As the next step, all possible synergies between the three selected industrial entities were identified by referring to desk study (Phase I) findings and data gathered through Phase III interviews. Key processes of the selected industries (refer to Table 6.2) were considered in identifying possible water synergies. As the main input, TWW is to be shared between the selected entities in compliance with the required water quality. Accordingly, six (06) water synergies between Industrial Entity A: Elastic manufacturing company, Entity B: Textile dyeing and washing plant and Entity C: Rubber toy manufacturing company were recognised, as specified in Figure 6.3.

Figure 6.3

Possible water synergies between selected industries



As shown in Figure 6.3, the TWW outflows from Entity A can be used for fabric dyeing in Entity B (textile dyeing and washing plant) and initial rubber processing and washing needs of Entity C (rubber toy manufacturing company). The TWW outflows of Entity B can be considered to use in Entity A for fabric washing. Further, as recognised in Phase I desk study findings, TWW from textile dyeing and washing plant can be used for cooling needs of rubber manufacturing industries where no TWW can be used for rubber products manufacturing. Hence, a synergy from Entity B to Entity C was proposed in which the TWW from Entity B can be suitably used for cooling needs in Entity C. The TWW outflows of Entity C can be used for cooling needs of Entity A and fabric washing in Entity B. The proposed synergies were re-considered through the interviews conducted with the selected professionals from each industrial entity.

The Mechanical Engineer in Industrial Entity A stated that the possibility of reusing TWW from other industrial entities *if it satisfies their quality requirements*. The Mechanical Engineer in Industrial Entity A stated that as:

“Our factory is mainly carried out the wet processing of fabric including dyeing and printing which discharges a considerable amount of industry effluent. According to our industry standards in elastic manufacturing, we could not reuse TWW for the dyeing and printing needs as it can affect to its quality. So, we are treating it to an acceptable quality level to discharge to common treatment. If any industry supplies us TWW with acceptable quality, we can use it for other steps in manufacturing processes like fabric washing

rather than for fabric dyeing and printing as well as for cooling needs. Also, since we are not highly using fabric dyeing in our manufacturing process, we can provide our TWW to other industries if it satisfies their quality requirements”.

As the Manager - Compliance in Industrial Entity B stated that there is a high demand for freshwater to be utilised in washing and dyeing process of Entity B, as it accepts all washing and dyeing requirements and standards of the companies in apparel industry in Sri Lanka. Further, many organisational level limitations, including quality constraints for reusing the TWW for their own purposes have influenced the industrial processes.

This was stated by the Manager – Compliance and Sustainability in Entity B as,

“We are the Sri Lanka’s leading service provider in garment finishing. So, we accept washing and dyeing requirements of all types of fabrications within our single facility. However, daily there is a high demand for city water to be utilised in dyeing and washing of garments, which has created a huge cost and a severe environmental issue. Since we are utilising fabric dyeing like pigment, reactive, direct and tie dyes, there is no possibility of reusing such TWW within the manufacturing process due to quality constraints and organisational level policies and procedures. Therefore, we treat wastewater to the acceptable quality during pre-treatment and send it to common treatment for final discharge. However, we are willing to share that amount of water with another industry if their quality requirements are being satisfied”.

By considering the company willingness, the feasibility of using TWW for manufacturing process and the expected water quality requirements, four (04) synergies (A-B, A-C, B-A, C-A) were finally selected for initiating an IS-based water exchange network within the selected industrial zone, as highlighted in Figure 6.3.

As specified in Figure 6.3, 02 synergies, that is TWW from Entity B to Entity C for cooling and TWW from Entity C to Entity B for fabric washing were rejected due to the organisational level requirements, manufacturing procedures and dyeing standards that need to be maintained in the respective industrial entities. TWW from Entity B to Entity C for cooling was not considered as the cooling requirements of Entity C is at a negligible level in the existing practice. Further, TWW from Entity C to Entity B was also rejected as it does not satisfy the Entity B’s expected water quality requirements of fabric washing.

It is stated by the Manager – Compliance and Sustainability in Entity B as:

“As a reputed fabric dyeing and washing plant in Sri Lanka, we have maintained many quality standards of fabrics complying with national and international standards available. We cannot use TWW if it does not satisfy the required quality. Also, many substances dissolved in TWW obtained from the rubber processing industries could react with fabric dye.”

The proposed IS based water exchange network embedding the selected synergetic relationships between the three selected industrial entities is shown in Figure 6.4.

Figure 6.4

Typical IS based water exchange network in the selected case study (proposed)

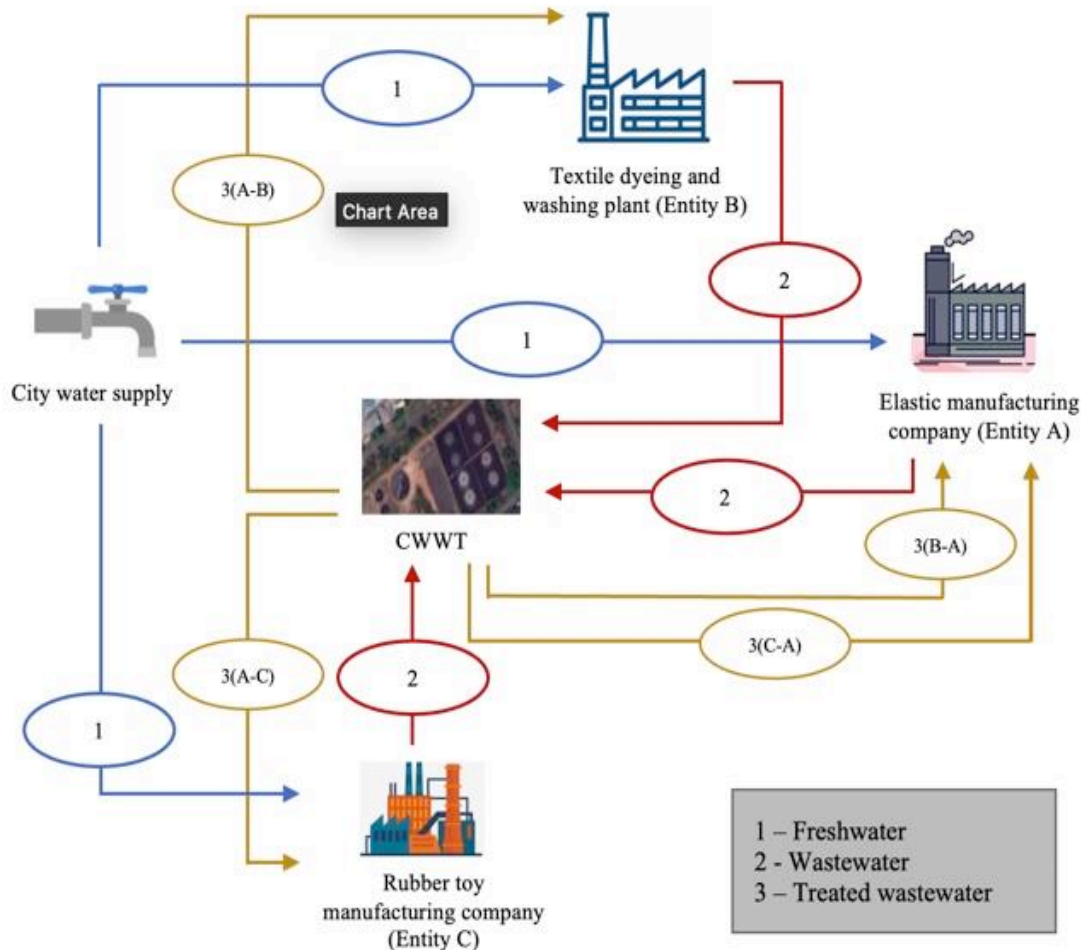


Figure 6.4 illustrates the flow of freshwater occurs to all three industrial entities from the city water supply. All entities outflow wastewater to CWWT. The inflow of TWW supply for each industrial entity is proposed by considering the identified water synergies. The developed context-specific robust optimum water flow assessment model was then applied to assess the optimum water flow between the three selected industrial entities in the proposed IS network. The adoption of the next step, namely, pre-evaluation and optimisation modelling in initiating an optimum water exchange network between selected industrial entities is described below.

6.5.2 Application of the developed model for assessing the optimum water flow of the proposed industrial symbiosis network

The identified water synergies between the three selected entities were assessed to identify the optimum water flow prior to its implementation. This emphasised the

importance of the developed context-specific robust optimum water flow assessment model in assessing the optimum water flow between the three selected industrial entities in the proposed IS network.

Accordingly, the context-specific problem statement, objective of optimisation, source and sink relationships, and water demand and supply, as well as the optimal solution were presented subsequently presented refer to Eqs. 4, 5, 6, 7 and 8 in Section 4.2.3.7. The data collected on the water balance at the water source and water sink and the quality constraints of freshwater & treated wastewater were fed into the software (SageMath) to develop the required coding to solve the given optimisation problem (refer to Appendix – 4).

Problem statement

Three participating industrial entities comprising, (i) elastic manufacturing company (Entity A), (ii) textile dyeing and washing plant (Entity B) and (iii) rubber toy manufacturing company (Entity C) and located within the same industrial zone within close proximity consume freshwater for their industrial processes and discharge wastewater to the environment with no wastewater recovery. This has created a severe burden on environment as well as a high freshwater cost for the selected industrial entities. Hence, the optimum water flow of the proposed IS network through maximum wastewater recovery was required to be assessed.

Objective of optimisation

It was intended that the total freshwater consumption (quantity) in the selected industrial zone be minimised by developing an optimum water flow between the participating industrial entities, which results to minimum wastewater discharge. Hence, a maximum recovery of wastewater through CWWT was considered, which has to be exchanged between participating industrial entities in order to reduce the freshwater consumption of the industrial zone as well as the individual entities.

Source and sink relationships between selected industrial entities

To assess the optimum water flow in the proposed IS network, four (04) source and sink relationships were considered as shown in Table 6.13.

Table 6.13

Source and sink relationships between entities A, B and C in proposed IS network

Industrial entity	A	B	C
A	0	1	1
B	1	0	0
C	1	0	0

Note: 0=No relationship; 1=Relationship exists

The robust network was designed by ensuring that all source-sink matches would be functional.

Limiting water data for water sources (Supply at water sources through CWWT)

The available TWW coming from each industrial entity (refer to Table 6.12) to fulfil the demand for water for cooling and industrial needs of other participating entities is shown in Table 6.14.

As can be seen in Table 6.14, the available water coming from entities A and B is greater than that from Entity C. Furthermore, the quality of water existing from each entity is maintained at the same level, as the wastewater outflow of each entity has undergone a secondary treatment through the CWWT plant prior to the exchange.

Table 6.14

Limiting water data for water sources

Industrial entity	m ³ /month	Quality (mg/l)		
		BOD	COD	TSS
A	25,610.12	5	10	500
B	16,176.82	5	10	500
C	1,452.96	5	10	500

Additional steps, such as coagulation, flocculation, chemical precipitation, filtration and disinfection, were proposed as an alteration to the existing CWWT in order to achieve the required water quality for TWW exchange. The existing CWWT plant with such proposed alterations to be utilised in order to achieve the expected water quality tolerance (upper) limits of the selected quality parameters (BOD, COD, TSS).

In addition to that maintaining the recommended pH level and the reduction of heavy metals in TWW were also considered in the proposed CWWT design (refer to Appendix - 5). The alterations were proposed by considering the present scenario of the selected industrial zone in which only three entities have been engaged in the proposed water exchange network where remaining industrial entities are operating the same. Therefore, alterations of CWWT have been adopted to treat the wastewater discharge from participating industrial entities to meet the expected water quality tolerance limits of TWW. Wastewater discharge from other industrial entities may undergo the existing CWWT and discharge into inland surface water bodies satisfying the required water quality standards proposed by BOI and CEA until engage in the proposed IS network.

Furthermore, a mass balance was obtained by considering the quality of wastewater inflows to the CWWT plant and TWW outflows from the CWWT plant to maintain the required quality of the TWW supply from each water source without any quality drop assuming that the quality of the selected parameters remains the same (refer to Appendix - 5).

Limiting water data for water sinks

The limiting water data for the water sinks is shown in Table 6.15. The water requirement for fulfilling the cooling and industrial needs in each industrial entity was considered. From Table 6.15, it can be seen that water demand at Entities A and B is greater than the demand at Entity C, since both companies are involved in wet processing of fabrics.

Table 6.15

Limiting water data for water sinks

Industrial entity	m ³ /month	Quality (mg/l)		
		BOD	COD	TSS
A	33,072.82	5	10	500
B	20,427.18	5	10	500
C	1,640.84	5	10	500

In the given scenario, all entities expect TWW with the upper tolerance limits of selected water quality parameters matching with the quality of city (potable) water.

6.5.2.1 Optimal water flow of the selected case study

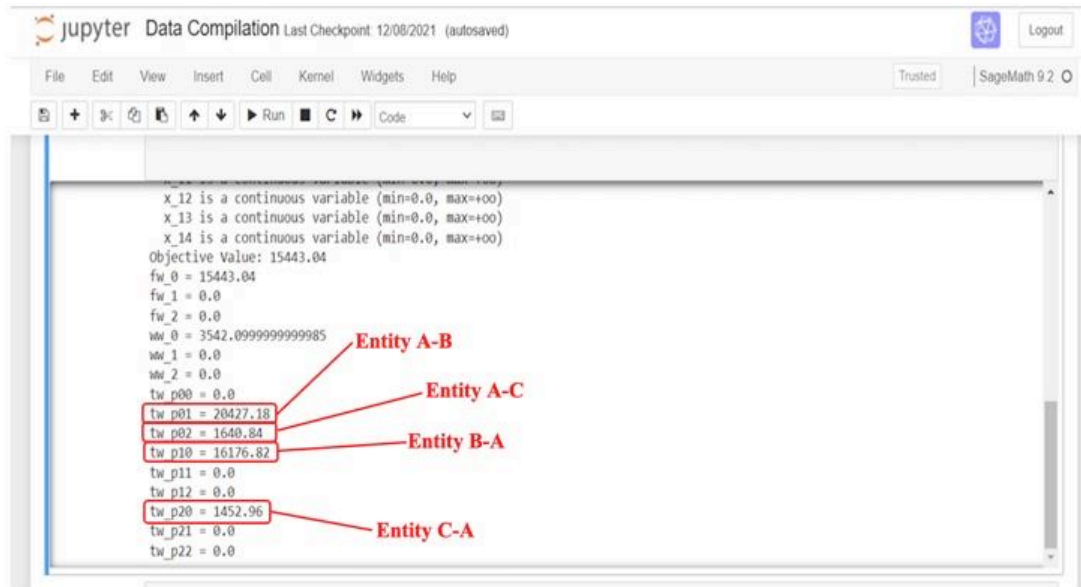
The robust model was applied to obtain the optimum water flow in order to reduce the freshwater consumption of the selected industrial zone as well as of each individual entity. As one of the major constraints of the model, water quality at demand and supply of water was limited to three (03) parameters, namely BOD, COD and TSS. The results of optimisation obtained through MILP approach in SageMath software are presented below (refer to Appendix 4).

Optimal water flow network

The TWW stream between each entity considering the source-sink relationships operated in the optimal network is obtained through assessment. A screenshot of test results obtained from the SageMath software is presented in Figure 6.5.

Figure 6.5

A screen shot of test results obtained from the SageMath software – TWW flow between industries



Note. Treated wastewater flow rates are illustrated in m³/month

As illustrated in Figure 6.4, four (04) treated wastewater streams were derived from the optimal scenario (A-B, A-C, B-A and C-A).

The summary of the test results obtained from data analysis is disclosed in Table 6.16.

Table 6.16

Optimal water exchange network

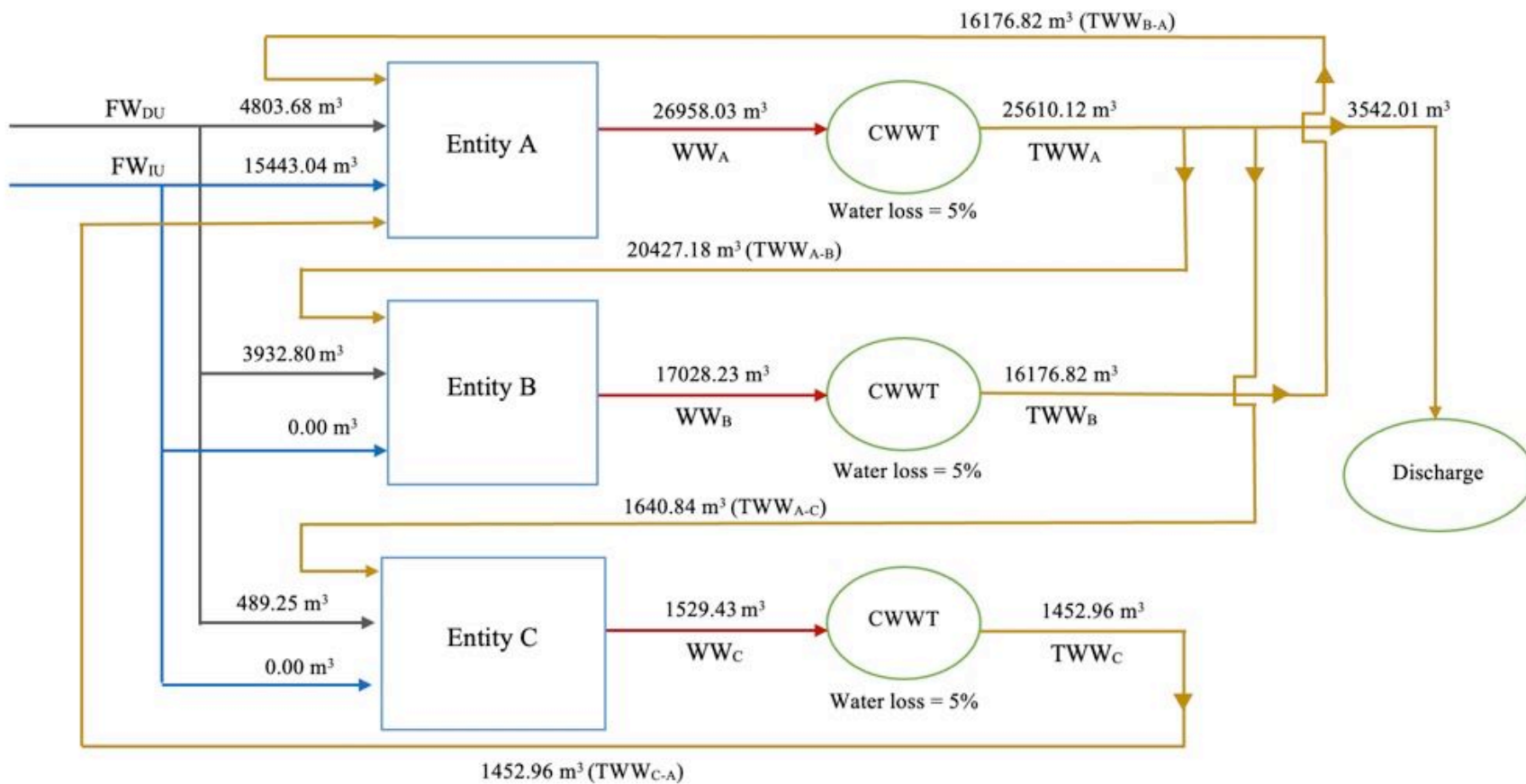
Source	Sinks		
	A	B	C
A	-	20,427.18	1,640.84
B	16,176.82	-	-
C	1,452.96	-	-
Freshwater	15,443.04	-	-
Wastewater	3,542.01	-	-

Note. Treated wastewater flow rates are illustrated in m³/month

As shown in Table 6.16, 22,068.02 m³/month of wastewater from Entity A to be utilised as TWW for Entities B and C in which 20,427.18 m³/month of TWW to be utilised for Entity B and 1,640.84m³/month of TWW to be utilised for Entity C. 16,176.82m³/month wastewater from Entity B to be utilised as TWW for Entity A and 1,452.96 m³/month wastewater from Entity C to be utilised as TWW for Entity A.

The optimal water flow network is visualised in Figure 6.6.

Figure 6.6
Optimal water flow network



FW_{DU}	Freshwater for domestic use	WW_A	Wastewater discharge – Entity A	WW_C	Wastewater discharge – Entity C
FW_{IU}	Freshwater for industrial use	WW_B	Wastewater discharge – Entity B	CWWT	Common wastewater treatment
TWW_A	Treated wastewater supply – Entity A	TWW_B	Treated wastewater supply – Entity B	TWW_C	Treated wastewater supply – Entity C

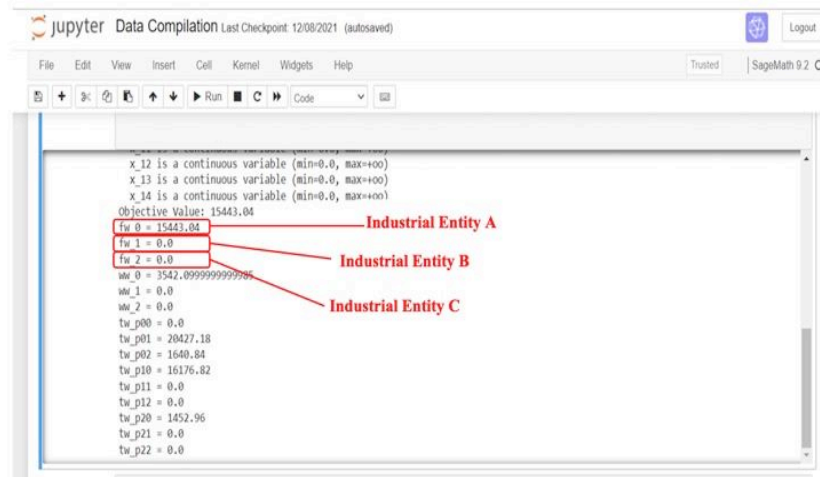
As illustrated in Figure 6.6, a total of 15,443.04 m³/month of freshwater is used up in the optimal network, which is 100% utilised by Entity A and only 3,542.01m³/month of wastewater is discharged within the optimal network, which is 100% done by Entity A.

