MULTIPERIOD PLANNING OF WATER NETWORKS IN INDUSTRIAL CITIES

A Thesis

by

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ABSTRACT

Freshwater is an important natural resource which is required in various processes of several industries . With rapid industrialization around the globe, there has been a steady rise in demand of freshwater. As freshwater reserves are limited, there is a need to use them efficiently. Optimization of water networks in industries is a step in the direction of efficient utilization of water and for cutting down cost. Several works have been dedicated and implemented in industries for the conservation of freshwater resources.

As industries grow in size with time, their water network should evolve accordingly. Current methodologies deal only with individual period optimization and do not consider the industrial city planning horizon. This is the first attempt to present a multi-period planning approach for synthesis of integrated water network within industrial cities

The formulations presented in this paper consider the cases of direct recycle and reuse (without treatment) and regeneration and reuse(with treatment). Source-sink mapping model has been implemented in both the cases The work presents optimization based models to determine the minimum freshwater usage and lowest cost design for direct recycle and reuse and lowest cost design for regeneration and reuse.

DEDICATION

To my mother and my friend Praneet.

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I am truly indebted to all those who have assisted me in the preparation and completion of this course of study. All the hard work, determination and persistence that culminated in creation of this thesis would never have been successful without all the support, patience and guidance that I have received.

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NOMENCLATURE

$DI_{i(p1),j(p2)}$	Diameter of pipe connecting ith source in plant p1 to jth sink in plant p2
$F_{i(p1),j(p2),t}$	Flowrate between ith source in plant p1 to jth sink in plant p2 time period t
$F_{i(p1),ww,t}$	Flowrate between ith source in plant p1 for waste water discharge in time period t
$F_{fw,j(p2),t}$	Flowrate between Freshwater source to jth sink of plant p2 in time period t
C_{fw}	Concentration of Freshwater
$C_{i(p1),t}$	Concentration of ith source of plant p1 time period t
$C_{j(p2),t}$	Concentration of jth sink in time period t
$X_{i(p1),j(p2),t}$	Binary variable representing connection between ith source and jth sink in time period t
$DI_{i(p1),j(p2)}$	Diameter of pipe connecting ith source in plant p1 to jth sink in plant p2
$F_{i(p1),j(p2),t}$	Flowrate between ith source in plant p1 to jth sink in plant p2 during time period t
$F_{i(p1),r1(s1),t}$	Flowrate between ith source in plant p1 to r1 interceptor of stage 1 during time period t

$F_{r1(s1),t}$	Flowrate to be treated by interceptor r1 of stage 1 during time period t.
$F_{r1(s1),r2(s2),t}$	Flowrate between r1 interceptor of stage 1 to r2 interceptor of stage 2 during time period t
$F_{r2(s2),t}$	Flowrate to be treated by interceptor r2 of stage 2 during time period t.
$F_{r2(s2),env,t}$	Flowrate between r2 interceptor of stage 2 to environment during time period t.
$F_{r2(s2),j(p2),t}$	Flowrate between r2 interceptor of stage 2 to j^{th} sink in plant p2 during time period t
$F_{i(p1),env,t}$	Flowrate between i^{th} source in plant p1 for waste water discharge in time period t
$F_{fw,j(p2),t}$	Flowrate between Freshwater source to j^{th} sink of plant p2 in time period t
$C_{b,fw}$	Concentration of contaminant b in Freshwater
$C_{b,i(p1),t}$	Concentration of contaminant b in i^{th} source of plant p1 time period t
$C_{b,j(p2),t}$	Concentration of contaminant b in j^{th} sink of plant p2 in time period t.
$C^{in}_{b,r1(s1),t}$	Inlet concentration of contaminant b in interceptor r1 of stage 1 in time period t.