6.5.2.2 Reduction of freshwater consumption in the optimal water network

As per the considered objective of optimisation, the reduction of freshwater consumption in the optimal water network is calculated. Figure 6.7 presents a screenshot of test results obtained from the SageMath software relate to the reduction of freshwater consumption in each industrial entity of the optimal water network.

Figure 6.7

A screen shot of test results obtained from the SageMath software – freshwater consumption



Note. Freshwater flow rates are illustrated in m³/month

In the assessment of the optimum water flow of the selected IS network, the reduced demand for freshwater consumption for industrial and cooling needs of each entity are elaborated in Table 6.17.

Table 6.17

Reduction of freshwater consumption in the optimal water network

Scenario	Entity A	Entity B	Entity C	Total network
Freshwater consumption in the conventional water network (for industrial and cooling needs)	33,072.82	20,427.18	1,640.84	55,140.84
Freshwater consumption in the optimal water exchange network	15,443.04	0	0	15,443.04
Reduction of FW utilisation	17,629.78	20,427.18	1,640.84	39,697.80
%	53.31	100	100	71.99

Note. Illustrated in m³/month

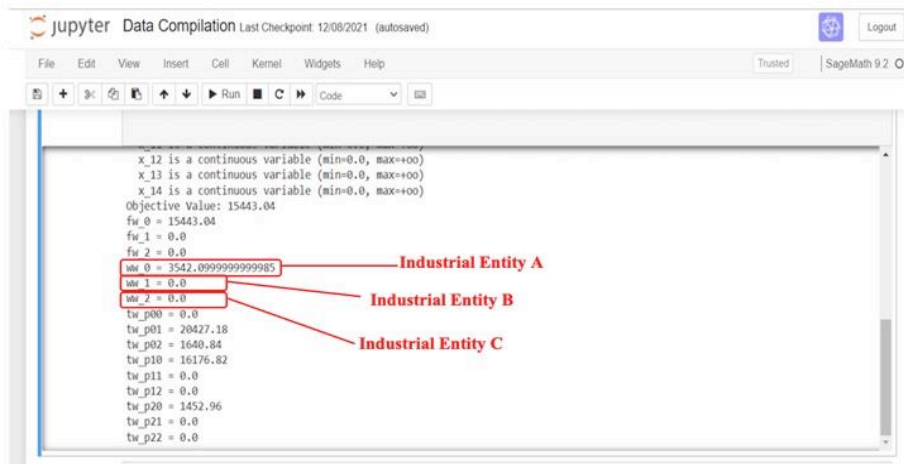
As shown in Table 6.17, in the optimal water network, freshwater consumption for industrial and cooling needs in Entity A has been reduced drastically from 33,072.82m³/month to 15,443.04 m³/month, which is 53.31% of reduction from freshwater consumption in the conventional water network. In both Entities B and C, freshwater consumption for industrial and cooling needs has been reduced by 100% as it is to be fulfilled by treated wastewater. Overall, the optimal water network results in a 71.99% reduction in freshwater consumption as all three entities utilise TWW as an alternative to fulfil their industrial and cooling needs.

6.5.2.3 Reduction of wastewater discharge in the optimal water network

The reduction of wastewater discharge in the optimal water network is also derived through data analysis. Figure 6.8 presents a screenshot of test results obtained from the analysis in SageMath software relate to the reduction of wastewater discharge in each industrial entity of the optimal water network.

Figure 6.8

A screen shot of test results obtained from the SageMath software – wastewater discharge



Note. Wastewater flow rates are illustrated in m³/month

Wastewater discharge in each industrial entity has been reduced significantly by engaging in the proposed optimum water network as shown in Table 6.18.

Table 6.18

Reduction of wastewater discharge in the optimal water network

Scenario	Entity A	Entity B	Entity C	Total network
WW discharge in the conventional water network	26,958.03	17,028.23	1,529.43	45,515.69
WW discharge in the optimal water exchange network	3,542.01	0	0	3,542.01
Reduction of WW discharge	23,416.02	17,028.23	1,529.43	41,973.68

Scenario	Entity A	Entity B	Entity C	Total network
%	86.86	100.00	100.00	92.22

Note. Illustrated in m³/month

As illustrated in Table 6.18, in the optimal water network, wastewater discharge in Entity A has been reduced significantly from 26,958.03m³/month to 3,542.01m³/month, which is a 86.86% reduction from wastewater discharge in the conventional water network. The optimal network has been resulted in a 100% of reduction in wastewater discharge in Entities B and C as their total wastewater is to be fully utilised by other entities in the network as treated wastewater.

Overall, in the optimal water network, monthly average wastewater discharge has been reduced from 45,515.69m³ to 3,542.01m³. Hence, the optimal network results in a 92.22% of reduction in wastewater discharge to inland surface water bodies as maximum recovery of wastewater has been taken place through CWWT.

In summary, the planned water synergies of the proposed IS network were evaluated prior to their implementation by using the developed assessment model. The optimal configuration of the water flow between participating industrial entities in the proposed IS network was determined by applying the developed context-specific robust optimum water flow assessment model. However, the robustness of the model was limited to available water demand at water sinks and water supply at water sources as well as the set water quality constraints of the selected context.

The feasibility in terms of environmental, economic and social benefits that can be achieved through optimal water flow of the proposed IS network are described below.

6.6 Environmental, Economic and Social Feasibility of the Proposed Optimal Network

The concept of sustainable development has become a major concern in the past decade as rapid industrialisation, ever-increasing human needs and uncontrollable resource consumption have resulted in potential health and environmental issues. According to the literature review in Chapter 2, specifically, both greenhouse gas (GHG) emissions and global freshwater consumption are rapidly approaching their proposed global limits. With the continuous increase of global population and the onset of global warming, the problems on freshwater availability and accessibility are expected to worsen. Furthermore, wastewater produced by various industries has been created a severe burden on human health as many people unavoidably consume unsafe water. Hence, it is important to develop strategies to ensure efficient allocation and utilisation of freshwater resources as well as reducing wastewater discharge. Similarly in Sri Lanka, various environmental complaints have been arisen due to high levels of raw water consumption by industries and improper discharge of industrial wastewater, thus requiring urgent attention.

As treated wastewater provides an alternative source of water to reduce the industrial water demand for freshwater, initiating IS based water exchange networks between industries creates an ideal platform to reuse and reshare treated wastewater. Hence, the proposed robust optimal water flow assessment model is conveniently used to initiate treated wastewater sharing networks among industries located within the same geographical boundary.

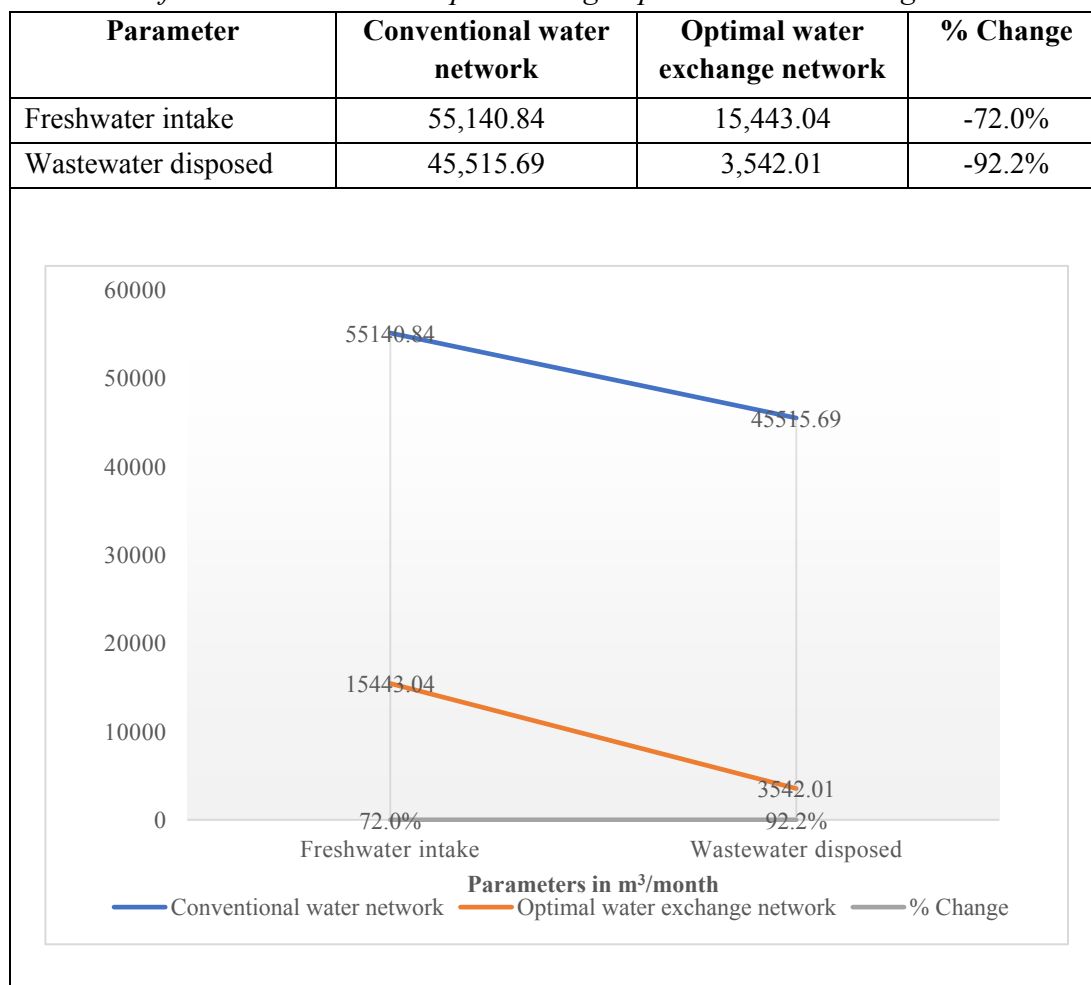
Furthermore, this may create various environmental, economic and social benefits over time through the research outcomes being of utmost significance and able to be applied in any similar context as described below.

6.6.1 Environmental feasibility of the proposed optimal network

As identified in the selected case study, industries are consuming freshwater for their industrial and cooling needs and discharging wastewater into inland surface water bodies after satisfying the water quality requirements, as specified under the BOI norms. As the interviewed experts in Phase II revealed, many industries are discharging industrial wastewater directly to the environment without undergoing primary and secondary treatments. Many investigations have found that the surrounding drinking water treatment facilities of the selected industrial zone have been severely compromised and environmentally sensitive wetlands as well as ground water sources have been polluted due to inappropriate industrial wastewater discharge. Furthermore, industries located in the selected EPZ are very close to a river into which treated wastewater is discharged. This has created a severe environmental issue as around 47% of the population in Pradeshiya Sabha area obtaining pipe borne water from the river. As the interviewed experts further explained, utilisation of freshwater for industrial needs could create a severe burden in the near future, conflicting with the need to expand the potable water supply network for Sri Lanka's domestic needs.

According to ISO 14040:2006, the reduction of both raw water extraction and discharge of wastewater are two key criteria considered in life cycle analysis (LCA). In comparison to the existing conventional water network in practice in the industrial zone, the proposed optimal water exchange network could create significant environmental return for industries within the industrial zone and the surrounding community. It significantly reduces freshwater consumption of the participating industrial entities by using TWW through maximum recovery of industrial wastewater.

Accordingly, in terms of two parameters: freshwater intake and wastewater disposed, the reduction of the environmental impact of the proposed optimal water exchange network than that is from the conventional water network is shown in Table 6.19.

Table 6.19*Reduction of the environmental impact through optimal water exchange network*

Note. Illustrated in m³/month

As shown in Table 6.19, the optimal water exchange network has a lower freshwater intake compared to the conventional water network in the selected industrial zone, which represents a 72% reduction. Wastewater discharge has also been reduced by 92.2% in the optimal water exchange network.

Indeed, the proposed optimal water exchange network reduces the extraction of raw water for fulfilling industrial and cooling needs, which may lower the impact on ground and surface water bodies, with the availability of clean and safe water having become a severe issue in many parts of Sri Lanka. Furthermore, maximum recovery of industrial wastewater reduces the environmental impact of industries in achieving the sustainable development goals (SDGs).

According to the ‘United Nations’ (UN) 17 SDGs, SDG14: ‘Life below water’ and SDG6: ‘Clean water and sanitation’ are directly related to the preservation of water bodies. In addition, SDG3 aims for good health and well-being, and for more ways to reduce ambient pollution including water pollution. SDG12 targets the efficient use of natural resources, including water bodies, through responsible consumption and production. SDG13 calls for taking climate change related actions while SDG15

targets among other conservation efforts, the restoration and sustainable use of terrestrial and inland water ecosystems and their services and reduction of the degradation of natural habitats and biodiversity loss.

Hence, the initiation of an optimal water exchange network between the industries may ensure the reduction of environmental impact through responsible consumption and production of water by industries. It also resolves the contradiction between industrial development, water resource supply and water environment protection.

Furthermore, the proposed optimal network may create various economic benefits in the long term as it reduces the cost of freshwater utilisation for each participating industry and the selected industrial zone as stated below.

6.6.2 Economic feasibility of the proposed optimal network (life cycle cost analysis)

Life cycle cost analysis (LCCA) is an ideal tool that assists the decision-making process, when deliberating on a selection of options available for organisations. LCCA further enables evaluation of investment options available to an organisation dealing with uncertainty (Fuller & Petersen, 1996). Hence, the current study conducted an economic assessment with the use of LCCA method to the existing and proposed water exchange networks.

The general considerations made for conducting LCCA are as follows:

- Direct financial flows that are relevant to both existing conventional network and the proposed optimal water exchange network including initial cost, recurring cost (freshwater cost, cost for pre-treatment by individual entity before send to CWWT, treatment cost to be borne by each entity for central treatment (Fee for CWWT), operations and maintenance cost of CWWT) and residual values were considered in assessing LCC.
- The initial cost of existing infrastructure and facilities (CWWT, pre-treatment plants, existing pipe network and water storages) were not accounted as they do not generate any initial cost to individual industrial entities. Any alteration, which is being made to the existing infrastructure and facilities was only considered.
- The economic life span of 50 years was considered for calculating the LCC as the useful lifetime of the CWWT plant and other existing infrastructure were counted as 50 years (Raghuvanshi et al., 2017).
- There will be a 5% annual increment in operations and maintenance cost of the CWWT as per the institutional level financial guidelines (as proposed by DGM - Sewerage - T1).
- Salvage value was not included as pipe fittings and the CWWT plant components do not generate any salvage value over the 50-year time period.
- Producer Price Index (PPI) was selected as the inflation rate to be considered over Consumer Price Index (CPI) and the Index of Industrial Production (IIP)

in Sri Lanka. CPI measures the changes in consumer prices including revenue and expenditure of households where IIP measures industrial production of the manufacturing sector. However, PPI considers all economic activities including agriculture, manufacturing and utilities, such as gas, electricity and water supply. As the current study considers to optimise the freshwater supply of the participating industries and the selected industrial zone, PPI was selected as the most suitable inflation rate in LCCA. Year on year inflation rate was considered to reduce the effect of short-term fluctuations.

- The real rate was determined based on the market interest rate (5%) and the PPI (16.3%) as at the date of 30 November 2021 (Department of Census and Statistics Sri Lanka, 2021; Central Bank of Sri Lanka, 2021). Accordingly, 9% was considered as the discount rate in LCCA. Year's purchase was calculated and considered in calculations of the present value (PV) of cost occurred annually during the total economic life span.

The calculations of the LCC for both decisions: (i) Option 1- Existing conventional water network and (ii) Option 2 - Proposed optimal water exchange network are presented below.

6.6.2.1 LCCA for existing conventional water network (Option 1)

The cost details obtained through interviews and documentary review in each industrial entity are considered in assessing the cost for the total network. The cost details collected relating to the existing conventional water network are shown in Table 6.20.

Table 6.20

Cost details of the existing conventional water network

Item	Entity A	Entity B	Entity C	Total network
Initial cost ¹	-	-	-	-
Freshwater cost per annum	38,117,318.00	17,126,465.00	1,731,678.91	56,975,461.91
Cost for pre-treatment by individual entity before send to CWWT per annum	19,719,947.00	41,739,768.00	3,016,976.27	64,476,691.27
Treatment cost to be borne by each entity for central treatment (Fee for CWWT) per annum	5,499,437.78	3,473,758.92	312,003.45	9,285,200.15
Operations and maintenance cost of water transfer (existing CWWT and	-	-	-	8,405,925.67

Item	Entity A	Entity B	Entity C	Total network
pipe network) per annum				
Salvage value	-	-	-	-

Note.: ¹The initial cost of existing infrastructure and facilities were not accounted since it does not generate any initial cost to individual industrial entities. Any alteration made to the existing infrastructure and facilities was only considered.

²Cost details are given in Sri Lankan rupees (LKR)

The considerations specifically used in conducting LCCA for the “Option 1: Existing conventional water network” are as follows:

- The initial cost of existing infrastructure and facilities were not accounted as the entity level pre-treatment facility and the zone level CWWT facility are already available to be used.
- Freshwater cost was calculated by considering the monthly average freshwater consumption of each industrial entity.
- The cost of pre-treatment includes the operation and maintenance cost of pre-treatment plant, labour charges and sludge removal.
- Fee for CWWT was calculated considering the monthly average wastewater discharge by each entity to the CWWT plant, which was multiplied by the rate of 17 Sri Lankan rupees (LKR) as specified by the BOI norms (BOI, 2011).
- The operation and maintenance cost of water transfer (CWWT and existing pipe network) was also accounted to assess the LCC of the total water network subject to 5% annual increment (as proposed by DGM – Sewerage -T1). Energy consumption was accounted for 40% of the operations cost of water transfer.
- Salvage value was not included as pipe fittings and the CWWT plant components do not generate any salvage value over the 50-year time period.

Accordingly, LCC is calculated for the existing conventional water network (refer to Appendix 6). The LCCA summary for each industrial entity and the total network, with this presented in Table 6.21.

Table 6.21

LCCA summary of the existing conventional water network

LCC item	Amount of LCC ²			
	Entity A	Entity B	Entity C	Total network
Initial cost ¹	-	-	-	-
Freshwater cost	417,765,805.28	187,706,056.40	18,979,200.85	624,451,062.53
Cost for pre-treatment by individual entity before send to CWWT	216,130,619.12	457,467,857.28	33,066,059.88	706,664,536.28
Treatment cost to be borne by each entity	60,273,838.07	38,072,397.76	3,419,557.79	101,765,793.62

LCC item	Amount of LCC ²			
	Entity A	Entity B	Entity C	Total network
for central treatment (Fee for CWWT)				
O&M cost of water transfer (existing CWWT and pipe network) with 5% annual increment	-	-	-	177,664,909.99
Salvage Value	-	-	-	-
Total LCC	694,170,262.47	683,246,311.44	55,464,818.53	1,610,546,302.43

Note.: ¹The initial cost of existing infrastructure and facilities were not accounted since it does not generate any initial cost to individual industrial entities. Any alteration made to the existing infrastructure and facilities was only considered.

²LCC is given in Sri Lankan rupees (LKR)

As illustrated in Table 6.21, the total LCC for Entity A for continuing the existing conventional water network is LKR694 million, while the LCC for Entities B and C are at LKR683 million and LKR55 million respectively. The LCC of the total network of participating industries in the selected industrial zone would be LKR 1,610 million.

In comparison to the existing conventional water network, the LCC for the investment decision to adopt the proposed optimal water exchange network is calculated as presented below.

6.6.2.2 LCCA for optimal water exchange network (Option 2)

The cost details, which were gathered from case study interviews and documentary review in relation to the optimal water exchange network are shown in Table 6.22.

Table 6.22

Cost details of the optimal water exchange network

Item	Entity A	Entity B	Entity C	Total network
Initial cost ¹ - pipe laying	-	-	-	13,303,400.00
Initial cost ¹ - supply and installation of CWWT unit (for proposed alteration)	-	-	-	50,000,000.00
Freshwater cost per annum	14,903,580.72	2,474,515.56	262,701.00	17,640,797.28
Treated water utilisation cost per annum	7,036,720.80	8,733,784.80	694,202.40	16,464,708.00
Cost for pre-treatment by individual entity before send to CWWT per annum	19,719,947.00	41,739,768.00	3,016,976.27	64,476,691.27

Item	Entity A	Entity B	Entity C	Total network
Treatment cost to be borne by each entity for central treatment (Fee for CWWT) per annum	5,499,437.78	3,473,758.92	312,003.45	9,285,200.15
O&M cost of water transfer (pipe network and CWWT) per annum with 5% annual increment	-	-	-	8,261,011.33
Salvage value	-	-	-	-

Note.: ¹The initial cost of existing infrastructure and facilities were not accounted since it does not generate any initial cost to individual industrial entities. Any alteration made to the existing infrastructure and facilities was only considered.

²Cost is given in Sri Lankan rupees (LKR)

The considerations specifically used to conduct the LCCA for “Option 2: Proposed optimal water exchange network” are as follows:

- The proposed optimal water network includes sharing of treated wastewater between the participating industrial entities, thus requires new infrastructure including pipe laying and water storage. Hence, there is an initial investment by the governing body of the zone (as the custodian of the total network) for pipe laying (water distribution), water storage and the alteration of CWWT in achieving the expected water quality for sharing treated wastewater.
- Since the proposed network includes only three industrial entities of the selected industrial zone, constructing treated wastewater storage facility was not considered assuming that all generated treated wastewater through the CWWT plant (with proposed alterations) distribute to the participating industrial entities in daily basis. However, development of new infrastructure including water storage facility (underground tank or water tower) can be considered in the future expansion of the proposed water network complying with the upcoming demand for TWW. The cost of supply and installation of a new CWWT unit as the proposed alteration for the existing system was also considered under initial cost.
- The relevant cost details of the proposed treatment system were obtained from previous similar projects. Freshwater cost was calculated based on the monthly average freshwater consumption of each industrial entity after proposed optimisation.
- The cost for pre-treatment by each individual entity and the fee for CWWT were included same as the existing conventional water network by considering the BOI norms.
- The cost of treated wastewater was calculated by considering the proposed treated wastewater flow rates of the optimal water exchange network. As reported by interviewed industry professionals, the rate of LKR30 was

considered as a half a rate of the drinking water supply charge for providing treated wastewater to participated industries.

- The operation and maintenance cost of water transfer (pipe network and CWWT) was considered with a 5% of an annual increment as proposed by the Deputy General Manager – Sewerage (T1).
- Similar to the existing conventional network, salvage value was not included as the pipes, fittings and the CWWT plant components do not generate any salvage value over the 50-year time period.

Accordingly, LCC was calculated for the optimal water exchange network specifying each participating industrial entity and the total network (refer to Appendix 7). The LCCA summary for the optimal water exchange network is presented in Table 6.23.

Table 6.23

LCCA summary of the optimal water exchange network

LCC item	Amount of LCC ²			
	Entity A	Entity B	Entity C	Total network
Initial cost ¹	-	-	-	63,303,400.00
Freshwater cost	163,343,244.69	27,120,690.54	2,879,202.96	193,343,138.19
Treated water cost	77,122,459.97	95,722,281.41	7,608,458.30	180,453,199.68
Cost for pre-treatment by individual entity before send to CWWT	216,130,619.12	457,467,857.28	33,066,059.88	706,664,536.28
Treatment cost to be borne by each entity for central treatment (Fee for CWWT)	60,273,838.07	38,072,397.76	3,419,557.79	101,765,793.62
O&M cost of water transfer (pipe network and CWWT)	-	-	-	174,602,047.65
Salvage value	-	-	-	-
Total LCC	516,870,161.85	618,383,226.99	46,973,278.94	1,420,132,115.42

Note.: ¹The initial cost of existing infrastructure and facilities were not accounted since it does not generate any initial cost to individual industrial entities. Any alteration made to the existing infrastructure and facilities was only considered.

²Cost is given in Sri Lankan rupees (LKR)

As illustrated in Table 6.23, the LCC for Entity A is LKR516 million to engage in the proposed optimal water network, where the LCC for Entities B and C are at LKR618 million and LKR46 million respectively. The LCC for the total optimal water exchange network of participating industries in the selected industrial zone would be LKR1,420 million.

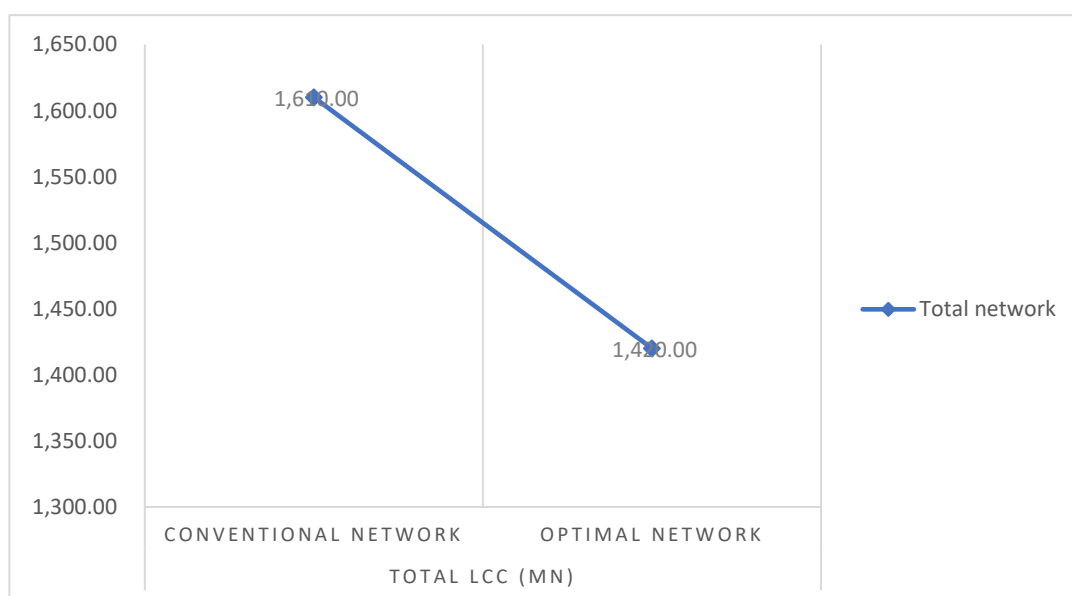
6.6.2.3 Comparison of the economic benefits of conventional and optimal water networks

Based on the LCCA, the economic benefits of the proposed optimal water exchange network are expressed in comparison to those of the existing conventional water network as shown in Table 6.24.

Table 6.24

Comparison of cost savings of existing and proposed water networks

Entity/ network	Total LCC*			
	Conventional network	Optimal network	Saving	%
Entity A	694,170,262.47	516,870,161.85	177,300,100.62	25.54%
Entity B	683,246,311.44	618,383,226.99	64,863,084.45	9.49%
Entity C	55,464,818.53	46,973,278.94	8,491,539.59	15.31%
Total network	1,610,546,302.43	1,420,132,115.42	190,414,187.01	11.82%



Note.: *Cost is given in Sri Lankan rupees (LKR)

As derived through LCCA of both networks, the proposed optimal water exchange network results in a lower total LCC over its economic life compared to the conventional water network. Even though optimal water exchange requires an initial investment of LKR63 million for infrastructure development, such as pipe laying for treated wastewater supply and the alteration of CWWT, the total LCC is considerably reduced over the time, generating LKR190 million of cost saving in the long term as illustrated in Table 6.24. As evident in LCCA, the cost saving that can be achieved through optimal water exchange network in the long term is 11.82%.

In considering the individual industrial entities, all three industries may achieve a significant economic return in the long term if engaged in the proposed optimal water

exchange network. The reduction of cost for freshwater consumption and utilisation of treated wastewater at lower prices drastically reduce the total LCC even though they may bear a huge cost for primary and secondary treatment of wastewater. According to LCCA, Entity A shows a 25.54% of cost saving in the long term by engaging in the proposed optimal water exchange network. Industrial Entity B also shows a 9.49% of cost saving and Entity C shows a 15.31% of cost saving through the optimal water exchange network. Hence, the LCCA provides evidence that initiating the proposed optimal water exchange network is a cost-effective investment decision in achieving long-term economic benefits as a collective advantage for all participating industries.

As decision makers could face various uncertain conditions in deciding on the proposed investment options, sensitivity analysis was also conducted as presented below.

6.6.2.4 Sensitivity analysis of the proposed investment decisions

Uncertain conditions can affect the actual economic outcome of investment decisions, thus, creating decision making a challenging task. The sensitivity analysis technique can be applied as a deterministic approach for measuring the impact on project outcomes due to various uncertain key input values at a time (Fuller & Petersen, 1995).

The economic outcomes of the proposed optimal water network and the existing conventional water network were further analysed by using the sensitivity analysis technique. The impact on the total LCC and savings of both investment options was measured due to changes in the PPI over the time.

In accordance with PPI movements during the period of January 2014- January 2022 (Department of Census and Statistics, 2022), $\pm 7\%$ of change in the PPI was considered in re-calculating the total LCC of both the proposed optimal water exchange network and the existing water network.

Hence, the real rate is first re-calculated by adopting the $\pm 7\%$ of change in the PPI while other input variables and assumptions remained unchanged. New real rates were obtained for three different scenarios as shown in Table 6.25.

Table 6.25

Calculation of real rates adopting $\pm 7\%$ of change in Production Price Index (PPI)

Variations in PPI	-7%	0	+7%	+14%
Real rate	4%	9%	14.8%	19.4%

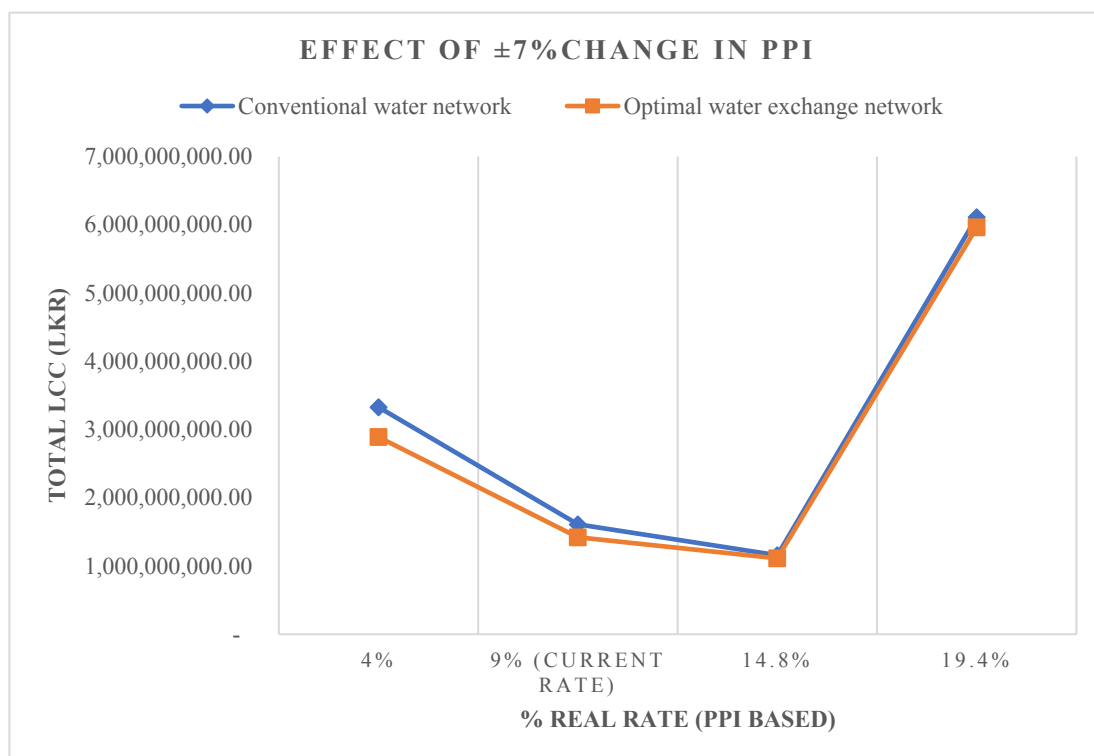
The cost calculations obtained under 9% were the original estimate of the LCC for both the proposed optimal water network and the existing conventional water network. The total LCC of both the proposed optimal water exchange network and the conventional water network were re-calculated for the above real rates to determine the deviations of the LCC from the original estimate (refer to Appendix 8). The results summary of the sensitivity analysis is shown in Table 6.26.

Table 6.26*Results summary of sensitivity analysis*

Total LCC* of investment options	Real Rate % (PPI based)			
	4%	9% (Original estimate)	14.8%	19.4%
Proposed optimal water exchange network	2,889,283,217.38	1,420,132,115.42	1,112,272,892.07	5,961,518,090.01
Conventional water network	3,326,574,690.94	1,610,546,302.43	1,157,386,003.48	6,109,800,271.55
Difference/ Saving	437,291,473.56	190,414,187.01	45,113,111.41	148,282,181.54
%	13.15%	11.82%	3.9%	2.43%

Note.: LCC is given in Sri Lankan rupees (LKR)

The graphical representation of the results of the sensitivity analysis is shown in Figure 6.9.

Figure 6.9*Results of sensitivity analysis*

As per the results showed in Table 6.26, the total LCC for both the proposed optimal water exchange network and the existing water network with respect to the changes in PPI were calculated. As illustrated in Figure 6.9, the PPI showed a very steeper curve,

which indicates a high degree of sensitivity to deviations of the LCC from the original LCC estimate. Compared to the conventional network, the proposed optimal network showed a considerable cost saving under each scenario even though the PPI showed a considerable effect on LCC. Hence, the LCCA provided evidence that the proposed optimal water exchange network was an economically feasible investment decision in achieving long-term economic benefits.

6.6.3 Social feasibility of the proposed optimal network

The generation of social benefits and contributions to enhance the socio-economic development by these industries offer various social insights that can be achieved through the proposed optimal water exchange network. The reduction of freshwater consumption for industrial and cooling needs of these industries could create a positive impact on domestic potable water supply for domestics within Sri Lanka.

As interviewed experts revealed, many areas of the country are suffering due to the unavailability of clean and safe water, thus expanding the NWSDB potable water supply network is a paramount need.

It is stated by the Project Director (T2) as:

“There is a target to ensure that everyone get safe water by year 2025. So we are planning to increase our pipe born water coverage. NWSDB is the sole agency to provide pipe born water in urban as well as the semi-urban sector. During the last 40+ years, we got around 42-45% coverage by 2020. In rural sector, covers around 10% of total population by community managed small-scale water supply facilities. When it comes to water sector industrial water is supplied under urban and semi-urban sector. When take out the challenge what we are having in industrial sector is, we have to get another 45% of coverage for people to provide safe water and thus the coverage by NWSDB has to be increased around 45-75% by 2025. It is really a big challenge since we must extract more water.”

Hence, the reduction of industrial demand for drinking water could lower the supply of potable water for industrial needs so it can be used to fulfil the country’s domestic needs.

Furthermore, fertiliser production with the use of sludge from CWWT (after dewatering and sun drying) will also create new job opportunities and generate benefits for local cultivation.

It is explained by the Deputy General Manager – Sewerage (T1) as:

“In the industrial zone, we have a biological treatment consisting maturation ponds to reduce the pathogens naturally. Afterward, TWW is sending to downstream salinity barrier in the river bank. The sludge is sending for drying after dewatering. If farmers could use, we can provide them for fertiliser production and finally for cultivation purposes in the surrounding area.”

According to recent reports, chronic kidney disease (CKD) has become a significant health problem in Sri Lanka. Since, industrial wastewater has identified as one of main polluters of water bodies as well as a risk factor of water-borne diseases, initiating optimal water exchange network within industrial zones in Sri Lanka will ensure the maximum recovery of industrial wastewater, which may reduce the wastewater discharge into surface water and groundwater bodies.

Hence, the proposed optimal water exchange network will be an ideal solution to enhance the status of health and wellbeing of people and other living beings in terms of water.

6.7 A Way Forward of the Developed Model

As one of following stages in IS initiation process, barrier removal of the identified water synergies has to be considered after evaluating its optimal configuration. The barriers, such as unavailability of information, lack of commitment of industry partners, trust and coordination issues, regulatory, social and economic concerns can be overcome through a successful negotiation. As the implementation of the proposed optimal water exchange network, a suitable approach to manage the IS could be considered prior implementing the exchanges. Furthermore, identifying and distributing the tasks and responsibilities between participating firms also come under this phase. Importantly, the involvement and contribution of the government within the water network could also be considered through the provisions of incentives, tax reductions, technology upgrades and infrastructure development. As an important stage for continuing the proposed optimal water exchange network in the long term, the continuous monitoring of its impact and dissemination of the outcomes is vital points to consider. The follow-up phase ensures the stability of the proposed initiative through continuous improvement. Furthermore, communicating the results and outcomes of the implemented IS relationship is important in expanding the water exchange network to other industrial entities within the selected industrial zone.

6.8 Uniqueness of the Model and Generalisation

As the key outcome of this research, the development of the robust optimum water flow assessment model shows a unique application in initiating optimal water exchange networks within a selected geographical boundary. This model considers optimum reduction of freshwater utilisation by participating industries through the maximum recovery of wastewater. The model includes clear and simple model functions and equations, which can be used by industry professionals to achieve the optimum configuration of IS based water exchange networks. The developed context-specific robust optimum water flow assessment model was applied successfully within the selected industrial zone of Sri Lanka, the proposed model is robust for use in similar industry settings and can be generalised to the selected context with confidence. The proposed conceptual model can be applied in any context for optimising the water flow of industrial symbiosis subject to context-specific variants and enhancements.

6.9 Chapter Summary

This chapter presented the analysis and results relating to the Phase III data collection and analysis, which was conducted to evaluate the applicability of the developed context-specific robust optimum water flow assessment model to an industrial zone in Sri Lanka. The analysis and findings related to the application of the developed model were then presented by following the key steps of the general procedure for initiating IS networks. Initially, possible water synergies between participating industrial entities were determined. By adopting the developed model functions and equations through the use of SageMath software, the optimal configuration of the water flow network was determined. As revealed in analysis, the optimal water exchange network showed a considerable reduction of freshwater consumption both in individual industrial entities as well as in the total network. Accordingly, LCCA was undertaken to provide evidence of the long-term economic benefits of the proposed optimal network. Social and environmental benefits were also described. Through its successful application, the developed context specific robust optimum water flow assessment model is proposed to be used in similar industry settings with confidence.

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

7.1 Introduction

This chapter initially provides the research aim and objectives, as well as the summary of key research findings to ensure the achievement of the ultimate research aim. The chapter then presents the overall conclusions of the research study. Finally, the original contributions to knowledge, recommendations for industry practitioners and further research directions emerging from this study are elaborated to conclude the chapter.

7.2 Overall Conclusions of the Research

The exchange of treated wastewater (TWW) between industries has been implemented as a modern industrial water management (IWM) strategy in many countries, under the concept of industrial symbiosis. Indeed, these industrial symbiosis networks have generated a considerable impact on environmental and economic development through water savings, reduction of raw material extraction and carbon emissions reductions. However, many of the water networks of industrial symbiosis have failed in the long term due to discrepancies in the industrial symbiosis planning procedure as well as inefficiencies of the water flow. The current industrial symbiosis planning process emphasises having a means for evaluating the identified water synergies to determine the optimum water flow between the participating industrial entities. Wastewater is not optimally reused within industrial symbiosis networks through its maximum recovery. However, many research studies have focused on analysing the structural characteristics of the resources flow, with less attention paid to optimising the water flow of industrial symbiosis by considering maximum wastewater recovery. Hence, this research aimed to **develop a model to assess the optimum water flow of industrial symbiosis**.

The first objective was **to review the current status and issues of water exchange between multiple industries in industrial symbiosis**. The planning process, current status, benefits and issues of existing global industrial symbiosis projects were reviewed. Industrial symbiosis engages the traditionally separated and geographically proximate industrial entities to achieve collaborative benefits through the physical exchange of resources including materials, energy, water, by-products, services and infrastructure. Water is one of the main resources exchanged in IS networks. Self-organising IS, planned IS and facilitated IS can be recognised as the key models in which IS could emerge in any context. A top-down planning approach involving planning, barrier removal & negotiation, implementation and, evaluation & follow-up has been mainly used in initiating IS networks.

As found in the key literature, deficiencies in the planning process were recognised. Even though several IS-based water networks exist across the globe, many have resulted in failures without achieving the expected results due to deficiencies in IS planning as well as inefficiencies in the water flow of IS in the long term. Further, the risk of interdependency on industry partners and, the authority of control over

decisions have also been influenced. Obstacles toward implementing water synergies can also be observed in these systems, which could undermine the expected collaborative gains. Thus, wastewater has not been optimally reused between industries. In the current process, no prior evaluation and optimisation are taking place before implementing the identified water synergies, which has hindered achieving the expected efficiencies and long-term stability of the water flow in IS networks. Hence, as a key outcome, as well as the first key contribution made in this research, a new stage of “pre-evaluation and optimisation modelling” was proposed to be included as the second stage of the industrial symbiosis development process (refer to Figure 2.11).

In addressing the second objective, **a conceptual model and mathematical formulae to assess the optimum water flow of industrial symbiosis were developed.** Initially, a flow chart was introduced, which guided the entire development process of the optimisation model. The optimisation model development process comprises four (04) key steps: (i) Step 1 – data compilation and initial processing, (ii) Step 2 – optimisation model design and development, (iii) Step 3 – assessment of the optimal configuration and (iv) Step 4 - evaluation of economic, environmental and social feasibility.

Step 1 of the process was to compile the collected water input and output data through initial processing. Firstly, a cluster of three ‘traditionally separated’ industrial entities, located in the same industrial park/ zone was considered to initiate the water network satisfying 04 different criteria: located within geographical proximity, showing the likelihood of exchanging wastewater, having water transferring connections between industrial entities, and satisfying the upper tolerance limit of water quality. Considering the source-sink relationship between the three hypothesised Industrial Entities A, B and C of the network, all possible water inputs and outputs, such as freshwater inputs, treated wastewater inputs and wastewater outputs were counted to obtain the optimal solution. Accordingly, the theoretical framework was developed, with this designed to convert the conventional water flow of industrial entities of the network into the optimum water flow through the proposed optimisation by ensuring the maximum recovery of wastewater (refer to Figure 4.10).

Step 2 of the process was devoted to presenting the optimisation model to assess the optimum water flow of IS, which was developed using MILP approach (Simplex coding method). The developed model consists of 03 key variables, namely, freshwater utilised by water sink, treated wastewater from water source to water sink and wastewater generated by the water source. Hence, the optimal value was presented as a function of these three key variables. Number of water sources & water sinks, and number & types of water quality parameters were the model parameters. The optimal value is restricted by two main constraints, namely water balance and water quality whereas an extra constraint was introduced to ensure single input flow and output flow of entities (refer Figure 3.8). The optimum water network was assessed subject to material balance and quality constraints based on the characteristics of the water sources and water sinks. The developed optimisation model consists of three key mathematical formulae: (i) objective function, (ii) water source and sink balance (water demand and supply), and, (iii) quality constraint.

In **Step 3**, the decision of the optimum solution, which supports the optimisation objective was considered. To make the model stable in its practical implementation, two options, namely, “re-processing” of identified water synergies and “re-consideration” of feasibility were encoded into the process. If the optimal value cannot be obtained or the water flow is not optimal, “re-processing” takes place to proceed again to Step 1 of the process.

Pre-evaluation can also be used to provide a feasibility impression of the planned water synergies before implementing them within the selected industrial setting. Hence, in **Step 4**, the economic, environmental and social feasibility of the developed optimal solution was evaluated. If the expected benefits cannot be achieved or the proposed optimal solution is not feasible in-terms of economic, environmental and social viability, “re-consideration” takes place to re-continue with Step 4 of the process.

Accordingly, the developed flow chart, the theoretical and conceptual model as well as the mathematical formulae can be expressed as the key research outcomes derived from achieving the study’s second objective.