$RR_{r1(s1)}$	Removal ratio of interceptor r1 in stage 1.
$C^{out}_{b,r1(s1),t}$	Outlet concentration of contaminant b in interceptor r1 of stage 1 during time period t.
$C^{in}_{r2(s2),t}$	Inlet concentration of contaminant b in interceptor r2 of stage 2 in time period t.
$RR_{r2(s2)}$	Removal ratio of interceptor r2 in stage 2.
$C^{out}_{r2(s2),t}$	Outlet concentration of contaminant b in interceptor r2 of stage 2 during time period t.
$X_{i(p1),j(p2),t}$	Binary variable representing connection between ith source and jth sink in time period t.
$X_{i(p1),r1(s1),t}$	Binary variable representing connection between ith source and interceptor r1 in time period t.
$X_{r2(s2),j(p2),t}$	Binary variable representing connection between interceptor r2 and jth sink in time period t.
$X_{r2(s2),env,t}$	Binary variable representing connection between interceptor r2 and environment in time period t.
$X_{r(s),t}$	Binary variable representing the existence of rth interceptor of stage s in time period t.
U	Large number used in equation in 6b and 14.
N_t	Maximum number of connections allowed in time period t
ϵ	Minimum value of flowrates.

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1. INTRODUCTION

In all production processes, raw materials are processed and transformed into goods and services. Water plays a very significant role in modern industries and significant amount of waste water is generated .With tight environmental regulations coming into effect , there is an urgent need for the industries to reduce the generation of waste water, effectively use their Freshwater resources and find out new avenues for waste water usage. A straight forward answer to the above stated needs can be designing of new and efficient processes but it takes a considerable amount of time to build and commission one. A feasible and a more reasonable approach is design a water network which optimizes the usage of Freshwater and generation of waste water. It also helps us to abide by the regulations and examine other usage of waste water generated. Designing of an efficient water network has both economic and social impact. It helps the industries in reducing their investment on water in the long run and also provides more amounts of water domestic and other needs

With this aim, concept of Eco-Industrial Park is becoming popular. Originally, these were mainly based upon the exchange of resources between heavy industries in industrial complexes.. Since then, the concept of eco-industrial parks has been extended to another relevant type of industrial park, the so-called mixed industrial park, which consists of various small- and medium-sized enterprises , sometimes complemented by a small number of larger industries[1]. The minimization of the water footprint of industrial cities or parks requires the development of efficient water reuse strategies.

Current methods for water integration do not consider the industrial city planning horizons in the development of optimal water strategies. This work is a first step in the direction of multi-period planning for industrial cities. Two kind of scenarios have been considered –

- Direct Recycle and Reuse
- Regeneration and Reuse

In direct recycle and reuse, contaminated water is being reused in plant without any treatment. Water from sources either go sinks or is discharged into the environment without any treatment. In regeneration and reuse scenario, water from sources can be sent to sinks and environment either without treatment or with treatment. Two different superstructure have been proposed for dealing with these scenarios.

The initial formulation considers direct reuse of water in between plants, and involves water streams with several pollutants. A source-sink water mapping model has been implemented, such that available water sources can either be allocated to water sinks, or discharged as wastewater streams. Freshwater streams were made available to mix with water sinks as necessary, to enable reuse in between plants. The work presents two optimization models to determine the minimum Freshwater use in the industrial city through maximum direct water reuse regardless of cost as well to determine the lowest cost design for direct water reuse.

For regeneration and reuse scenario, this work considers presence of a two stage off-site centralized treatment system and water streams having several contaminants. A source-sink mapping model has been implemented such that water sources can either be allocated to water sinks, treatment units or discharged to environment. Freshwater streams and treated water are made available to mix with water sinks to enable reuse between plants. Waste water is allowed to be discharged into environment at threshold contaminant levels.

Several illustrative examples are presented to demonstrate the proposed methods. The results indicate great potential for achieving considerable savings of resources when integration strategies for plants were developed over an entire planning period rather than individual time periods.

2. LITERATURE REVIEW

Process integration is defined as “a holistic approach to process design, retrofitting and operation which emphasizes the unity of the process (El-Halwagi, 1997[2]). It is an approach towards minimizing resource consumption by designing and planning utility networks within industrial process plants. The efficient use of resources in one of the key features of a successful process and chemical industry and is driven by competitiveness of market, dwindling of resources and stricter environmental regulation. Water is one of the most important resource in process industry and is used for various operations and utility applications. Use of water in industries result in generation of significant amount of waste water which in turn is discharged into the environment. With Freshwater resources becoming more scarce and environmental regulation tightening, there is a strong need for the industries and their regulators to reduce the water footprints of industrial operations in terms of water intake and generation of waste water.

Water integration within and across processes presents a practical approach to reduce water footprints by exploiting synergies at the level of the processing system. Many strategies involving a single plant for a single period have been developed. Early works by El-Halwagi and Manuosiouthakis[3], as well as Wang and Smith[4] implements the concept of pinch analysis for the water treatment, exchange and integration within a single plant. Apart from these, Liu et al[5], Kuo and Smith[6], Hallale [7], El-Halwagi et al[8], Manan et al[9], Almutaq and El-Halwagi[10], and

Shenoy and Bandyopadhyay[11]. Almutlaq et al [12], Dhole et al [13], Foo et al [14], Polley and Polley [15]. Chung et al [16] developed a process based graphical approach for simultaneous targeting and design of water networks. Bandyopadhyay and Cormos[17] also used a graphical representation to address water management issues of integrated processes that involve regeneration and recycle through a single treatment unit.

In addition, Kuo and Smith[18], Bandyopadhyay et al[19], Agrawal and Shenoy [20], Ng et al[21 a, 21b], Bai et al[22] and Feng et al[23] have proposed targeting approaches for the minimization of regeneration costs and treatment flowrates. Recent work in graphical technique include Parand et al[24], Pombo et al[25], Agana et al[26] and Liu et al[27].

In terms of algebraic approaches, work has considered the case of a single plant. Takama et al[28] proposed a method for solving the planning problem of optimal water allocation combining all alternatives into an integrated system. El-Halwagi et al[29] presented a mathematical model to determine the optimal water usage and interception network while accounting for the process model. Chakraborty [30] has developed a source –sink equivalent of the above problem and proposed a MINLP and MILP model Chakraborty et al. (Chakraborty and Linninger [31] , Chakraborty et al [32]) proposed MILP models for the plant-wide synthesis of water integration via recycle and reuse. Alva-Argáez, Vallianatos, and Kokossis[33] proposed a strategy to mass exchanger network and wastewater minimization problems El-Halwagi et al [34] developed a rule-based approach for matching sources and sinks by applying dynamic-optimality conditions to the graphical targeting problem. Gabriel and El-Halwagi [35] developed a globally solvable optimization approach for the simultaneous synthesis of waste interception and material reuse networks. Karuppiah and Grossmann[36] proposed a mixed integer non-linear programming (MINLP) formulation to optimize the synthesis of integrated wastewater systems considering different alternatives for wastewater treatment.

The above mentioned work considered integration of processes within an individual plant. A lot of work has been done for inter plant integration considering presence of single and multiple contaminant water streams. If graphical technique is examined, Olesen and Polley[37] presented one of the first methods based on pinch analysis. Spriggs et al[38] used the material recovery pinch diagram. Bandyopadhyay et al[39] presented a generalized technique decomposition for determining optimal resource usage in segregated targeting problems with a single quality index through pinch analysis, and Chew et al[40] and Chew et al[41] presented a paper series based on pinch analysis for describing a new algorithm for targeting minimum fresh resource and waste flowrates for an inter-plant resource conservation network. Chew et al[42] paper extends the automated water system for single plant integration to inter plant integration and the optimization technique in this paper is based on water pinch analysis.

Graphical methods can be used for solving small scale problems, but with larger problems concepts of mathematical optimization are utilized to solve the problem. Several work has been done for inter-plant water network integration using both deterministic and stochastic methods. Lovelady et al[43] reported a systematic approach for the reduction of water usage and wastewater discharge in pulp and paper plants; the model included mass integration strategies to handle multiple pollutants. Chew et al[44] proposed an MINLP formulation for the synthesis of direct and indirect inter-plant water networks but with a limitations that type of treatment unit was not set as optimization variable, direct discharge from source environment was not allowed and there was not restriction on the contaminant levels of the discharge. These limitations are addressed in Castro et al[45] which presents a Mixed Integer Non Linear Programming model to design an eco-industrial plant by retrofitting existing water networks from different industrial plants in the same industrial zone and proposes a superstructure and takes into account both in-plant and inter-plant structural modifications.

Lovelady et al[46] developed a property-integration optimization approach for designing eco-industrial parks that are constrained by properties. Lim and Park[47] presented a nonlinear programming model to retrofit a conventional industrial park into a green eco-industrial park through the minimization of the total consumption of industrial water. Klemes[48] have presented a recent review of water integration techniques and methodologies. Montastruc et al [49] discussed the capacity of EIP to sustain sudden variations in concentration level of pollutants. Boix et al[50] highlighted the importance of EIPs for water and energy integration. Boix et al [51] proposed a multi-objective optimization problem that involves minimizing Freshwater, waste water and the number of stream connections. Aviso[52] proposed a mathematical model for identifying a robust water exchange network. Chen et al[53] presented an MINLP problem for the inter-plant water integration of an industrial complex exploiting the opportunities for water reuse/recycle across plants. Lee at al [54] developed a mathematical optimization model for inter-plant water network for processes involving both batch and continuous units. Sabla et al [55] developed water integration model for an industrial city taking into account the spatial representation of plants.