The third objective was **to investigate the existing methods & issues of industrial water management and enablers & barriers to initiate water exchange networks in Sri Lanka**, as this was the selected context in which to apply the developed model. According to the empirical findings derived through analysis, 16 current methods used for managing industrial water were identified. The methods applied at national and institutional levels include following international level industry effluent discharge standards, providing common treatment facilities within industrial parks, introducing the national policies and a national regulatory framework for governing industries and providing industry specific pre-treatment to reduce the micro pollutants of industry effluent.

As derived from analysis, 19 issues in industrial water management in Sri Lanka were identified. Among others, these issues included ignorance by industries, use of freshwater bodies and sea outfall as industrial effluent discharging points and, surface and ground water pollution due to illegal effluent discharge by industries.

Key barriers that need to be overcome for initiating treated wastewater exchange networks between industries in Sri Lanka included expected water quality for industrial needs, outdated technologies used in water management, lack of expertise and awareness, non-operational infrastructure, isolated industries situated in different geographical boundaries, cultural attitude of organisations toward water reuse, difficulty in synchronising synergies from different types of industries and less investment on water management by industries. As derived from analysis, 17 areas of potential for initiating treated wastewater exchange networks in Sri Lanka were recognised, such as industries located within the same geographical proximity, willingness of industries to engage in water exchange, industry-level water management initiatives, industries governed under one ownership, existing national policies for water management, technology available to use for water treatment and existing infrastructure and facilities.

Accordingly, the identified methods & issues and the enablers & barriers highlighted the importance of initiating water exchange networks in Sri Lanka. Hence, the identified areas of potential can be further enriched while taking actions to overcome the identified barriers to initiating treated wastewater exchange networks in Sri Lanka as a timely need, thus achieving the third objective of the research.

To address the fourth objective, **a context-specific robust optimum water flow assessment model for industrial symbiosis in Sri Lanka was developed** by refining the developed conceptual model to the selected context. Compared to the conceptual model developed, a few variations were determined. Two variables, that is, freshwater from surface water sources (lakes) and untreated wastewater supply, were not considered. Two additional variables were added, namely, freshwater from groundwater sources (tube wells) and domestic wastewater (kitchen water, etc.). Furthermore, a 5% deduction from the outlet flow rate of treated wastewater (TWW) due to removal of sludge was also adjusted. Further to the present monitoring procedure of industries and the regulatory requirements enforced by the CEA, as well as the industry's expected water quality requirements, the quality parameters of the context-specific model were limited to three main water parameters: biological oxygen demand (BOD), chemical oxygen demand (COD) and total suspended solids (TSS). As a result, the conceptual model was refined to the selected context and the enhanced context-specific model was presented (refer to Figure 5.7). The model was finally tested by using hypothetical data. The context-specific revision made to the conceptual model can be expressed as the key outcome derived from achieving the fourth objective of the research.

As the fifth and final objective of the research, **the applicability and feasibility of the developed model to an industrial zone in Sri Lanka were evaluated**. An export processing zone (EPZ) in Sri Lanka was selected as the suitable case study in which to apply the developed model. Three industrial entities, which were located within geographical proximity (not exceeding a distance of 1.5 km): (i) Entity A: Elastic manufacturer; (ii) Entity B: Textile dyeing and washing plant; and (iii) Entity C: Rubber toy manufacturer, were studied to identify the possible water synergies to develop the water exchange network. By considering the company willingness, feasibility of using requirements, four synergies (A–B, A–C, B–A and C–A) were finally selected for initiating an industrial symbiosis-based water exchange network (refer to Figure 6.4).

Water availability for supply at water source industrial entities and water demand of water sink industrial entities were fed into the software with the constraints of water balance and water quality. The mixed integer linear programming (MILP) approach was adopted, with the optimal water network then derived. In the proposed optimal water network, 22,068.02 m³/month of wastewater from Entity A is to be utilised as TWW for Entities B and C (of which 20,427.18 m³/month of TWW is to be utilised for Entity B and 1,640.84 m³/month of TWW is to be utilised for Entity C, while 16,176.82 m³/month of wastewater from Entity B is to be utilised as TWW for Entity A and 1,452.96 m³/month of wastewater from Entity C is to be utilised as TWW for

Entity A. Furthermore, a total of 15,443.04 m³/month of freshwater is used in the optimal network, of which 100% is utilised by Entity A and only 3,542.01m³/month of wastewater is discharged, as maximum recovery of wastewater has taken place through common wastewater treatment (CWWT).

The feasibility of the developed model in the selected context was evaluated in terms of economic, environmental and social feasibility. With the use of LCCA, an economic assessment was conducted over a period of 50 years related to the existing conventional water network and the proposed optimal water exchange network. Based on the LCCA, economic feasibility of the proposed optimal water exchange network was expressed in comparison to the existing conventional water network. The proposed optimal water exchange network resulted in less total LCC over its economic life compared to the conventional water network. Even though optimal water exchange would require an initial investment of LKR63 million for infrastructure development, the total LCC has been considerably reduced over the time generating LKR190 million of cost saving (11.82%) in the long term. According to the LCCA, Entity A showed a 25.54% of cost saving in the long term by engaging in the proposed optimal water exchange network. Industrial Entity B also showed a 9.49% and Entity C showed a 15.31% of cost saving through the proposed optimal water exchange network. The impact of changes in Production Price Index (PPI) on the total LCC and cost savings of both investment options was measured using the sensitivity analysis technique. The total LCC of both the proposed optimal water exchange network and the conventional water network was re-calculated by adopting $\pm 7\%$ of change in the PPI in three different scenarios (4%, 14.8% and 19.4%) to determine the LCC deviations from the original estimate (9%). The PPI showed a very steeper curve (between 14.8 %–19.4%), which indicates a high degree of sensitivity to deviations of the LCC from the original LCC estimate. The proposed optimal network showed possible cost savings under each scenario; thus, it can be considered as a cost-effective investment decision in achieving long-term economic benefits.

Under environmental feasibility, two criteria namely, (i) reduction of raw water extraction and (ii) discharge of wastewater were considered to analyse the environmental feasibility of the proposed water exchange network. In terms of environmental benefits, the optimal water exchange network showed a lower freshwater intake compared to the conventional water network in the selected industrial zone, with a reduction of 72%. Wastewater discharge was also reduced by 92.2% in the optimal water exchange network. Furthermore, maximum recovery of industrial wastewater reduces the environmental impact of industrial development, while achieving the sustainable development goals (SDGs), such as SDG3, SDG6, SDG12, SDG13, SDG14 and SDG15.

As the social benefits, the reduction of industrial demand for drinking water could lower the supply of potable water for industrial needs which could instead be used to fulfil the domestic needs of Sri Lanka. Furthermore, initiating optimal water exchange networks ensures the use of wastewater through its maximum recovery, which reduces the wastewater discharge into surface and groundwater bodies. As industrial

wastewater has been identified as one of the main polluters of water bodies as well as a risk factor of water-borne diseases, initiating an optimal water exchange network within industrial zones in Sri Lanka would enhance the status of health and well-being of the people and other living beings. Fertiliser production using sludge from CWWT (after dewatering and sun drying) would also create new job opportunities and generate benefits to local cultivation. The key research outcomes obtained through evaluation of the applicability and feasibility of the developed model ensured the achievement of the fifth objective.

Accordingly, the achievement of the first, second, third, fourth and fifth objectives by generating significant research outcomes ensures and justifies the achievement of the ultimate research aim.

7.3 Limitations of the Model Application

The scope of this research was to develop a model to assess the optimum water flow of industrial symbiosis. The proposed generic model can be applied in any context for optimising the water flow of industrial symbiosis, subject to context-specific variants and constraints. Accordingly, the developed model was applied and a context specific robust model was developed to assess the optimum water flow of IS in Sri Lanka. The applicability and feasibility of the developed context specific model was then evaluated to a selected industrial zone embedding a cluster of three different industrial entities in Sri Lanka (refer Table 6.2).

While the general limitations of the overall research were clarified in Section 1.5, the limitations of the applicability of the context specific model can be recognised as described below.

- A very limited number of industrial zones are in-operation in Sri Lanka and among them, one industrial zone locating highly water intensive industries was selected as the suitable case study with a greater necessity of reducing freshwater demand and wastewater discharge through maximum wastewater recovery.
- The evaluation of model was also limited to a single case study due to the restricted access to data during COVID-19 outbreak. Industrial zones were the highly affected community of COVID19 in large scale, which created a huge impact on data collection. Hence, the data were gathered mainly through documents review and face-to face & online interviews (complying with social distancing guidelines) ensuring that there may unlikely be any risks from taking part in the interview.
- Three industrial entities were selected for the water exchange network based on the theory of industrial symbiosis. Industrial sectors showing a high level of freshwater consumption and wastewater discharge as well as possible water synergies were selected to evaluate the applicability of the model. However, the industrial entities, located with the same geographical proximity by satisfying the selection criteria mentioned in Table 6.1, can also be engaged in

the proposed IS network for exchanging TWW for reducing freshwater demand and waste water discharge.

- Since the utilisation of treated wastewater for drinking purposes of the industrial entities was not practical to be considered (as per the real practices of the industries selected), freshwater consumption for the industrial and cooling purposes was only considered in assessing the optimum water flow among the industrial entities of the selected case study assuring ecological validity of the research.

Considering the above discussion, the developed context specific model is more robust and convenient for applying in similar industry settings, thus can be generalised to the particular context with confidence.

Even though the applicability of the proposed conceptual model was limited to context of an industrial zone in Sri Lanka, the model can be applied in any context or different industrial setting subjected to context specific enhancements and modifications. The key variables of the model can be refined to the selected context to assure a robust assessment of the optimal water flow. Further, the proposed model has been developed to pre-evaluate the planned water synergies prior to implementation. Hence, the robustness of the model can be conveniently sustained at the stage of ‘pre-evaluation and optimisation modelling’ since the selection criteria of industrial entities (regulations of water quality, water quality requirements of the participating industries, industrial water needs and possible water synergies between industries) will already be considered during the stage of planning in the proposed top-down planning approach of IS (refer Figure 2.11).

In summary, the proposed conceptual model can be significantly adopted in any context subjected to context specific enhancements and modifications while the context specific model is more robust to be applied in similar industrial settings in any context.

7.4 Contribution to Knowledge

This research contributes significantly to new knowledge on industrial symbiosis as follows:

Firstly, this research contributes to the body of knowledge on industrial symbiosis by expanding the previous research contributions during the last three decades through a comprehensive review and analysis. Consequently, this research provides an underpinned overview, at a glance, about the scientific growth of the industrial symbiosis concept for researchers seeking to initiate new research directions.

Secondly, empirical studies revealed that the literature on industrial symbiosis has been developed and disseminated over the last decade by prominent research scholars. By considering the various insights made by previous researchers in defining the concept of industrial symbiosis, the researcher developed the following working definition of the concept of industrial symbiosis to facilitate this research:

“The engagement of traditionally separated and geographically proximate industrial entities to achieve collaborative benefits through the physical exchange of resources including materials, energy, water, by-products, services and infrastructure,”

which will be contributed to the industrial symbiosis literature as a very recent and vivid definition of industrial symbiosis.

Thirdly, as found in previous research, many industrial symbiosis networks across the globe have failed in the long term due to inefficient planning of the water synergies. The traditional top-down planning approach of industrial symbiosis has especially showed a deficiency, lacking a standardised way to pre-evaluate the planned water synergies prior to implementation. Hence, this research proposes a re-development of the traditional top-down planning approach by adding a new stage of “pre-evaluation and optimisation modelling”, which will add value to the industrial symbiosis literature.

Fourthly, many studies have focused on developing optimisation models for water exchange with economic and environmental objectives, including water minimisation and reduction of water transportation and treatment cost, etc. The current study’s optimisation model, developed by considering the objective of reducing freshwater consumption of the industrial symbiosis network through maximum wastewater recovery, underpins the novelty of this research. Furthermore, the variables, functions and formulae embedded in the conceptual model create a unique foundation for assessing the optimum water flow of industrial symbiosis, thus contributing to new knowledge on industrial symbiosis.

This research also shows a significant contribution in sustainable development and circular economy literature specially, the outcomes of the research (the proposed model) can be adopted as a global mechanism in achieving SDGs specially to overcome the presence of the burdens on water bodies through efficient and responsible consumption and production of natural resources and reuse of wastewater. Furthermore, since IS is a key strategy that supports the transition of circular economy in the industries through closing the flow of resources, this research can be used as a basis to enhance the industrial reuse, recycling and resharing of waste and wastewater within a circular nature.

7.5 Recommendations for Industry Practitioners

The proposed holistic re-development of the top-down approach is an innovative solution which will support industry professionals in achieving a decline in the discontinuity ratio of industrial symbiosis-based water exchange networks.

The proposed model can be used to assist industry practitioners to obtain a holistic idea about their engagement in industrial symbiosis which may reduce the interdependency risk of industrial symbiosis partners. The optimisation model is more robust and convenient for application in similar industry settings by industry

practitioners in assessing the optimum water flow of industrial symbiosis. Furthermore, it ensures the successful implementation of optimum water exchange networks with warranted economic, environmental and social benefits in the long term at both institutional and industrial park levels.

Indeed, the proposed model can be used as an iconic solution for countries suffering from water stress to reduce the industrial demand for freshwater. Hence, the proposed conceptual model can be applied in any context for optimising the water flow of industrial symbiosis, subject to context-specific variants and constraints. This research can be used as a role model for initiating optimum water exchange networks in all developed and developing countries by reducing the environmental impact of industrialisation through optimum water sharing.

Moreover, the study's key findings will serve as a benchmark for future researchers, academics, industry professionals and policy makers willing to investigate this same initiative from different perspectives as described next.

7.6 Recommendations for Further Research

The assessment of the optimum water flow was considered in this research to achieve the objective of minimising freshwater consumption through maximum wastewater recovery. Further research could be conducted by adopting multi-objective optimisation wherein significant economic, social and environmental objectives could be achieved.

The evaluation of the applicability and feasibility of the developed model was limited to industrial zones in Sri Lanka. Hence, the developed model could be used in various contexts to initiate optimum water exchange networks, subject to context-specific variations and enhancements.

This research was limited to assess the optimum water flow of industrial symbiosis. Further research could be extended to explore different combinations of the multiple resources flows of industrial symbiosis, such as water and energy flows, or water, services and infrastructure flows, etc. to obtain sustainable benefits.

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APPENDICES

APPENDIX 1: Semi-structured interview guideline used for Phase II: Interviews with industry experts and a sample of transcribed copy

PLAIN LANGUAGE STATEMENT AND CONSENT FORM



TO: Professionals/ Experts in the field

Plain Language Statement

Date:

Full Project Title: Developing a Model to Assess the Optimum Wastewater Flow of Industrial Symbiosis (IS)

Principal Researcher: Dr. Gayani Karunasena

Student Researcher: Bhadra Harshini Mallawaarachchi

Associate Researcher(s): Associate Professor Chunlu Liu

External Supervisor: Prof. Yasangika Sandanayake

You are invited to take part in this research study. Participation in any research project is voluntary. If you do not wish to take part you are not obligated to.

This plain language Statement will explain the details of the research project. Feel free to ask questions regarding any information in the document. Once you have read this form and agreed to participate, please sign the attached consent form and return via email (hmallawarachchi@gmail.com).

The aim and objectives of this research are as follows;

Aim:

To develop a model to assess the optimum wastewater flow of industrial symbiosis

Objectives:

1. review the current status and issues of wastewater exchange between industries in IS

2. establish a conceptual analytic model to assess the optimum wastewater flow of IS
3. develop a mathematical model to assess the optimum wastewater flow of IS
4. evaluate the applicability of the developed model in a real industry scenario

Your responses will be preserved confidentially. Since the information collected will be non-identifiable; the publication of research results and outcomes will not be revealed the actual details of you and your organisation. Thus, the interview has no risk involved for participants. Further, you are free to withdraw yourself from the interview at any time.

By considering the existing health conditions and risk due to COVID-19 outbreak, following measures will be specially considered during the interview. Thus, there may unlikely be any risks from taking part in the interview.

- In order to call you, you will need to provide your phone number when we arrange the date for you to take part. Once we have confirmed you are eligible to participate, we will no longer need your phone number so it will be permanently deleted.
- To reduce the spread of COVID-19, we will ask you to wash or sanitise your hands when you arrive to participate and prior to departing. While we are together, it is important that we follow social distancing guidelines. That means that we will need to stay at least 1.5m away from you and we won't be able to shake your hand, or engage in any other form of physical contact. It's not necessary for you to wear a mask unless you have been advised to do so by your doctor but we do ask that you cover your nose and mouth with a tissue if you cough or sneeze. If you don't have a tissue, you should cough or sneeze into your upper sleeve or elbow. After each participant leaves, we will sanitize all work surfaces, door handles etc. to avoid the risk of infection.

The face to face interview will be conducted and it will take approximately one hour. With your consent, we wish to record (audio) the interview ensuring the accuracy of data. The audio recording of the interview will be transcribed and the recording will be destroyed. However, if you do not wish the interview to be recorded, we will take handwritten notes of the interview. The handwritten notes will also be transcribed supporting the audio recording of the interview and finally be destroyed.

Further, all the audio recordings and the hand written notes of each interview will be transcribed (to make them de-identifiable) within a one month's period of time from the date of interview so that you, as a prospective participant, will be provided with an opportunity to withdraw yourself from the interview if required. The data will be deleted during the given period of time before the research begins.

Data collected in this research will be stored in non-identifiable form at both institutions (School of Architecture and Built Environment, Deakin University and the University of Moratuwa) with required security, for a period of at least five years after the final publication of the research outcomes. The data in both physical form and electronic form will be stored in University of Moratuwa. The electronic data will be submitted to be stored in a secure server at School of Architecture and Built Environment in Deakin University to maintain the data security.

Further, the research will be monitored by the principal supervisor, co-supervisor and the external supervisor through weekly meetings, which will be conducted via zoom/Skype. The members of the supervisory team may have access to the collected data, data analysis and findings of the research.

There is no guarantee that you will receive any benefits from the research; however, your willingness to participate will contribute to the benefits of the research. As the possible benefits to the wider community, this research may result in high stability of the wastewater exchange among the co-located industries in which firms may maintain the required optimum flow efficiency by continuing the wastewater input and output flows in long term. This may also reduce the resource cost especially for fresh water consumption and wastewater disposal as aimed in this research.

Thus, the outcomes of the research will be published in the PhD Thesis of the student researcher and in the peer reviewed journals and conference papers which may support disseminating the new knowledge to the community and especially to the industrial sector to obtain the intended benefits.

The research is funded by Deakin University as a part of the requirements for a PhD. Approval to undertake the research is granted by the Human Research Ethics Committee of Deakin University.

Complaints:

If you have any complaints about any aspect of the project, the way it is being conducted or any questions about your rights as a research participant, then you may contact:

The Human Research Ethics Office, Deakin University, 221 Burwood Highway, Burwood Victoria 3125, Telephone: 9251 7129, research-ethics@deakin.edu.au

Please quote project number:

Bhadra Harshini Mallawaarachchi (PhD Student)

Department of Building Economics,

University of Moratuwa / Email: hmallawarachchi@gmail.com / Mobile: +94

718943433

For further information or if you have problems concerning this project, you can contact the principal researchers. The researchers responsible for this project are:

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PLAIN LANGUAGE STATEMENT AND CONSENT FORM

TO: Professionals/ Experts in the field

Consent Form

Date:

Full Project Title: Developing a Model to Assess the Optimum Wastewater Flow of Industrial Symbiosis (IS)

Reference Number: SEBE-2020-33

I have read, and I understand the attached Plain Language Statement.

I freely agree to participate in this project according to the conditions in the Plain Language Statement.

I agree that the interview will be audio recorded.

I have been given a copy of the Plain Language Statement and Consent Form to keep.

The researcher has agreed not to reveal my identity and personal details, including where information about this project is published, or presented in any public form.

Participant's Name (printed)

Signature Date

Bhadra Harshini Mallawaarachchi
Department of Building Economics,
University of Moratuwa,
Sri Lanka
Ph: +94 718943433
Email: hmallawarachchi@gmail.com



PLAIN LANGUAGE STATEMENT AND CONSENT FORM

TO: Professionals/ Experts in the field

Withdrawal of Consent Form

(To be used for participants who wish to withdraw from the project)

Date:

Full Project Title: Developing a Model to Assess the Optimum Wastewater Flow of Industrial Symbiosis (IS)

Reference Number:

I hereby wish to WITHDRAW my consent to participate in the above research project and understand that such withdrawal WILL NOT jeopardise my relationship with Deakin University and University of Moratuwa.

Participant's Name (printed)

Signature Date

Please post or email this form to:

Bhadra Harshini Mallawaarachchi
Department of Building Economics,
University of Moratuwa,
Sri Lanka
Ph: +94 718943433
Email: hmallawarachchi@gmail.com

INTERVIEW GUIDELINE FOR EXPERTS IN THE FIELD OF INDUSTRIAL WATER AND WASTEWATER MANAGEMENT (PHASE – II)

Dear Sir/ Madam,

I, Harshini Mallawaarachchi, am a PhD student jointly supervised by the University of Moratuwa, Sri Lanka and Deakin University, Australia. I am conducting my research in the field of industrial symbiosis for treated wastewater exchange between industries, which is aiming to develop a model to assess the optimum water flow of industrial symbiosis. I am at the stage of data collection, and I highly believed that your expertise and opinions would be valuable towards this research to serve the data collection purpose.

With your expertise in the field of industrial water and wastewater management, I highly appreciate that you can spend your valuable time participating for this research. The interview guideline is attached with this email. Also, the interview, which will be conducted by the researcher, will take approximately a half an hour to complete.

Please also find the Plain Language Statement which explains in detail about the research. Please be assured that all information provided for this research will be strictly confidential and will be used for academic purpose only. Should you require any further information, please do not hesitate to contact me. Also, kindly send me the signed consent form attached in this email if you could accept my request to participate in this research. Further, kindly let me know a possible date and time that is convenient to you to make necessary arrangements for the interview (Online).

Thank you for your time and consideration on this matter. Looking forward to your favorable response.

Thank you.

Regards,

Harshini Mallawaarachchi

**Department of Building Economics,
Faculty of Architecture,
University of Moratuwa,
Sri Lanka
Ph: +94 718943433
Email: hmallawarachchi@gmail.com**

THE INTERVIEW GUIDELINE

DETAILS OF INTERVIEW

Designation of interviewee		
Field of specialisation		
Years of experience in the field		
Date of interview		
Time and Duration		hours

1.0 INFORMATION OF THE INTERVIEWEE

- 1.1) Can you briefly explain about your role in this organisation/ field?
- 1.2) Can you briefly explain about your experience in industrial water and wastewater management?

2.0 INDUSTRIAL WATER MANAGEMENT

- 2.1) What is the importance of 'water' as a resource to countries like Sri Lanka?
- 2.2) What are the issues in obtaining and utilising freshwater in industries?
- 2.3) What are the current strategies, policies and procedures applied for industrial water management in Sri Lanka?
- 2.4) What are the issues in current practice related to industrial water management?

3.0 INDUSTRIAL WASTEWATER MANAGEMENT

- 3.1) What are the current strategies, policies and procedures applied internally for wastewater management in industries?
- 3.2) What are the existing national policies for industrial wastewater management in Sri Lanka and its impact to industry?
- 3.3) What are the issues in current practice related to wastewater treatment and disposal in industries?

4.0 INDUSTRIAL WASTEWATER EXCHANGE

- 4.1) What are the benefits of reusing treated wastewater to the industries?
- 4.2) Are you aware about the possibility of exchanging treated wastewater among the co-located industries (Industrial Symbiosis) to reduce the freshwater demand?
- 4.3) What are the barriers to exchange the treated wastewater among the industries?
- 4.4) Do you think the following factors are important to be considered in exchanging wastewater between the industries?

Factors		Is it important?		
		Yes	No	If 'YES' - for which purpose/s If 'NO' - Reasons
1	Number of industrial firms in the IS network			
2	Close-proximity of industries (Average distance between the industries/firms in industrial park)			
3	Ownership of the facility			
4	Having pre-connections for transferring water (No water will be transferred when there are no connections exist)			
5	Considering input and output water flows to each industry (the internal processes of the industries will not be considered - black box approach)			
6	Having a central wastewater treatment plant within the network			
7	Predetermined tolerance limit of water quality for freshwater			
8	Predetermined tolerance limit of water quality for treated wastewater			
9	Cost for wastewater treatment and disposal by industry/ firm			
10	Cost for treated wastewater exchange by industry/ firm			
11	Initial investment required by industry/ firm to imitate water synergies between the industries			
12	Expected return (environmental and economic) for industry/ firm by engaging in the IS network for exchanging water			
13	Collective advantage by whole industrial network			
	Other factors			

5.0 AVAILABILITY OF WATER DATA

5.1) How do industries obtain freshwater (water sources)?

5.2) How do industries measure the current freshwater consumption from above sources?

5.2) What are the existing techniques used by the industries to measure and record the discharge and reuse of wastewater?

5.3) What are the water quality parameters currently applied by industries for (i) the use of freshwater and (ii) the use of treated wastewater and (iii) wastewater discharge?

5.4) Are industries currently utilising the following variables for measuring and recording water related data?

	Water related variables	Yes	No	If 'YES' - for which purpose/s If 'NO' - Reasons
1.0	Freshwater utilisation			
1.1	Number of freshwater sources (external)			
1.2	Number of freshwater sources (internal)			
1.3	Freshwater supply (m ³ /day)			
1.4	Freshwater demand (m ³ /day)			
1.5	Average freshwater consumption/ input flowrate (m ³ /day)			
2.0	Wastewater generation			
2.1	Volume of wastewater generated by firm (m ³ /day)			
3.0	Wastewater treatment and reuse			
3.1	Total volume of treated wastewater (m ³ /day)			
3.2	Rate of loss for the treated wastewater (m ³ /day)			
3.3	Volume of treated wastewater reused within the firm (m ³ /day)			
3.4	Volume of treated wastewater send to disposal (m ³ /day)			
3.5	Volume of wastewater reused without treatment (m ³ /day)			
3.6	Current rate of reduction of freshwater consumption (m ³ /day)			
4.0	Water quality			
4.1	Number of contaminants considered			
4.2	Water quality limit (lower and upper range) for fresh water (mg/1)			
4.3	Water quality limit (lower and upper range) for treated wastewater - for reuse (mg/1)			
4.4	Water quality limit (lower and upper range) for treated wastewater - for disposal (mg/1)			
5.0	Other			
5.1	Number of firms in the industrial network			
5.2	Distance between each firm			

.....**THANK YOU**.....

INTERVIEW GUIDELINE FOR EXPERTS IN THE FIELD OF INDUSTRIAL WATER AND WASTEWATER MANAGEMENT (PHASE – II)

Dear Sir/ Madam,

I, Harshini Mallawaarachchi, am a PhD student jointly supervised by the University of Moratuwa, Sri Lanka and Deakin University, Australia. I am conducting my research in the field of industrial symbiosis for treated wastewater exchange between industries, which is aiming to develop a model to assess the optimum water flow of industrial symbiosis. I am at the stage of data collection, and I highly believed that your expertise and opinions would be valuable towards this research to serve the data collection purpose.

With your expertise in the field of industrial water and wastewater management, I highly appreciate that you can spend your valuable time participating for this research. The interview guideline is attached with this email. Also, the interview, which will be conducted by the researcher, will take approximately a half an hour to complete.

Please also find the Plain Language Statement which explains in detail about the research. Please be assured that all information provided for this research will be strictly confidential and will be used for academic purpose only. Should you require any further information, please do not hesitate to contact me. Also, kindly send me the signed consent form attached in this email if you could accept my request to participate in this research. Further, kindly let me know a possible date and time that is convenient to you to make necessary arrangements for the interview (Online).

Thank you for your time and consideration on this matter. Looking forward to your favorable response.

Thank you.

Regards,

Harshini Mallawaarachchi

**Department of Building Economics,
Faculty of Architecture,
University of Moratuwa,
Sri Lanka
Ph: +94 718943433
Email: hmallawarachchi@gmail.com**

THE INTERVIEW GUIDELINE FOR PHASE II: INTERVIEWS WITH INDUSTRY EXPERTS

(A Transcribed Copy)

DETAILS OF INTERVIEW

Designation of interviewee	Manager – Compliance and Sustainability	
Field of specialisation	Facilities Management	
Years of experience in the field	9 years	
Date of interview	05/11/2021	
Time and Duration	12.00pm – 1.00pm	01 hour

1.0 INFORMATION OF THE INTERVIEWEE

1.1) Can you briefly explain about your role in this organisation/ field?

I am the compliance and Sustainability manager who looks after all the matters relating to water, waste and environmental concerns.

1.2) Can you briefly explain about your experience in industrial water and wastewater management?

In our organisation, we are currently considering about reducing the water consumption and domestic wastewater discharge through own reuse. We use domestic wastewater for gardening purposes.

2.0 INDUSTRIAL WATER MANAGEMENT

2.1) What is the importance of 'water' as a resource to countries like Sri Lanka?

Simply, water is a scared resource for most of the countries including Sri Lanka. Even though we have sufficient water bodies, only very lesser amount can be actually used.

2.2) What are the issues in obtaining and utilising freshwater in industries?

Currently, there is not any issue regarding this since our factory mainly includes sewing and cutting only. So, there is no heavy water consumption. We obtain water from NWSDB.

2.3) What are the current strategies, policies and procedures applied for industrial water management in Sri Lanka?

As a BOI approved company, there are some BOI guidelines that are applied. They provide u water through NWSDB.

2.4) What are the issues in current practice related to industrial water management?

As I explained earlier, currently, there is not any issue regarding this since our factory mainly includes sewing and cutting only.

3.0 INDUSTRIAL WASTEWATER MANAGEMENT

3.1) What are the current strategies, policies and procedures applied internally for wastewater management in industries?

We are following the BOI guidelines. Since the beginning we have agreed to follow them. As per the guidelines, we can send the domestic wastewater directly to the central treatment without any pre-treatment. Further, we are using wastewater of AHU for cooling towers.

3.2) What are the existing national policies for industrial wastewater management in Sri Lanka and its impact to industry?

We have obtained EPL as per the CEA guideline and have to maintain and renew it.

3.3) What are the issues in current practice related to wastewater treatment and disposal in industries?

Since we are not intensively use water for our industrial processes, the current wastewater discharge is manageable however, sometimes, when there are issues related to central treatment, we face difficulties in discharging domestic wastewater.

4.0 INDUSTRIAL WASTEWATER EXCHANGE

4.1) What are the benefits of reusing treated wastewater to the industries?

Currently, we are reusing domestic wastewater to some extent for the gardening purposes since it does not require any treatment. Remaining amount is sending to central treatment. Further, we are applying water efficiency measures for water reduction.

4.2) Are you aware about the possibility of exchanging treated wastewater among the co-located industries (Industrial Symbiosis) to reduce the freshwater demand?

It is an ideal concept that can be used by the industries to reuse their wastewater in a higher level by going beyond their own reuse. But we could not find any application here in Sri Lanka yet.

4.3) What are the barriers to exchange the treated wastewater among the industries?

If we are exchanging treated wastewater, we have to have a proper process for treating them to high quality level because different industries require different quality levels for using them in the industrial process. So, maintaining the required quality will be a matter.

4.4) Do you think the following factors are important to be considered in exchanging wastewater between the industries?

Factors		Is it important?		
		Yes	No	If 'YES' - for which purpose/s If 'NO' - Reasons
1	Number of industrial firms in the IS network			
2	Close-proximity of industries (Average distance between the industries/firms in industrial park)	Y		
3	Ownership of the facility	Y		
4	Having pre-connections for transferring water (No water will be transferred when there are no connections exist)	Y		
5	Considering input and output water flows to each industry (the internal processes of the industries will not be considered - black box approach)	Y		
6	Having a central wastewater treatment plant within the network	Y		It does not create an additional investment cost
7	Predetermined tolerance limit of water quality for freshwater	Y		
8	Predetermined tolerance limit of water quality for treated wastewater	Y		
9	Cost for wastewater treatment and disposal by industry/ firm	Y		
10	Cost for treated wastewater exchange by industry/ firm	Y		
11	Initial investment required by industry/ firm to imitate water synergies between the industries	Y		
12	Expected return (environmental and economic) for industry/ firm by engaging in the IS network for exchanging water	Y		
13	Collective advantage by whole industrial network	Y		
	Other factors			

5.0 AVAILABILITY OF WATER DATA

5.1) How do industries obtain freshwater (water sources)?

We are mainly obtaining water from NWSDB and that is sufficient for us.

5.2) How do industries measure the current freshwater consumption from above sources?

Usually, there are water meters fixed by the water board. Further, BOI and all companies are required to maintain records on daily consumption of water as well as the wastewater discharge.

5.2) What are the existing techniques used by the industries to measure and record the discharge and reuse of wastewater?

BOI and all companies are required to maintain records on daily consumption of water as well as the wastewater discharge. But there are no meters to measure the discharge. Usually, we are considering 80% thumb rule. That means, 80% of freshwater that is utilised by any industry is discharged as wastewater. That is the base to pay for central treatment by BOI.

5.3) What are the water quality parameters currently applied by industries for (i) the use of freshwater and (ii) the use of treated wastewater and (iii) wastewater discharge?

Since we are not utilising water for industry purposes; we only consider the freshwater quality. So, we assured that water board supplies us a right quality and safe water.

5.4) Are industries currently utilising the following variables for measuring and recording water related data?

	Water related variables	Yes	No	If 'YES' - for which purpose/s If 'NO' - Reasons
1.0	Freshwater utilisation			
1.1	Number of freshwater sources (external)			
1.2	Number of freshwater sources (internal)			
1.3	Freshwater supply (m ³ /day)	Y		
1.4	Freshwater demand (m ³ /day)	Y		
1.5	Average freshwater consumption/ input flowrate (m ³ /day)	Y		
2.0	Wastewater generation			
2.1	Volume of wastewater generated by firm (m ³ /day)	Y		
3.0	Wastewater treatment and reuse			
3.1	Total volume of treated wastewater (m ³ /day)			
3.2	Rate of loss for the treated wastewater (m ³ /day)			
3.3	Volume of treated wastewater reused within the firm (m ³ /day)	Y		
3.4	Volume of treated wastewater send to disposal (m ³ /day)	Y		
3.5	Volume of wastewater reused without treatment (m ³ /day)			
3.6	Current rate of reduction of freshwater consumption (m ³ /day)			
4.0	Water quality			
4.1	Number of contaminants considered			
4.2	Water quality limit (lower and upper range) for fresh water (mg/l)	Y		

4.3	Water quality limit (lower and upper range) for treated wastewater – for reuse (mg/l)			
4.4	Water quality limit (lower and upper range) for treated wastewater – for disposal (mg/l)			
5.0	Other			
5.1	Number of firms in the industrial network			
5.2	Distance between each firm			

..... **THANK YOU**

APPENDIX 2: Semi-structured interview guideline used for Phase III: Case study and a sample of transcribed copy

**PLAIN LANGUAGE STATEMENT AND CONSENT
FORM**



TO: Professionals/ Experts in the field

Plain Language Statement

Date:

Full Project Title: Developing a Model to Assess the Optimum Wastewater Flow of Industrial Symbiosis (IS)

Principal Researcher: Dr. Gayani Karunasena

Student Researcher: Bhadra Harshini Mallawaarachchi

Associate Researcher(s): Associate Professor Chunlu Liu

External Supervisor: Prof. Yasangika Sandanayake

You are invited to take part in this research study. Participation in any research project is voluntary. If you do not wish to take part you are not obligated to.

This plain language Statement will explain the details of the research project. Feel free to ask questions regarding any information in the document. Once you have read this form and agreed to participate, please sign the attached consent form and return via email (hmallawarachchi@gmail.com).

The aim and objectives of this research are as follows;

Aim:

To develop a model to assess the optimum wastewater flow of industrial symbiosis

Objectives:

5. review the current status and issues of wastewater exchange between industries in IS
6. establish a conceptual analytic model to assess the optimum wastewater flow of IS
7. develop a mathematical model to assess the optimum wastewater flow of IS

8. evaluate the applicability of the developed model in a real industry scenario

Your responses will be preserved confidentially. Since the information collected will be non-identifiable; the publication of research results and outcomes will not be revealed the actual details of you and your organisation. Thus, the interview has no risk involved for participants. Further, you are free to withdraw yourself from the interview at any time.

By considering the existing health conditions and risk due to COVID-19 outbreak, following measures will be specially considered during the interview. Thus, there may unlikely be any risks from taking part in the interview.

- In order to call you, you will need to provide your phone number when we arrange the date for you to take part. Once we have confirmed you are eligible to participate, we will no longer need your phone number so it will be permanently deleted.
- To reduce the spread of COVID-19, we will ask you to wash or sanitise your hands when you arrive to participate and prior to departing. While we are together, it is important that we follow social distancing guidelines. That means that we will need to stay at least 1.5m away from you and we won't be able to shake your hand, or engage in any other form of physical contact. It's not necessary for you to wear a mask unless you have been advised to do so by your doctor but we do ask that you cover your nose and mouth with a tissue if you cough or sneeze. If you don't have a tissue, you should cough or sneeze into your upper sleeve or elbow. After each participant leaves, we will sanitize all work surfaces, door handles etc. to avoid the risk of infection.

The face to face interview will be conducted and it will take approximately one hour. With you consent, we wish to record (audio) the interview ensuring the accuracy of data. The audio recording of the interview will be transcribed and the recording will be destroyed. However, if you do not wish the interview to be recorded, we will take handwritten notes of the interview. The handwritten notes will also be transcribed supporting the audio recording of the interview and finally be destroyed.

Further, all the audio recordings and the hand written notes of each interview will be transcribed (to make them de-identifiable) within a one month's period of time from the date of interview so that you, as a prospective participant, will be provided with an opportunity to withdraw yourself from the interview if required. The data will be deleted during the given period of time before the research begins.

Data collected in this research will be stored in non-identifiable form at both institutions (School of Architecture and Built Environment, Deakin University and the University of Moratuwa) with required security, for a period of at least five years after the final publication of the research outcomes. The data in both physical form and

electronic form will be stored in University of Moratuwa. The electronic data will be submitted to be stored in a secure server at School of Architecture and Built Environment in Deakin University to maintain the data security.

Further, the research will be monitored by the principal supervisor, co-supervisor and the external supervisor through weekly meetings, which will be conducted via zoom/Skype. The members of the supervisory team may have access to the collected data, data analysis and findings of the research.

There is no guarantee that you will receive any benefits from the research; however, your willingness to participate will contribute to the benefits of the research. As the possible benefits to the wider community, this research may result in high stability of the wastewater exchange among the co-located industries in which firms may maintain the required optimum flow efficiency by continuing the wastewater input and output flows in long term. This may also reduce the resource cost especially for fresh water consumption and wastewater disposal as aimed in this research.

Thus, the outcomes of the research will be published in the PhD Thesis of the student researcher and in the peer reviewed journals and conference papers which may support disseminating the new knowledge to the community and especially to the industrial sector to obtain the intended benefits.

The research is funded by Deakin University as a part of the requirements for a PhD. Approval to undertake the research is granted by the Human Research Ethics Committee of Deakin University.

Complaints:

If you have any complaints about any aspect of the project, the way it is being conducted or any questions about your rights as a research participant, then you may contact:

The Human Research Ethics Office, Deakin University, 221 Burwood Highway, Burwood Victoria 3125, Telephone: 9251 7129, research-ethics@deakin.edu.au

Please quote project number:

Bhadra Harshini Mallawaarachchi (PhD Student)

Department of Building Economics,

University of Moratuwa / Email: hmallawarachchi@gmail.com / Mobile: +94

718943433

For further information or if you have problems concerning this project, you can contact the principal researchers. The researchers responsible for this project are:

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School of Architecture and Built Environment

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Sri Lanka
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Email: hmallawarachchi@gmail.com



PLAIN LANGUAGE STATEMENT AND CONSENT FORM

TO: Professionals/ Experts in the field

Consent Form

Date:

Full Project Title: Developing a Model to Assess the Optimum Wastewater Flow of Industrial Symbiosis (IS)

Reference Number: SEBE-2020-33

I have read, and I understand the attached Plain Language Statement.

I freely agree to participate in this project according to the conditions in the Plain Language Statement.

I agree that the interview will be audio recorded.

I have been given a copy of the Plain Language Statement and Consent Form to keep.

The researcher has agreed not to reveal my identity and personal details, including where information about this project is published, or presented in any public form.

Participant's Name (printed)

Signature Date

Bhadra Harshini Mallawaarachchi
Department of Building Economics,
University of Moratuwa,
Sri Lanka
Ph: +94 718943433
Email: hmallawarachchi@gmail.com



PLAIN LANGUAGE STATEMENT AND CONSENT FORM

TO: Professionals/ Experts in the field

Withdrawal of Consent Form

(To be used for participants who wish to withdraw from the project)

Date:

Full Project Title: Developing a Model to Assess the Optimum Wastewater Flow of Industrial Symbiosis (IS)

Reference Number:

I hereby wish to WITHDRAW my consent to participate in the above research project and understand that such withdrawal WILL NOT jeopardise my relationship with Deakin University and University of Moratuwa.

Participant's Name (printed)

Signature Date

Please post or email this form to:

Bhadra Harshini Mallawaarachchi
Department of Building Economics,
University of Moratuwa,
Sri Lanka
Ph: +94 718943433
Email: hmallawarachchi@gmail.com

INTERVIEW GUIDELINE (PHASE III – CASE STUDY)

DETAILS OF INTERVIEW

Type of organisation/ industry		
Designation of interviewee		
Date of interview		
Time and Duration		hours

1.0 INFORMATION OF THE ORGANISATION

- 1.1) Can you give brief introduction to the organisation?
- 1.2) What are types of the internal processes available?

2.0 INFORMATION OF THE INTERVIEWEE

- 2.1) Can you briefly explain about your role in this organisation?
- 2.2) Can you briefly explain about your experience in wastewater management?

3.0 FRESHWATER UTILISATION

- 3.1) Can you briefly explain about the current fresh water supply, consumption level of your organisation (for industrial processes/ cooling/ human use) and quality requirements for freshwater?

Freshwater supply

Freshwater from ground water sources (tube wells)	
City water supply by NWSDB	
other if any	

Freshwater consumption

Industry need	m ³ / month during last 12 months											
	Sep-20	Oct-20	Nov-20	Dec-20	Jan-21	Feb-21	Mar-21	Apr-21	May-21	Jun-21	Jul-21	Aug-21
Industrial processes												
process 1												
process 2												
Cooling												
Domestic/ human use												
Other if any												

Quality requirements of freshwater

	Rate of contaminant concentration (mg/l)					
	*BOD	**COD	***TSS	pH		
Industrial						
Cooling	-					
Domestic/ human use						
*Biochemical Oxygen Demand (BOD), **Chemical Oxygen Demand (COD), ***Total Suspended Solids (TSS),						

3.2) Is the current water consumption efficient? Yes/No. Justify your answer.

3.3) What are the strategies used to enhance the water efficiency of you organisation (for industrial processes/ cooling/ human use)?

4.0 CURRENT STATUS OF INDUSTRIAL WASTEWATER MANAGEMENT

4.1) What are the existing strategies used to reduce freshwater consumption in industrial processes?

4.2) What is the level of wastewater generation (monthly average)?

4.3) What are the existing strategies used to discharge wastewater?

4.4) What are the organisational policies available for wastewater management?

5.0 EXTENT OF WASTEWATER RECYCLING AND REUSE

5.1) Do you have your own plant for wastewater recycling? (Yes/No) If not, how do you currently recycling wastewater to maintain its quality for final disposal?

5.2) Could you rate the level of wastewater recycling of your organisation? Justify your answer.

-2	-1	0	1	2
Very Low	Low	Medium	High	Very High

5.3) Could you rate the level of reuse of regenerated/ recycled wastewater of your organisation? Justify your answer.

-2	-1	0	1	2
Very Low	Low	Medium	High	Very High

5.4) What are the existing uses of recycled wastewater?