Apart from deterministic methods, work has been done by utilizing the stochastic methods. . Lavric et al [56] utilized a genetic algorithm for the optimization of water consumption and waste water network topology, Prakotpol and Srinophakun [57] developed a genetic algorithm tool-box for water pinch analysis, Shafiei et al [58] used genetic algorithm for synthesizing optimal water network for a pulp and paper mill and Jezowski et al [59] employed a genetic algorithm for the optimization of water usage in chemical industry. Tan et al [60] developed a methodology for the design of efficient resource conservation networks using adaptive swarm intelligence.

So far, all research efforts that have been mentioned focus on water integration with an assumption that a plant or industrial city will not change with time. However, this is certainly not the case in rapidly industrializing nations where capacity of plants often expand and new plants are developed. To deal with this scenario, multi-period water network design approaches would be required to determine the optimal utilization of water over the planning horizon and beyond. Burgara-Montero et al [61] developed an optimization approach that incorporates seasonal variations in the optimal treatment of industrial wastewater effluents. Liao et al [62] proposed an approach to the design of water networks in a single plant considering a single contaminant. Bishnu et al[63] proposed a mathematical model for synthesizing optimal water network in industrial cities considering multi-period planning for direct recycle and reuse case.

Outside the area of water network synthesis, multi-period planning approaches have been proposed for many applications, including oil field development (Iyer and Grossman [64]; Barnes et al [65]; Gupta and Grossman [66]), heat and mass exchange network design (Isafiade and Fraser[67]; Papalexandri and Pistikopolous [68]), batch reactor design (Rooney and Biegler [69]) , hydrogen network design (Heever and Grossman [70], Almansoori and Shah [71]), scheduling problem(Costa et al[72], Fumero et al [73],Tong et al[74]).

This work is a first attempt to apply the concept of multi-period planning for integration of water networks in Industrial Cities. Section 3 presents the direct recycle and reuse scenario while Section 4 deals with regeneration and reuse considering the presence of two stage centralized treatment system. Each section presents the problem statement, its formulation together with case studies to show that multi-period planning has advantages over individual period planning.

3. DIRECT RECYCLE AND REUSE WATER NETWORKS

3.1 Problem Statement

The general problem addressed in this section is the mapping of water sources and sinks existing in an industrial city over a planning time horizon, via direct water reuse. The main objective is to determine the most water efficient water reuse allocation, as well as the most economically efficient water network design. The problem is formally stated as:

Given

- An industrial city hosting a number of plants,
- A number of contaminants to be considered across the industrial city,
- A number of waste water streams (sources) of known flow rate and composition in each plant,
- A number of water using operations (sinks) together with flowrate requirements and constraints on feed water contamination,
- Existing connections between sources and sinks and their corresponding flow rate constraints,
- A number of time periods over which to develop water reuse network designs,
- A known expansion schedule detailing the addition of new plants and associated sources and sinks and alterations in existing plants the corresponding sources and sinks in each time period,

- Lengths of the shortest connections between all sources and sinks in the industrial city, and
- Known topological constraints that restrict the number of pipes in a given time period,

Determine

- The allocation of water between sources and sinks and the corresponding water flows rates over the entire planning horizon so as to maximize direct water reuse and minimize Freshwater requirements (target).
- The cost-optimal direct water reuse network that connects sources and sinks within the industrial city together with its evolution over the time periods (design).