.....**THANK YOU**.....

INTERVIEW GUIDELINE (PHASE III – CASE STUDY) (A Transcribed Copy)

DETAILS OF INTERVIEW

Type of organisation/ industry	Rubber toy manufacturing	
Designation of interviewee	Facility Manager	
Date of interview	15/11/2021	
Time and Duration	11.00am-12.00pm	01 hour

1.0 INFORMATION OF THE ORGANISATION

1.1) Can you give brief introduction to the organisation?

An export-oriented manufacturer of soft toys and infant garments and a specialist in organic and natural rubber toys. It is one of the primary exporters in Sri Lanka distributing toys to over 48 countries. The factory uses natural rubber to produce its natural rubber products range rather than using synthetic rubber.

1.2) What are types of the internal processes available?

Our industrial process includes concept and design, washing of rubber, moulding, baking and painting. The monthly average production is from 250,000–275,000 soft toys and 60,000–75,000 rubber toys.

2.0 INFORMATION OF THE INTERVIEWEE

2.1) Can you briefly explain about your role in this organisation?

I am working as the Facility Manager of this organisation. So, all key tasks including facility maintenance, property management, waste management, energy management and environmental compliance come under my role.

2.2) Can you briefly explain about your experience in wastewater management?

I have more than 10 years of experience in the field. I have involved in many company level sustainability initiatives including water efficiency and management.

3.0 FRESHWATER UTILISATION

3.1) Can you briefly explain about the current fresh water supply, consumption level of your organisation (for industrial processes/ cooling/ human use) and quality requirements for freshwater?

Freshwater supply

Freshwater from ground water sources (tube wells)	NA
City water supply by NWSDB	71

other if any	NA
--------------	----

Freshwater consumption

Industry need	m ³ / month during last 12 months											
	Sep-20	Oct-20	Nov-20	Dec-20	Jan-21	Feb-21	Mar-21	Apr-21	May-21	Jun-21	Jul-21	Aug-21
Industrial processes												
process 1												
process 2	1424.34	1443.2	1758.65	1370.72	1861.6	1859.2	1833.84	1572.96	1260.53	1809.61	1771.22	1724.16
Cooling	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Domestic / human use	330	320	330	280	330	320	325	290	260	296	320	340
Other if any												

Quality requirements of freshwater

	Rate of contaminant concentration (mg/l)					
	*BOD	**COD	***TSS	pH		
Industrial	5	10	500	7.9		
Cooling	-	-	-	-		
Domestic/human use				7.9		
*Biochemical Oxygen Demand (BOD), **Chemical Oxygen Demand (COD), ***Total Suspended Solids (TSS),						

3.2) Is the current water consumption efficient? Yes/No. Justify your answer.

No. there is a high demand for water for utilising in the manufacturing process.

3.3) What are the strategies used to enhance the water efficiency of you organisation (for industrial processes/ cooling/ human use)?

The company has undergone many operational changes in production and packaging to make its processes more sustainable, such as the use of biodegradable bags, natural rubber, recycled materials, non-toxic vegetable dyes, etc.

4.0 CURRENT STATUS OF INDUSTRIAL WASTEWATER MANAGEMENT

4.1) What are the existing strategies used to reduce freshwater consumption in industrial processes?

The company has undergone many operational changes in production and packaging to make its processes more sustainable, such as the use of biodegradable bags, natural rubber, recycled materials, non-toxic vegetable dyes, etc.

4.2) What is the level of wastewater generation (monthly average)?

Type	m ³ / month during last 12 months											
	1	2	3	4	5	6	7	8	9	10	11	12
Domestic wastewater	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Wastewater with sewerage	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Industry effluent	142.4	144.32	175.8	137.072	186.16	185.92	183.384	157.296	126	180.96	177.12	172.416

4.3) What are the existing strategies used to discharge wastewater?

We have a pre-treatment facility. The industry effluent is treated to required standard and send it to common treatment at the zone to discharge.

4.4) What are the organisational policies available for wastewater management?

We have certain institutional level procedures for rubber toy manufacturing to make them safe to the users specifically for babies. At the same time, we are currently considering about water efficiency improvements within the process.

5.0 EXTENT OF WASTEWATER RECYCLING AND REUSE

5.1) Do you have your own plant for wastewater recycling? (Yes/No) If not, how do you currently recycling wastewater to maintain its quality for final disposal?

Yes. We have our own pre-treatment facility. There is BOI norm to be considered in treating water. So we are following those and send pre-treated wastewater to central treatment.

5.2) Could you rate the level of wastewater recycling of your organisation? Justify your answer.

-2	-1	0	1	2
Very Low	Low	Medium	High	Very High

5.3) Could you rate the level of reuse of regenerated/ recycled wastewater of your organisation? Justify your answer.

-2	-1	0	1	2
Very Low	Low	Medium	High	Very High

5.4) What are the existing uses of recycled wastewater?

Inhouse water-saving strategies have been implemented including using domestic wastewater for the factory's internal non-potable water requirements, such as toilet flushing, gardening, etc

.....**THANK YOU**.....

APPENDIX 3: Test run results (screen shots) of the model obtained from SageMath software

```

jupyter Water Consumption Last Checkpoint: Last Saturday at 10:14 PM (autosaved)
File Edit View Insert Cell Kernel Widgets Help Trusted SageMath 9.2
20.0 x_5 + 20.0 x_6 + 20.0 x_7 <= 24000.0
20.0 x_9 + 20.0 x_10 + 20.0 x_11 <= 10000.0
500.0 x_1 + 500.0 x_2 + 500.0 x_3 <= 600000.0
500.0 x_5 + 500.0 x_6 + 500.0 x_7 <= 600000.0
500.0 x_9 + 500.0 x_10 + 500.0 x_11 <= 250000.0
9.0 x_1 + 9.0 x_2 + 9.0 x_3 <= 10200.0
9.0 x_5 + 9.0 x_6 + 9.0 x_7 <= 10200.0
9.0 x_9 + 9.0 x_10 + 9.0 x_11 <= 4250.0
Variables:
x_0 is a continuous variable (min=0.0, max=+oo)
x_1 is a continuous variable (min=0.0, max=+oo)
x_2 is a continuous variable (min=0.0, max=+oo)
x_3 is a continuous variable (min=0.0, max=+oo)
x_4 is a continuous variable (min=0.0, max=+oo)
x_5 is a continuous variable (min=0.0, max=+oo)
x_6 is a continuous variable (min=0.0, max=+oo)
x_7 is a continuous variable (min=0.0, max=+oo)
x_8 is a continuous variable (min=0.0, max=+oo)
x_9 is a continuous variable (min=0.0, max=+oo)
x_10 is a continuous variable (min=0.0, max=+oo)
x_11 is a continuous variable (min=0.0, max=+oo)
x_12 is a continuous variable (min=0.0, max=+oo)
x_13 is a continuous variable (min=0.0, max=+oo)
x_14 is a continuous variable (min=0.0, max=+oo)
Objective Value: 161.11111111111111
fw_0 = 66.66666666666671
fw_1 = 66.66666666666663
fw_2 = 27.777777777777777
ww_0 = 0.0
ww_1 = 561.11111111111113
ww_2 = 0.0
tw_p10 = 0.0
tw_p11 = 966.6666666666666
tw_p12 = 166.66666666666666
tw_p20 = 500.0
tw_p21 = 0.0
tw_p22 = 633.3333333333334
tw_p30 = 0.0
tw_p31 = 472.22222222222223
tw_p32 = 0.0

```

Test Results

FRESHWATER CONSUMPTION (m³/ month)				
	Plant A	Plant B	Plant C	Total
FWC after optimisation	66.67	66.67	27.78	161.12
Reduction of FW	1133.33	1133.33	472.22	2738.88
WASTEWATER GENERATION (m³/ month)				
	Plant A	Plant B	Plant C	Total
WW discharge after optimisation	0	561.11	0	561.11
THE OPTIMAL NETWORK (FLOWRATE OF TWW – m³/ month)				
Source	Sinks			
	A	B	C	
A	0	500		0
B		966.67	0	472.22
C		166.67	633.33	0

APPENDIX 4: The coding developed to solve the optimisation problem and the experimental results obtained from SageMath software

The coding

1/14/22, 11:00 PM

Data Compilation

```
In [1]: p = MixedIntegerLinearProgram(maximization=False, solver = "GLPK")

fw= p.new_variable(real=True,nonnegative=True)

# Waste Water
ww= p.new_variable(real=True,nonnegative=True)

# Treated Waste Water
tw_p0= p.new_variable(real=True,nonnegative=True)
tw_p1= p.new_variable(real=True,nonnegative=True)
tw_p2= p.new_variable(real=True,nonnegative=True)

# Water Demand of each Sink
d_0=33072.82; d_1=20427.18; d_2=1640.84;
# Water Supply of each Source
#s_0=26958.03; s_1=17028.23; s_2=1529.43;
s_0=25610.12; s_1=16176.82; s_2=1452.96;

BOD_sink=5; BOD_fw=5; BOD_Sou=5;
COD_Sink=10; COD_fw=10; COD_Sou=10;
#TDS_Sink=300; TDS_fw=300; TDS_Sou=300;
PH_Sink=500; PH_fw=500; PH_Sou=500;

# Sink
p.add_constraint ( fw[0] + tw_p0[0] + tw_p1[0] + tw_p2[0] == d_0)
p.add_constraint ( fw[1] + tw_p0[1] + tw_p1[1] + tw_p2[1] == d_1)
p.add_constraint ( fw[2] + tw_p0[2] + tw_p1[2] + tw_p2[2] == d_2)

# Source
p.add_constraint( ww[0] + tw_p0[0] + tw_p0[1] + tw_p0[2] == s_0)
p.add_constraint( ww[1] + tw_p1[0] + tw_p1[1] + tw_p1[2] == s_1)
p.add_constraint( ww[2] + tw_p2[0] + tw_p2[1] + tw_p2[2] == s_2)

p.add_constraint( tw_p0[0] == 0)
p.add_constraint( tw_p1[1] == 0)
p.add_constraint( tw_p2[2] == 0)

#p.add_constraint( tw_p2[1] == 0)
p.add_constraint( tw_p1[2] == 0)
#p.add_constraint( tw_p2[0] == 0)

# BOD Quality of Treated Water
```

1/14/22, 11:00 PM

Data Compilation

```
#p.add_constraint( BOD_Sou*tw_p1[0] + BOD_Sou*tw_p1[1] + BOD_Sou*tw_p1[2] <= BOD_sink*d_1)
#p.add_constraint( BOD_Sou*tw_p2[0] + BOD_Sou*tw_p2[1] + BOD_Sou*tw_p2[2] <= BOD_sink*d_2)
#p.add_constraint( BOD_Sou*tw_p0[0] + BOD_Sou*tw_p0[1] + BOD_Sou*tw_p0[2] <= BOD_sink*d_0)

# BOD Quality of Fresh Water
#fw[0]*BOD_fw <= d_0*BOD_sink
#fw[1]*BOD_fw <= d_1*BOD_sink
#fw[2]*BOD_fw <= d_2*BOD_sink

# COD Quality of Treated Water
#p.add_constraint( COD_Sou*tw_p0[0] + COD_Sou*tw_p0[1] + COD_Sou*tw_p0[2] <= COD_Sink*d_0)
#p.add_constraint( COD_Sou*tw_p1[0] + COD_Sou*tw_p1[1] + COD_Sou*tw_p1[2] <= COD_Sink*d_1)
#p.add_constraint( COD_Sou*tw_p2[0] + COD_Sou*tw_p2[1] + COD_Sou*tw_p2[2] <= COD_Sink*d_2)

# COD Quality of Fresh Water
#fw[0]*COD_fw <= d_0*COD_Sink
#fw[1]*COD_fw <= d_1*COD_Sink
#fw[2]*COD_fw <= d_2*COD_Sink

# TDS Quality of Treated Water
#p.add_constraint( TDS_Sou*tw_p0[0] + TDS_Sou*tw_p0[1] + TDS_Sou*tw_p0[2] <= TDS_Sink*d_0)
#p.add_constraint( TDS_Sou*tw_p1[0] + TDS_Sou*tw_p1[1] + TDS_Sou*tw_p1[2] <= TDS_Sink*d_1)
#p.add_constraint( TDS_Sou*tw_p2[0] + TDS_Sou*tw_p2[1] + TDS_Sou*tw_p2[2] <= TDS_Sink*d_2)

# TDS Quality of Fresh Water
#fw[0]*TDS_fw <= d_0*TDS_Sink
#fw[1]*TDS_fw <= d_1*TDS_Sink
#fw[2]*TDS_fw <= d_2*TDS_Sink

# pH Quality of Treated Water
#p.add_constraint( PH_Sou*tw_p0[0] + PH_Sou*tw_p0[1] + PH_Sou*tw_p0[2] <= PH_Sink*d_0)
#p.add_constraint( PH_Sou*tw_p1[0] + PH_Sou*tw_p1[1] + PH_Sou*tw_p1[2] <= PH_Sink*d_1)
#p.add_constraint( PH_Sou*tw_p2[0] + PH_Sou*tw_p2[1] + PH_Sou*tw_p2[2] <= PH_Sink*d_2)

# pH Quality of Fresh Water
#fw[0]*PH_fw <= d_0*PH_Sink
#fw[1]*PH_fw <= d_1*PH_Sink
#fw[2]*PH_fw <= d_2*PH_Sink

p.set_objective (fw[0] + fw[1] + fw[2])

p.show()
```

```

p.solve()

print('Objective Value: {}'.format(p.solve()))

for i, v in sorted(p.get_values(fw).items()):
    print(f'fw_{i} = {v}')

for i, v in sorted(p.get_values(ww).items()):
    print(f'ww_{i} = {v}')

for i, v in sorted(p.get_values(tw_p0).items()):
    print(f'tw_p0{i} = {v}')

for i, v in sorted(p.get_values(tw_p1).items()):
    print(f'tw_p1{i} = {v}')

for i, v in sorted(p.get_values(tw_p2).items()):
    print(f'tw_p2{i} = {v}')
    
```

jupyter Data Compilation Last Checkpoint: 12/08/2021 (autosaved) Logout

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```

x_12 is a continuous variable (min=0.0, max=+oo)
x_13 is a continuous variable (min=0.0, max=+oo)
x_14 is a continuous variable (min=0.0, max=+oo)
Objective Value: 15443.04
fw_0 = 15443.04
fw_1 = 0.0
fw_2 = 0.0
ww_0 = 3542.0999999999985
ww_1 = 0.0
ww_2 = 0.0
tw_p00 = 0.0
tw_p01 = 20427.18
tw_p02 = 1640.84
tw_p10 = 16176.82
tw_p11 = 0.0
tw_p12 = 0.0
tw_p20 = 1452.96
tw_p21 = 0.0
tw_p22 = 0.0
    
```

Entity A-B (points to ww_0)

Entity A-C (points to tw_p01)

Entity B-A (points to tw_p02)

Entity C-A (points to tw_p20)

jupyter Data Compilation Last Checkpoint: 12/08/2021 (autosaved) Logout

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```

x_12 is a continuous variable (min=0.0, max=+oo)
x_13 is a continuous variable (min=0.0, max=+oo)
x_14 is a continuous variable (min=0.0, max=+oo)
Objective Value: 15443.04
fw_0 = 15443.04
fw_1 = 0.0
fw_2 = 0.0
ww_0 = 3542.0999999999985
ww_1 = 0.0
ww_2 = 0.0
tw_p00 = 0.0
tw_p01 = 20427.18
tw_p02 = 1640.84
tw_p10 = 16176.82
tw_p11 = 0.0
tw_p12 = 0.0
tw_p20 = 1452.96
tw_p21 = 0.0
tw_p22 = 0.0
    
```

Industrial Entity A (points to fw_0)

Industrial Entity B (points to fw_1)

Industrial Entity C (points to fw_2)

```
jupyter Data Compilation Last Checkpoint: 12/08/2021 (autosaved) Logout
File Edit View Insert Cell Kernel Widgets Help Trusted SageMath 9.2
Run C Code
x_12 is a continuous variable (min=0.0, max=+oo)
x_13 is a continuous variable (min=0.0, max=+oo)
x_14 is a continuous variable (min=0.0, max=+oo)
Objective Value: 15443.04
fw_0 = 15443.04
fw_1 = 0.0
fw_2 = 0.0
wr_0 = 3542.0999999999985
wr_1 = 0.0
wr_2 = 0.0
tw_p00 = 0.0
tw_p01 = 20427.18
tw_p02 = 1640.84
tw_p10 = 16176.82
tw_p11 = 0.0
tw_p12 = 0.0
tw_p20 = 1452.96
tw_p21 = 0.0
tw_p22 = 0.0
```

The image shows a Jupyter Notebook interface with a code cell. The code cell contains the output of a linear programming solver. The output lists variables and their values. Three variables, wr_0 , wr_1 , and wr_2 , are highlighted with red boxes. Red arrows point from these boxes to labels: wr_0 is labeled "Industrial Entity A", wr_1 is labeled "Industrial Entity B", and wr_2 is labeled "Industrial Entity C".

APPENDIX 5: Proposed design for the common wastewater treatment (CWWT) plant alteration

Proposed Design for the Common Wastewater Treatment (CWWT) Plant Alteration

The industry effluent of three different industrial entities was considered for the purpose of this proposed alteration. The wastewater of the selected industrial entities is pre-treated within the industry premises itself up to a certain extend (as per the BOI norms) and then send it to the CWWT plant which consists of a biological treatment process. The current practice is to treat the water up to the discharge standard for inland water bodies and water is not reused for any purpose. Hence, this study proposes an alteration to treat the effluent of the CWWT plant up to the potable level ensuring the sharing of treated wastewater between industrial entities.

Some of the characteristics of the effluent of the CWWT plant are as flows;

Table 1

Characteristics of the effluent of the central treatment plant

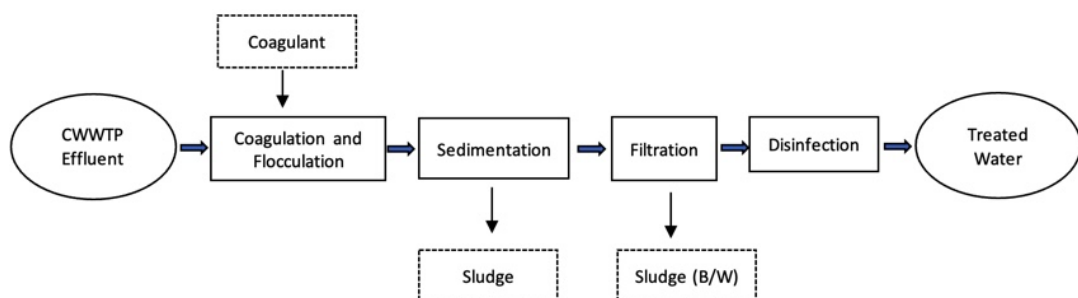
Parameter	Value
BOD	30 mg/l
COD	250 mg/l
TSS	50 mg/l
TTURBIDITY	21 NTU

Note. The turbidity value is based on the TSS to Turbidity factor which is 2.4 (Metcalf, 2003)

An alteration to the existing conventional water treatment process is proposed to reach the drinking water standard of Sri Lanka. A conventional water treatment process includes coagulation, flocculation, sedimentation, filtration and disinfection. The schematic diagram of the proposed water treatment process is shown in Figure 1.

Figure 1

Schematic diagram of the proposed water treatment process



Coagulation process gathers the suspended solid in water with the addition of chemical or a natural coagulant and the flocculation process makes the floccules which can be separated in the sedimentation process. The sedimentation process is responsible for removing a significant quantity of suspended solids as the residual sludge. The coagulants used in water treatment are available as chemicals or natural coagulant. Aluminum sulphate (Alum) is one of the most commonly used coagulants in coagulation and flocculation process because of the lowest price, effectiveness and the ability to entrap the bacteria (Omar, Zin, & Salleh, 2017).

The experimental study by Ismail, Fawzy, Abdel-Monem, Mahmoud, & El-Halwany, (2012) concluded that with the 60 mg/l of optimum alum dosage, TSS, BOD and COD removal efficiency can be obtained as 83%, 55% and 65% respectively. Based on the findings of Ismail, Fawzy, Abdel-Monem, Mahmoud, & El-Halwany, (2012), the total solids production due to TSS, BOD and COD was evaluated as presented in Table 2.

Table 2

Calculation of total sludge production

Component	Dosage/ Concentration in the Inflow (mg/l)	Conversion Factor/ Removal Efficiency	Produced Solids (mg/l)
Alum	60	0.26	16
TSS	50	83%	41.5
BOD	30	55%	16.5
COD	250	65%	162.5
Total Dry Solids			236.5

Note. Ismail et al. (2012). Combined coagulation flocculation pre-treatment unit for municipal wastewater. Journal of Advanced Research, 331-336.

Omar et al. (2017). A review on performance of chemical, natural and composite coagulant. International Journal of Engineering & Technology.

Based on the total solids produced during the flocculation stage, the mass balance analysis was carried out as described below (The design criteria, standards and the assumptions were adopted from the American Water Works Association's publications, 2012).

Maximum Plant flow	=	1517	m ³ / day
Total dry solids concentration	=	237	mg/l
Total dry solids quantity	=	359	kg/day
The above dry solid calculation is based on the average values of water quality parameters and due to many variations in raw water quality, chemical usage and the amount of water inflow, it is a common practice to increase this value by 20-60 %. Hence, the dry solid quantity was assumed as 502 kg/d, allocating 40 % for the uncertainties.			
Total solid production	=	502	kg/day

It is assumed that 90% of solids of the solids produced are removed from the sedimentation basin.			
Hence, removal of solids from sedimentation basin	=	452	kg/day
Concentration of sludge from the sedimentation basin	=	2	%
Hence, water removed with sludge	=	22	m ³ / day
Amount of water in to the filter	=	1495	m ³ / day
Solids into filter	=	50	kg/day
It is assumed that 90% of solids of the solids enter into the filter is removed from the filter with the backwash water			
Hence, removal of solids from filter	=	45	kg/day
Solids enter into the clear water tank	=	5	kg/day
Amount of water in to the clear water tank	=	1495	m ³ /d
Hence, suspended solids of the clear water tank	=	3	mg/l
TSS to Turbidity factor	=	2.24	
Hence, turbidity of final effluent of the treatment	=	1.4	NTU

Note. American Water Works Association. (2012). Water Treatment Plant Design. New York: McGraw-Hill.

As per the Sri Lankan standard for drinking water (SLS 614:2013), the turbidity value is to be less than 2 NTU and since the turbidity level of the final effluent of the proposed treatment is less than 2 NTU, the proposed treatment can be accepted as the suitable option for wastewater re-using.

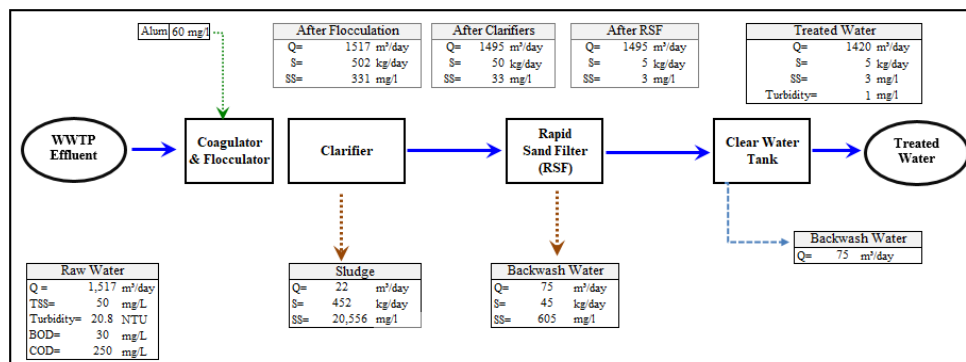
Water for the filter backwashing is obtained from clear water tank and normally it is 5 % of the total water production.

$$\text{Hence, quantity of backwash water} = 74.8 \text{ m}^3/\text{day}$$

The Figure 2 indicates the mass balance analysis of the proposed water treatment process.

Figure 2

Mass balance analysis of the proposed water treatment process



APPENDIX 6: Life cycle cost analysis for existing conventional water network

Cost Details (in LKR)

Item	Entity A	Entity B	Entity C	Total network
Initial cost	0	0	0	0
freshwater cost per annum	38,117,318.00	17,126,465.00	1,731,678.91	56,975,461.91
Cost for pre-treatment by individual entity before send to CWWT per annum	19,719,947.00	41,739,768.00	3,016,976.27	64,476,691.27
Treatment cost to be borne by each entity for central treatment (Fee for CWWT) per annum	5,499,437.78	3,473,758.92	312,003.45	9,285,200.15
O&M cost of water transfer (existing CWWT and pipe network) per annum				8,405,925.67
Expected life time 50 years				
Market Rate 5%				
Inflation Rate 16.3%				
Real Rate 9%				

LCC for Entity A

Year	Description	Amount	d/f	Present Value
0	Initial cost	0	1.00	-
0-50	Freshwater cost per annum	38,117,318.00	10.96	417,765,805.28
0-50	Treatment cost to be borne by each entity for central treatment (Fee for CWWT) per annum	5,499,437.78	10.96	60,273,838.07
0-50	Cost for pre-treatment by individual entity before send to CWWT per annum	19,719,947.00	10.96	216,130,619.12
	Total LCC			694,170,262.47

LCC for Entity B

Year	Description	Amount	d/f	Present Value
0	Initial cost	0	1.00	-
0-50	Freshwater cost per annum	17,126,465.00	10.96	187,706,056.40
0-50	Treatment cost to be borne by each entity for central treatment (Fee for CWWT) per annum	3,473,758.92	10.96	38,072,397.76
0-50	Cost for pre-treatment by individual entity before send to CWWT per annum	41,739,768.00	10.96	457,467,857.28
	Total LCC			683,246,311.44

LCC for Entity C

Year	Description	Amount	d/f	Present Value
0	Initial cost	0	1.00	-
0-50	Freshwater cost per annum	1,731,678.91	10.96	18,979,200.85
0-50	Treatment cost to be borne by each entity for central treatment (Fee for CWWT) per annum	312,003.45	10.96	3,419,557.79
0-50	Cost for pre-treatment by individual entity before send to CWWT per annum	3,016,976.27	10.96	33,066,059.88
	Total LCC			55,464,818.53

LCC for the Total Network

Year	Description	Amount	d/f	Present Value
0	Initial cost	0	1	-
0-50	Freshwater cost per annum	56,975,461.91	10.96	624,451,062.53
0-50	Treatment cost to be borne by each entity for central treatment (Fee for CWWT) per annum	9,285,200.15	10.96	101,765,793.62
0-50	Cost for pre-treatment by individual entity before send to CWWT per annum	64,476,691.27	10.96	706,664,536.28
1	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	0.917	7,708,233.84

Year	Description	Amount	d/f	Present Value
2	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,826,221.95	0.842	7,431,678.88
3	O&M cost of water transfer (existing CWWT and pipe network) per annum	9,267,533.05	0.772	7,154,535.52
4	O&M cost of water transfer (existing CWWT and pipe network) per annum	9,730,909.70	0.708	6,889,484.07
5	O&M cost of water transfer (existing CWWT and pipe network) per annum	10,217,455.19	0.65	6,641,345.87
6	O&M cost of water transfer (existing CWWT and pipe network) per annum	10,728,327.95	0.596	6,394,083.46
7	O&M cost of water transfer (existing CWWT and pipe network) per annum	11,264,744.35	0.547	6,161,815.16
8	O&M cost of water transfer (existing CWWT and pipe network) per annum	11,827,981.56	0.502	5,937,646.74
9	O&M cost of water transfer (existing CWWT and pipe network) per annum	12,419,380.64	0.46	5,712,915.09
10	O&M cost of water transfer (existing CWWT and pipe network) per annum	13,040,349.67	0.422	5,503,027.56
11	O&M cost of water transfer (existing CWWT and pipe network) per annum	13,692,367.16	0.388	5,312,638.46
12	O&M cost of water transfer (existing CWWT and pipe network) per annum	14,376,985.51	0.356	5,118,206.84
13	O&M cost of water transfer (existing CWWT and pipe network) per annum	15,095,834.79	0.326	4,921,242.14
14	O&M cost of water transfer (existing CWWT and pipe network) per annum	15,850,626.53	0.299	4,739,337.33

Year	Description	Amount	d/f	Present Value
15	O&M cost of water transfer (existing CWWT and pipe network) per annum	16,643,157.86	0.275	4,576,868.41
16	O&M cost of water transfer (existing CWWT and pipe network) per annum	17,475,315.75	0.252	4,403,779.57
17	O&M cost of water transfer (existing CWWT and pipe network) per annum	18,349,081.54	0.231	4,238,637.84
18	O&M cost of water transfer (existing CWWT and pipe network) per annum	19,266,535.61	0.212	4,084,505.55
19	O&M cost of water transfer (existing CWWT and pipe network) per annum	20,229,862.39	0.194	3,924,593.30
20	O&M cost of water transfer (existing CWWT and pipe network) per annum	21,241,355.51	0.178	3,780,961.28
21	O&M cost of water transfer (existing CWWT and pipe network) per annum	22,303,423.29	0.164	3,657,761.42
22	O&M cost of water transfer (existing CWWT and pipe network) per annum	23,418,594.45	0.15	3,512,789.17
23	O&M cost of water transfer (existing CWWT and pipe network) per annum	24,589,524.18	0.138	3,393,354.34
24	O&M cost of water transfer (existing CWWT and pipe network) per annum	25,819,000.39	0.126	3,253,194.05
25	O&M cost of water transfer (existing CWWT and pipe network) per annum	27,109,950.41	0.116	3,144,754.25
26	O&M cost of water transfer (existing CWWT and pipe network) per annum	28,465,447.93	0.106	3,017,337.48
27	O&M cost of water transfer (existing CWWT and pipe network) per annum	29,888,720.32	0.098	2,929,094.59

Year	Description	Amount	d/f	Present Value
28	O&M cost of water transfer (existing CWWT and pipe network) per annum	31,383,156.34	0.09	2,824,484.07
29	O&M cost of water transfer (existing CWWT and pipe network) per annum	32,952,314.15	0.082	2,702,089.76
30	O&M cost of water transfer (existing CWWT and pipe network) per annum	34,599,929.86	0.075	2,594,994.74
31	O&M cost of water transfer (existing CWWT and pipe network) per annum	36,329,926.36	0.069	2,506,764.92
32	O&M cost of water transfer (existing CWWT and pipe network) per annum	38,146,422.67	0.063	2,403,224.63
33	O&M cost of water transfer (existing CWWT and pipe network) per annum	40,053,743.81	0.058	2,323,117.14
34	O&M cost of water transfer (existing CWWT and pipe network) per annum	42,056,431.00	0.053	2,228,990.84
35	O&M cost of water transfer (existing CWWT and pipe network) per annum	44,159,252.55	0.049	2,163,803.37
36	O&M cost of water transfer (existing CWWT and pipe network) per annum	46,367,215.17	0.045	2,086,524.68
37	O&M cost of water transfer (existing CWWT and pipe network) per annum	48,685,575.93	0.041	1,996,108.61
38	O&M cost of water transfer (existing CWWT and pipe network) per annum	51,119,854.73	0.038	1,942,554.48
39	O&M cost of water transfer (existing CWWT and pipe network) per annum	53,675,847.47	0.035	1,878,654.66
40	O&M cost of water transfer (existing CWWT and pipe network) per annum	56,359,639.84	0.032	1,803,508.47

Year	Description	Amount	d/f	Present Value
41	O&M cost of water transfer (existing CWWT and pipe network) per annum	59,177,621.83	0.029	1,716,151.03
42	O&M cost of water transfer (existing CWWT and pipe network) per annum	62,136,502.92	0.027	1,677,685.58
43	O&M cost of water transfer (existing CWWT and pipe network) per annum	65,243,328.07	0.024	1,565,839.87
44	O&M cost of water transfer (existing CWWT and pipe network) per annum	68,505,494.47	0.023	1,575,626.37
45	O&M cost of water transfer (existing CWWT and pipe network) per annum	71,930,769.20	0.021	1,510,546.15
46	O&M cost of water transfer (existing CWWT and pipe network) per annum	75,527,307.66	0.019	1,435,018.85
47	O&M cost of water transfer (existing CWWT and pipe network) per annum	79,303,673.04	0.017	1,348,162.44
48	O&M cost of water transfer (existing CWWT and pipe network) per annum	83,268,856.69	0.016	1,332,301.71
49	O&M cost of water transfer (existing CWWT and pipe network) per annum	87,432,299.53	0.015	1,311,484.49
50	O&M cost of water transfer (existing CWWT and pipe network) per annum	91,803,914.50	0.013	1,193,450.89
	Total LCC			1,610,546,302.43

APPENDIX 7: Life cycle cost analysis for proposed optimal water exchange network

Cost Details

Item	Entity A	Entity B	Entity C	Total network
Initial cost - pipe laying				13,303,400.00
Initial cost - supply and installaiton of CWWT unit				50,000,000.00
freshwater cost per annum	14,903,580.72	2,474,515.56	262,701.00	17,640,797.28
Treated water utilisation cost per annum	7,036,720.80	8,733,784.80	694,202.40	16,464,708.00
Cost for pre-treatment by individual entity before send to CWWT per annum	19,719,947.00	41,739,768.00	3,016,976.27	64,476,691.27
Treatment cost to be borne by each entity for central treatment (Fee for CWWT) per annum	5,499,437.78	3,473,758.92	312,003.45	9,285,200.15
O&M cost of water transfer (pipe network & CWWT with alteration) per annum				8,261,011.33
Expected life time 50 years				
Bank interest rate 5%				
Inflation rate 16.3% (YoY rate considered)				

LCC for Entity A

Year	Description	Amount	d/f	Present Value
0	Initial cost	0	1.00	
0-50	Freshwater cost per annum	14,903,580.72	10.96	163,343,244.69
0-50	Treated wastewater utilisation cost per annum	7,036,720.80	10.96	77,122,459.97
0-50	Cost for pre-treatment by individual entity before send to CWWT per annum	19,719,947.00	10.96	216,130,619.12
0-50	Treatment cost to be borne by each entity for central treatment (Fee for CWWT) per annum	5,499,437.78	10.96	60,273,838.07
	Total LCC			516,870,161.85

LCC for Entity B

Year	Description	Amount	d/f	Present Value
0	Initial cost	0	1.00	-
0-50	Freshwater cost per annum	2,474,515.56	10.96	27,120,690.54
0-50	Treated water utilisation cost per annum	8,733,784.80	10.96	95,722,281.41
0-50	Cost for pre-treatment by individual entity before send to CWWT per annum	41,739,768.00	10.96	457,467,857.28
0-50	Treatment cost to be borne by each entity for central treatment (Fee for CWWT) per annum	3,473,758.92	10.96	38,072,397.76
	Total LCC			618,383,226.99

LCC for Entity C

Year	Description	Amount	d/f	Present Value
0	Initial cost	0	1.00	-
0-50	Freshwater cost per annum	262,701.00	10.96	2,879,202.96
0-50	Treated water utilisation cost per annum	694,202.40	10.96	7,608,458.30
0-50	Cost for pre-treatment by individual entity before send to CWWT per annum	3,016,976.27	10.96	33,066,059.88
0-50	Treatment cost to be borne by each entity for central treatment (Fee for CWWT) per annum	312,003.45	10.96	3,419,557.79
	Total LCC			46,973,278.94

LCC for Total Network

Year	Description	Amount	d/f	Present Value
0	Initial cost (pipe laying and supply & installaiton of CWWT unit)	63,303,400.00	1.00	63,303,400.00
0-50	Freshwater cost per annum	17,640,797.28	10.96	193,343,138.19
0-50	Treated water utilisation cost per annum	16,464,708.00	10.96	180,453,199.68
0-50	Cost for pre-treatment by individual entity before send to CWWT per annum	64,476,691.27	10.96	706,664,536.28
0-50	Treatment cost to be borne by each entity for central treatment (Fee for CWWT) per annum	9,285,200.15	10.96	101,765,793.62

Year	Description	Amount	d/f	Present Value
1	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	0.917	7,575,347.39
2	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,674,061.90	0.842	7,303,560.12
3	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	9,107,764.99	0.772	7,031,194.57
4	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	9,563,153.24	0.708	6,770,712.49
5	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	10,041,310.90	0.65	6,526,852.09
6	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	10,543,376.45	0.596	6,283,852.36
7	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	11,070,545.27	0.547	6,055,588.26
8	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	11,624,072.53	0.502	5,835,284.41
9	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	12,205,276.16	0.46	5,614,427.03
10	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	12,815,539.97	0.422	5,408,157.87
11	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	13,456,316.97	0.388	5,221,050.98
12	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	14,129,132.82	0.356	5,029,971.28
13	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	14,835,589.46	0.326	4,836,402.16
14	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	15,577,368.93	0.299	4,657,633.31
15	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	16,356,237.38	0.275	4,497,965.28
16	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	17,174,049.24	0.252	4,327,860.41
17	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	18,032,751.71	0.231	4,165,565.64

Year	Description	Amount	d/f	Present Value
18	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	18,934,389.29	0.212	4,014,090.53
19	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	19,881,108.76	0.194	3,856,935.10
20	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	20,875,164.19	0.178	3,715,779.23
21	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	21,918,922.40	0.164	3,594,703.27
22	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	23,014,868.52	0.15	3,452,230.28
23	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	24,165,611.95	0.138	3,334,854.45
24	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	25,373,892.55	0.126	3,197,110.46
25	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	26,642,587.18	0.116	3,090,540.11
26	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	27,974,716.53	0.106	2,965,319.95
27	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	29,373,452.36	0.098	2,878,598.33
28	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	30,842,124.98	0.09	2,775,791.25
29	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	32,384,231.23	0.082	2,655,506.96
30	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	34,003,442.79	0.075	2,550,258.21
31	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	35,703,614.93	0.069	2,463,549.43
32	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	37,488,795.68	0.063	2,361,794.13
33	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	39,363,235.46	0.058	2,283,067.66
34	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	41,331,397.23	0.053	2,190,564.05

Year	Description	Amount	d/f	Present Value
35	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	43,397,967.09	0.049	2,126,500.39
36	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	45,567,865.45	0.045	2,050,553.95
37	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	47,846,258.72	0.041	1,961,696.61
38	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	50,238,571.66	0.038	1,909,065.72
39	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	52,750,500.24	0.035	1,846,267.51
40	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	55,388,025.25	0.032	1,772,416.81
41	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	58,157,426.51	0.029	1,686,565.37
42	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	61,065,297.84	0.027	1,648,763.04
43	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	64,118,562.73	0.024	1,538,845.51
44	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	67,324,490.87	0.023	1,548,463.29
45	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	70,690,715.41	0.021	1,484,505.02
46	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	74,225,251.18	0.019	1,410,279.77
47	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	77,936,513.74	0.017	1,324,920.73
48	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	81,833,339.43	0.016	1,309,333.43
49	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	85,925,006.40	0.015	1,288,875.10
50	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	90,221,256.72	0.013	1,172,876.34
	Total LCC			1,420,132,115.42

APPENDIX 8: Sensitivity analysis – Calculations and results

Calculation of real rates adopting $\pm 7\%$ of change in Production Price Index (PPI)

Variations in PPI	-7%	0	+7%	+14%
Real rate	4%	9%	14.8%	19.4%

Sensitivity analysis – Existing conventional water network

LCC for the Total Network - 4%				
Year	Description	Amount	d/f	Present Value
0	Initial cost	0	1	-
0-50	Freshwater cost per annum	56,975,461.91	21.5	1,224,972,431.07
0-50	Treatment cost to be borne by each entity for central treatment (Fee for CWWT) per annum	9,285,200.15	21.5	199,631,803.18
0-50	Cost for pre-treatment by individual entity before send to CWWT per annum	64,476,691.27	21.5	1,386,248,862.23
1	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	0.962	8,086,500.49
2	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,826,221.95	0.925	8,164,255.31
3	O&M cost of water transfer (existing CWWT and pipe network) per annum	9,267,533.05	0.889	8,238,836.88
4	O&M cost of water transfer (existing CWWT and pipe network) per annum	9,730,909.70	0.855	8,319,927.80
5	O&M cost of water transfer (existing CWWT and pipe network) per annum	10,217,455.19	0.822	8,398,748.17
6	O&M cost of water transfer (existing CWWT and pipe network) per annum	10,728,327.95	0.79	8,475,379.08
7	O&M cost of water transfer (existing CWWT and pipe network) per annum	11,264,744.35	0.76	8,561,205.70

LCC for the Total Network - 4%				
Year	Description	Amount	d/f	Present Value
8	O&M cost of water transfer (existing CWWT and pipe network) per annum	11,827,981.56	0.731	8,646,254.52
9	O&M cost of water transfer (existing CWWT and pipe network) per annum	12,419,380.64	0.703	8,730,824.59
10	O&M cost of water transfer (existing CWWT and pipe network) per annum	13,040,349.67	0.676	8,815,276.38
11	O&M cost of water transfer (existing CWWT and pipe network) per annum	13,692,367.16	0.65	8,900,038.65
12	O&M cost of water transfer (existing CWWT and pipe network) per annum	14,376,985.51	0.625	8,985,615.95
13	O&M cost of water transfer (existing CWWT and pipe network) per annum	15,095,834.79	0.601	9,072,596.71
14	O&M cost of water transfer (existing CWWT and pipe network) per annum	15,850,626.53	0.577	9,145,811.51
15	O&M cost of water transfer (existing CWWT and pipe network) per annum	16,643,157.86	0.555	9,236,952.61
16	O&M cost of water transfer (existing CWWT and pipe network) per annum	17,475,315.75	0.534	9,331,818.61
17	O&M cost of water transfer (existing CWWT and pipe network) per annum	18,349,081.54	0.513	9,413,078.83
18	O&M cost of water transfer (existing CWWT and pipe network) per annum	19,266,535.61	0.493	9,498,402.06
19	O&M cost of water transfer (existing CWWT and pipe network) per annum	20,229,862.39	0.475	9,609,184.64

LCC for the Total Network - 4%				
Year	Description	Amount	d/f	Present Value
20	O&M cost of water transfer (existing CWWT and pipe network) per annum	21,241,355.51	0.456	9,686,058.11
21	O&M cost of water transfer (existing CWWT and pipe network) per annum	22,303,423.29	0.439	9,791,202.82
22	O&M cost of water transfer (existing CWWT and pipe network) per annum	23,418,594.45	0.422	9,882,646.86
23	O&M cost of water transfer (existing CWWT and pipe network) per annum	24,589,524.18	0.405	9,958,757.29
24	O&M cost of water transfer (existing CWWT and pipe network) per annum	25,819,000.39	0.39	10,069,410.15
25	O&M cost of water transfer (existing CWWT and pipe network) per annum	27,109,950.41	0.375	10,166,231.40
26	O&M cost of water transfer (existing CWWT and pipe network) per annum	28,465,447.93	0.361	10,276,026.70
27	O&M cost of water transfer (existing CWWT and pipe network) per annum	29,888,720.32	0.347	10,371,385.95
28	O&M cost of water transfer (existing CWWT and pipe network) per annum	31,383,156.34	0.333	10,450,591.06
29	O&M cost of water transfer (existing CWWT and pipe network) per annum	32,952,314.15	0.321	10,577,692.84
30	O&M cost of water transfer (existing CWWT and pipe network) per annum	34,599,929.86	0.308	10,656,778.40
31	O&M cost of water transfer (existing CWWT and pipe network) per annum	36,329,926.36	0.296	10,753,658.20

LCC for the Total Network - 4%				
Year	Description	Amount	d/f	Present Value
32	O&M cost of water transfer (existing CWWT and pipe network) per annum	38,146,422.67	0.285	10,871,730.46
33	O&M cost of water transfer (existing CWWT and pipe network) per annum	40,053,743.81	0.274	10,974,725.80
34	O&M cost of water transfer (existing CWWT and pipe network) per annum	42,056,431.00	0.264	11,102,897.78
35	O&M cost of water transfer (existing CWWT and pipe network) per annum	44,159,252.55	0.253	11,172,290.89
36	O&M cost of water transfer (existing CWWT and pipe network) per annum	46,367,215.17	0.244	11,313,600.50
37	O&M cost of water transfer (existing CWWT and pipe network) per annum	48,685,575.93	0.234	11,392,424.77
38	O&M cost of water transfer (existing CWWT and pipe network) per annum	51,119,854.73	0.225	11,501,967.31
39	O&M cost of water transfer (existing CWWT and pipe network) per annum	53,675,847.47	0.217	11,647,658.90
40	O&M cost of water transfer (existing CWWT and pipe network) per annum	56,359,639.84	0.208	11,722,805.09
41	O&M cost of water transfer (existing CWWT and pipe network) per annum	59,177,621.83	0.2	11,835,524.37
42	O&M cost of water transfer (existing CWWT and pipe network) per annum	62,136,502.92	0.193	11,992,345.06
43	O&M cost of water transfer (existing CWWT and pipe network) per annum	65,243,328.07	0.185	12,070,015.69

LCC for the Total Network - 4%				
Year	Description	Amount	d/f	Present Value
44	O&M cost of water transfer (existing CWWT and pipe network) per annum	68,505,494.47	0.178	12,193,978.02
45	O&M cost of water transfer (existing CWWT and pipe network) per annum	71,930,769.20	0.171	12,300,161.53
46	O&M cost of water transfer (existing CWWT and pipe network) per annum	75,527,307.66	0.165	12,462,005.76
47	O&M cost of water transfer (existing CWWT and pipe network) per annum	79,303,673.04	0.158	12,529,980.34
48	O&M cost of water transfer (existing CWWT and pipe network) per annum	83,268,856.69	0.152	12,656,866.22
49	O&M cost of water transfer (existing CWWT and pipe network) per annum	87,432,299.53	0.146	12,765,115.73
50	O&M cost of water transfer (existing CWWT and pipe network) per annum	91,803,914.50	0.141	12,944,351.94
	Total LCC			3,326,574,690.94

LCC for the Total Network - 14.8%				
Year	Description	Amount	d/f	Present Value
0	Initial cost	0	1	-
0-50	Freshwater cost per annum	56,975,461.91	4.291	244,481,707.06
0-50	Treatment cost to be borne by each entity for central treatment (Fee for CWWT) per annum	9,285,200.15	4.291	39,842,793.84
0-50	Cost for pre-treatment by individual entity before send to CWWT per annum	64,476,691.27	4.291	276,669,482.23
1	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	0.871	7,321,561.26

LCC for the Total Network - 14.8%				
Year	Description	Amount	d/f	Present Value
2	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	0.759	6,380,097.58
3	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	0.661	5,556,316.87
4	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	0.576	4,841,813.19
5	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	0.502	4,219,774.69
6	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	0.437	3,673,389.52
7	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	0.381	3,202,657.68
8	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	0.331	2,782,361.40
9	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	0.289	2,429,312.52
10	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	0.252	2,118,293.27
11	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	0.219	1,840,897.72
12	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	0.191	1,605,531.80
13	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	0.166	1,395,383.66

LCC for the Total Network - 14.8%				
Year	Description	Amount	d/f	Present Value
14	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	0.145	1,218,859.22
15	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	0.126	1,059,146.63
16	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	0.11	924,651.82
17	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	0.096	806,968.86
18	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	0.083	697,691.83
19	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	0.072	605,226.65
20	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	0.063	529,573.32
21	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	0.055	462,325.91
22	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	0.048	403,484.43
23	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	0.041	344,642.95
24	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	0.036	302,613.32
25	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	0.031	260,583.70

LCC for the Total Network - 14.8%				
Year	Description	Amount	d/f	Present Value
26	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	0.028	235,365.92
27	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	0.024	201,742.22
28	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	0.021	176,524.44
29	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	0.018	151,306.66
30	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	0.016	134,494.81
31	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	0.014	117,682.96
32	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	0.012	100,871.11
33	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	0.011	92,465.18
34	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	9.162	77,015,090.99
35	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	7.981	67,087,692.77
36	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	6.952	58,437,995.26
37	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	6.056	50,906,285.86

LCC for the Total Network - 14.8%				
Year	Description	Amount	d/f	Present Value
38	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	5.275	44,341,257.91
39	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	4.595	38,625,228.45
40	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	4.002	33,640,514.53
41	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	3.486	29,303,056.89
42	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	3.037	25,528,796.26
43	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	2.645	22,233,673.40
44	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	2.304	19,367,252.74
45	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	2.007	16,870,692.82
46	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	1.749	14,701,964.00
47	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	1.523	12,802,224.80
48	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	1.327	11,154,663.36
49	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	1.156	9,717,250.07

LCC for the Total Network - 14.8%				
Year	Description	Amount	d/f	Present Value
50	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	1.007	8,464,767.15
	Total LCC			1,157,386,003.48

LCC for the Total Network - 19.4%				
Year	Description	Amount	d/f	Present Value
0	Initial cost	0	1	-
0-50	Freshwater cost per annum	56,975,461.91	5.154	293,651,530.68
0-50	Treatment cost to be borne by each entity for central treatment (Fee for CWWT) per annum	9,285,200.15	5.154	47,855,921.57
0-50	Cost for pre-treatment by individual entity before send to CWWT per annum	64,476,691.27	5.154	332,312,866.81
1	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,405,925.67	0.838	7,044,165.71
2	O&M cost of water transfer (existing CWWT and pipe network) per annum	8,826,221.95	0.701	6,187,181.59
3	O&M cost of water transfer (existing CWWT and pipe network) per annum	9,267,533.05	0.587	5,440,041.90
4	O&M cost of water transfer (existing CWWT and pipe network) per annum	9,730,909.70	0.492	4,787,607.57
5	O&M cost of water transfer (existing CWWT and pipe network) per annum	10,217,455.19	0.412	4,209,591.54
6	O&M cost of water transfer (existing CWWT and pipe network) per annum	10,728,327.95	0.345	3,701,273.14
7	O&M cost of water transfer (existing CWWT and pipe network) per annum	11,264,744.35	0.29	3,266,775.86

LCC for the Total Network - 19.4%				
Year	Description	Amount	d/f	Present Value
8	O&M cost of water transfer (existing CWWT and pipe network) per annum	11,827,981.56	0.242	2,862,371.54
9	O&M cost of water transfer (existing CWWT and pipe network) per annum	12,419,380.64	0.203	2,521,134.27
10	O&M cost of water transfer (existing CWWT and pipe network) per annum	13,040,349.67	0.17	2,216,859.44
11	O&M cost of water transfer (existing CWWT and pipe network) per annum	13,692,367.16	0.142	1,944,316.14
12	O&M cost of water transfer (existing CWWT and pipe network) per annum	14,376,985.51	0.119	1,710,861.28
13	O&M cost of water transfer (existing CWWT and pipe network) per annum	15,095,834.79	0.1	1,509,583.48
14	O&M cost of water transfer (existing CWWT and pipe network) per annum	15,850,626.53	0.084	1,331,452.63
15	O&M cost of water transfer (existing CWWT and pipe network) per annum	16,643,157.86	0.07	1,165,021.05
16	O&M cost of water transfer (existing CWWT and pipe network) per annum	17,475,315.75	0.059	1,031,043.63
17	O&M cost of water transfer (existing CWWT and pipe network) per annum	18,349,081.54	0.049	899,105.00
18	O&M cost of water transfer (existing CWWT and pipe network) per annum	19,266,535.61	0.041	789,927.96
19	O&M cost of water transfer (existing CWWT and pipe network) per annum	20,229,862.39	0.034	687,815.32

LCC for the Total Network - 19.4%				
Year	Description	Amount	d/f	Present Value
20	O&M cost of water transfer (existing CWWT and pipe network) per annum	21,241,355.51	0.028	594,757.95
21	O&M cost of water transfer (existing CWWT and pipe network) per annum	22,303,423.29	0.024	535,282.16
22	O&M cost of water transfer (existing CWWT and pipe network) per annum	23,418,594.45	0.02	468,371.89
23	O&M cost of water transfer (existing CWWT and pipe network) per annum	24,589,524.18	0.017	418,021.91
24	O&M cost of water transfer (existing CWWT and pipe network) per annum	25,819,000.39	0.014	361,466.01
25	O&M cost of water transfer (existing CWWT and pipe network) per annum	27,109,950.41	0.012	325,319.40
26	O&M cost of water transfer (existing CWWT and pipe network) per annum	28,465,447.93	9.951	283,259,672.35
27	O&M cost of water transfer (existing CWWT and pipe network) per annum	29,888,720.32	8.334	249,092,595.15
28	O&M cost of water transfer (existing CWWT and pipe network) per annum	31,383,156.34	6.98	219,054,431.25
29	O&M cost of water transfer (existing CWWT and pipe network) per annum	32,952,314.15	5.846	192,639,228.52
30	O&M cost of water transfer (existing CWWT and pipe network) per annum	34,599,929.86	4.896	169,401,256.59
31	O&M cost of water transfer (existing CWWT and pipe network) per annum	36,329,926.36	4.102	149,025,357.93

LCC for the Total Network - 19.4%				
Year	Description	Amount	d/f	Present Value
32	O&M cost of water transfer (existing CWWT and pipe network) per annum	38,146,422.67	3.434	130,994,815.45
33	O&M cost of water transfer (existing CWWT and pipe network) per annum	40,053,743.81	2.876	115,194,567.20
34	O&M cost of water transfer (existing CWWT and pipe network) per annum	42,056,431.00	2.409	101,313,942.28
35	O&M cost of water transfer (existing CWWT and pipe network) per annum	44,159,252.55	2.018	89,113,371.65
36	O&M cost of water transfer (existing CWWT and pipe network) per annum	46,367,215.17	1.689	78,314,226.42
37	O&M cost of water transfer (existing CWWT and pipe network) per annum	48,685,575.93	1.415	68,890,089.94
38	O&M cost of water transfer (existing CWWT and pipe network) per annum	51,119,854.73	1.185	60,577,027.86
39	O&M cost of water transfer (existing CWWT and pipe network) per annum	53,675,847.47	9.927	532,840,137.83
40	O&M cost of water transfer (existing CWWT and pipe network) per annum	56,359,639.84	8.314	468,574,045.63
41	O&M cost of water transfer (existing CWWT and pipe network) per annum	59,177,621.83	6.963	412,053,780.80
42	O&M cost of water transfer (existing CWWT and pipe network) per annum	62,136,502.92	5.832	362,380,085.03
43	O&M cost of water transfer (existing CWWT and pipe network) per annum	65,243,328.07	4.884	318,648,414.29

LCC for the Total Network - 19.4%				
Year	Description	Amount	d/f	Present Value
44	O&M cost of water transfer (existing CWWT and pipe network) per annum	68,505,494.47	4.091	280,255,977.88
45	O&M cost of water transfer (existing CWWT and pipe network) per annum	71,930,769.20	3.426	246,434,815.28
46	O&M cost of water transfer (existing CWWT and pipe network) per annum	75,527,307.66	2.869	216,687,845.68
47	O&M cost of water transfer (existing CWWT and pipe network) per annum	79,303,673.04	2.403	190,566,726.32
48	O&M cost of water transfer (existing CWWT and pipe network) per annum	83,268,856.69	2.013	167,620,208.52
49	O&M cost of water transfer (existing CWWT and pipe network) per annum	87,432,299.53	1.686	147,410,857.01
50	O&M cost of water transfer (existing CWWT and pipe network) per annum	91,803,914.50	1.412	129,627,127.27
	Total LCC			6,109,800,271.55

Sensitivity analysis – Proposed optimal water exchange network

LCC for Total Network - 4%				
Year	Description	Amount	d/f	Present Value
0	Initial cost (pipe laying and supply & installaiton of CWWT unit)	63,303,400.00	1.00	63,303,400.00
0-50	Freshwater cost per annum	17,640,797.28	21.5	379,277,141.52
0-50	Treated water utilisation cost per annum	16,464,708.00	21.5	353,991,222.00
0-50	Cost for pre-treatment by individual entity before send to CWWT per annum	64,476,691.27	21.5	1,386,248,862.23
0-50	Treatment cost to be borne by each entity for central treatment (Fee for CWWT) per annum	9,285,200.15	21.5	199,631,803.18
1	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	0.962	7,947,092.90

LCC for Total Network - 4%				
Year	Description	Amount	d/f	Present Value
2	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,674,061.90	0.925	8,023,507.25
3	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	9,107,764.99	0.889	8,096,803.08
4	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	9,563,153.24	0.855	8,176,496.02
5	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	10,041,310.90	0.822	8,253,957.56
6	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	10,543,376.45	0.79	8,329,267.39
7	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	11,070,545.27	0.76	8,413,614.41
8	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	11,624,072.53	0.731	8,497,197.02
9	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	12,205,276.16	0.703	8,580,309.14
10	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	12,815,539.97	0.676	8,663,305.02
11	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	13,456,316.97	0.65	8,746,606.03
12	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	14,129,132.82	0.625	8,830,708.01
13	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	14,835,589.46	0.601	8,916,189.26
14	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	15,577,368.93	0.577	8,988,141.87
15	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	16,356,237.38	0.555	9,077,711.74
16	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	17,174,049.24	0.534	9,170,942.30
17	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	18,032,751.71	0.513	9,250,801.63
18	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	18,934,389.29	0.493	9,334,653.92
19	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	19,881,108.76	0.475	9,443,526.66
20	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	20,875,164.19	0.456	9,519,074.87

LCC for Total Network - 4%				
Year	Description	Amount	d/f	Present Value
21	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	21,918,922.40	0.439	9,622,406.94
22	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	23,014,868.52	0.422	9,712,274.52
23	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	24,165,611.95	0.405	9,787,072.84
24	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	25,373,892.55	0.39	9,895,818.09
25	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	26,642,587.18	0.375	9,990,970.19
26	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	27,974,716.53	0.361	10,098,872.67
27	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	29,373,452.36	0.347	10,192,587.97
28	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	30,842,124.98	0.333	10,270,427.62
29	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	32,384,231.23	0.321	10,395,338.22
30	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	34,003,442.79	0.308	10,473,060.38
31	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	35,703,614.93	0.296	10,568,270.02
32	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	37,488,795.68	0.285	10,684,306.77
33	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	39,363,235.46	0.274	10,785,526.52
34	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	41,331,397.23	0.264	10,911,488.87
35	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	43,397,967.09	0.253	10,979,685.67
36	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	45,567,865.45	0.244	11,118,559.17
37	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	47,846,258.72	0.234	11,196,024.54
38	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	50,238,571.66	0.225	11,303,678.62
39	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	52,750,500.24	0.217	11,446,858.55

LCC for Total Network - 4%				
Year	Description	Amount	d/f	Present Value
40	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	55,388,025.25	0.208	11,520,709.25
41	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	58,157,426.51	0.2	11,631,485.30
42	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	61,065,297.84	0.193	11,785,602.48
43	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	64,118,562.73	0.185	11,861,934.11
44	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	67,324,490.87	0.178	11,983,759.37
45	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	70,690,715.41	0.171	12,088,112.34
46	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	74,225,251.18	0.165	12,247,166.45
47	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	77,936,513.74	0.158	12,313,969.17
48	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	81,833,339.43	0.152	12,438,667.59
49	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	85,925,006.40	0.146	12,545,050.93
50	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	90,221,256.72	0.141	12,721,197.20
	Total LCC			2,889,283,217.38

LCC for Total Network - 14.8%				
Year	Description	Amount	d/f	Present Value
0	Initial cost (pipe laying and supply & installaiton of CWWT unit)	63,303,400.00	1.00	63,303,400.00
0-50	Freshwater cost per annum	17,640,797.28	4.291	75,696,661.13
0-50	Treated water utilisation cost per annum	16,464,708.00	4.291	70,650,062.03
0-50	Cost for pre-treatment by individual entity before send to CWWT per annum	64,476,691.27	4.291	276,669,482.23
0-50	Treatment cost to be borne by each entity for central treatment (Fee for CWWT) per annum	9,285,200.15	4.291	39,842,793.84
1	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	0.871	7,195,340.87

LCC for Total Network - 14.8%				
Year	Description	Amount	d/f	Present Value
2	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	0.759	6,270,107.60
3	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	0.661	5,460,528.49
4	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	0.576	4,758,342.53
5	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	0.502	4,147,027.69
6	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	0.437	3,610,061.95
7	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	0.381	3,147,445.32
8	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	0.331	2,734,394.75
9	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	0.289	2,387,432.27
10	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	0.252	2,081,774.86
11	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	0.219	1,809,161.48
12	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	0.191	1,577,853.16
13	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	0.166	1,371,327.88
14	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	0.145	1,197,846.64
15	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	0.126	1,040,887.43
16	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	0.11	908,711.25
17	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	0.096	793,057.09
18	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	0.083	685,663.94
19	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	0.072	594,792.82
20	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	0.063	520,443.71

LCC for Total Network - 14.8%				
Year	Description	Amount	d/f	Present Value
21	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	0.055	454,355.62
22	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	0.048	396,528.54
23	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	0.041	338,701.46
24	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	0.036	297,396.41
25	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	0.031	256,091.35
26	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	0.028	231,308.32
27	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	0.024	198,264.27
28	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	0.021	173,481.24
29	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	0.018	148,698.20
30	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	0.016	132,176.18
31	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	0.014	115,654.16
32	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	0.012	99,132.14
33	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	0.011	90,871.12
34	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	9.162	75,687,385.81
35	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	7.981	65,931,131.42
36	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	6.952	57,430,550.77
37	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	6.056	50,028,684.61
38	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	5.275	43,576,834.77
39	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	4.595	37,959,347.06

LCC for Total Network - 14.8%				
Year	Description	Amount	d/f	Present Value
40	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	4.002	33,060,567.34
41	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	3.486	28,797,885.50
42	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	3.037	25,088,691.41
43	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	2.645	21,850,374.97
44	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	2.304	19,033,370.10
45	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	2.007	16,579,849.74
46	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	1.749	14,448,508.82
47	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	1.523	12,581,520.26
48	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	1.327	10,962,362.03
49	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	1.156	9,549,729.10
50	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	1.007	8,318,838.41
	Total LCC			1,112,272,892.07

LCC for Total Network - 19.4%				
Year	Description	Amount	d/f	Present Value
0	Initial cost (pipe laying and supply & installaiton of CWWT unit)	63,303,400.00	1.00	63,303,400.00
0-50	Freshwater cost per annum	17,640,797.28	5.154	90,920,669.18
0-50	Treated water utilisation cost per annum	16,464,708.00	5.154	84,859,105.03
0-50	Cost for pre-treatment by individual entity before send to CWWT per annum	64,476,691.27	5.154	332,312,866.81
0-50	Treatment cost to be borne by each entity for central treatment (Fee for CWWT) per annum	9,285,200.15	5.154	47,855,921.57
1	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,261,011.33	0.838	6,922,727.49

LCC for Total Network - 19.4%				
Year	Description	Amount	d/f	Present Value
2	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	8,674,061.90	0.701	6,080,517.39
3	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	9,107,764.99	0.587	5,346,258.05
4	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	9,563,153.24	0.492	4,705,071.39
5	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	10,041,310.90	0.412	4,137,020.09
6	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	10,543,376.45	0.345	3,637,464.88
7	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	11,070,545.27	0.29	3,210,458.13
8	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	11,624,072.53	0.242	2,813,025.55
9	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	12,205,276.16	0.203	2,477,671.06
10	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	12,815,539.97	0.17	2,178,641.79
11	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	13,456,316.97	0.142	1,910,797.01
12	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	14,129,132.82	0.119	1,681,366.81
13	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	14,835,589.46	0.1	1,483,558.95
14	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	15,577,368.93	0.084	1,308,498.99
15	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	16,356,237.38	0.07	1,144,936.62
16	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	17,174,049.24	0.059	1,013,268.91
17	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	18,032,751.71	0.049	883,604.83
18	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	18,934,389.29	0.041	776,309.96
19	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	19,881,108.76	0.034	675,957.70
20	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	20,875,164.19	0.028	584,504.60

LCC for Total Network - 19.4%				
Year	Description	Amount	d/f	Present Value
21	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	21,918,922.40	0.024	526,054.14
22	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	23,014,868.52	0.02	460,297.37
23	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	24,165,611.95	0.017	410,815.40
24	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	25,373,892.55	0.014	355,234.50
25	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	26,642,587.18	0.012	319,711.05
26	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	27,974,716.53	9.951	278,376,404.19
27	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	29,373,452.36	8.334	244,798,351.97
28	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	30,842,124.98	6.98	215,278,032.36
29	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	32,384,231.23	5.846	189,318,215.77
30	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	34,003,442.79	4.896	166,480,855.90
31	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	35,703,614.93	4.102	146,456,228.44
32	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	37,488,795.68	3.434	128,736,524.37
33	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	39,363,235.46	2.876	113,208,665.18
34	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	41,331,397.23	2.409	99,567,335.93
35	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	43,397,967.09	2.018	87,577,097.59
36	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	45,567,865.45	1.689	76,964,124.75
37	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	47,846,258.72	1.415	67,702,456.09
38	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	50,238,571.66	1.185	59,532,707.42
39	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	52,750,500.24	9.927	523,654,215.88

LCC for Total Network - 19.4%				
Year	Description	Amount	d/f	Present Value
40	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	55,388,025.25	8.314	460,496,041.93
41	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	58,157,426.51	6.963	404,950,160.79
42	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	61,065,297.84	5.832	356,132,817.00
43	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	64,118,562.73	4.884	313,155,060.37
44	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	67,324,490.87	4.091	275,424,492.15
45	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	70,690,715.41	3.426	242,186,390.99
46	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	74,225,251.18	2.869	212,952,245.64
47	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	77,936,513.74	2.403	187,281,442.52
48	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	81,833,339.43	2.013	164,730,512.27
49	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	85,925,006.40	1.686	144,869,560.79
50	O&M cost of water transfer (pipe network & CWWT with alteration) per annum	90,221,256.72	1.412	127,392,414.49
	Total LCC			5,961,518,090.01