Figure 1 illustrate the expansion of an industrial city over three time periods. The changes within the city over time are summarized in an industrial city development plan, which in turn specifies all information pertaining to all plants involved, as well as the corresponding water sources and sinks present in each time period. This includes any capacity expansion of existing plants that results in capacity changes of individual sources and sinks over the time periods as well as information on the addition of new plants in different time periods, with corresponding new sources and sinks. A number of sets are defined as a basis for our problem formulation:

I $\{i = 1, 2, \dots N_{sources} \mid I$ is a set of process sources$\}$

J $\{j = 1, 2, \dots N_{sinks} \mid J$ is a set of process sinks$\}$

$T\ \{t = 1, 2, \dots N_{time} \mid T \text{ is a set of time periods}\}$

$P\ \{p = 1, 2, \dots N_{plant} \mid P \text{ is a set of plant}\}$

$B\ \{b = 1, 2, \dots N_{contaminants} \mid B \text{ is a set of contaminants}\}$

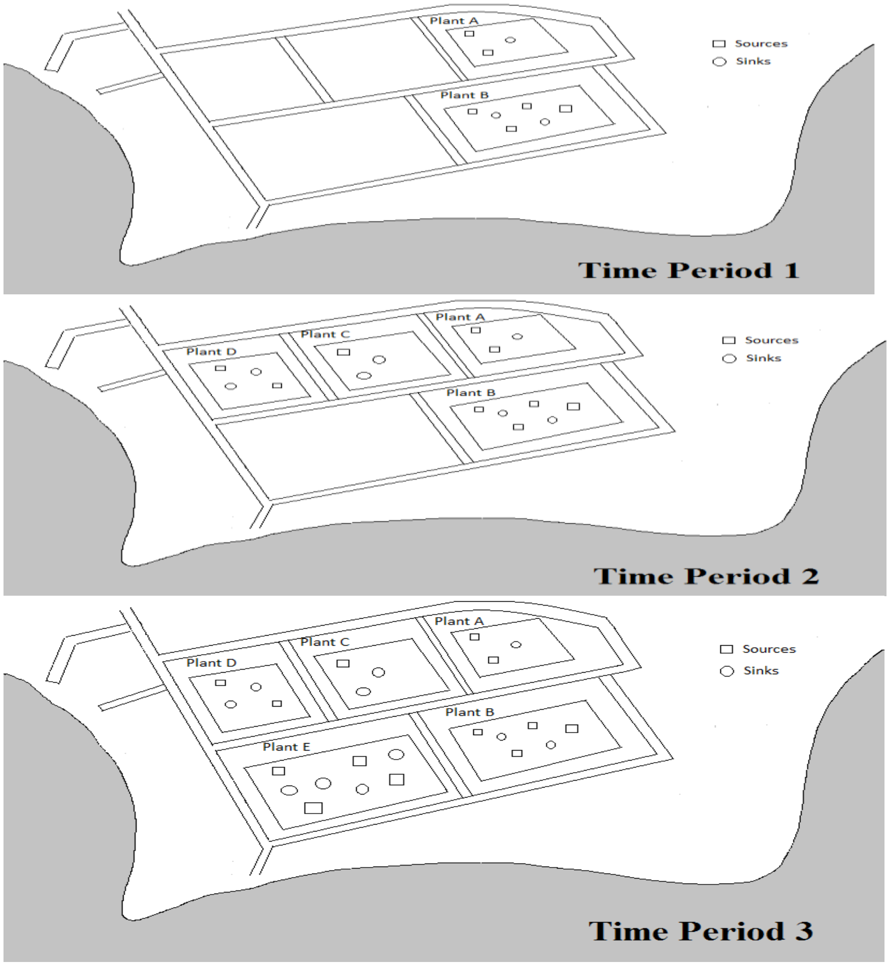

Figure 1 – Multi-period representation of an Industrial City

Figure 2 illustrates a source-sink mapping for direct water reuse in a single time period, showing p Plants with i sources and j sinks, a source of Freshwater and a waste water discharge. Each source can be split into several streams: (1) Source-to-Sink flows ($F_{i(p1),j(p2),t}$) representing the flow from ith source of plant p1 to jth sink of plant p2 in time period t ($p1,p2 \epsilon P$) and (2) Source-to-Waste flows ($F_{i(p1), ww ,t}$) which represents the flow from each source of plant p1 to environment for discharge. The freshwater source is split and allocated to different sinks as($F_{fw,j(p2), t}$) . A constraint on the number of connections between sources and sinks is placed with the help of a binary variable $X_{i(p1), j(p2), t}$ which represents the connection between i^{th} source of plant p1 and j^{th} sink of plant p2. X assumes a value of unity if the flow rate associated with the particular stream is non-zero and greater than a given minimum required value. As pipelines are major capital items with long life times, any connections made within a particular time period will remain in subsequent time periods.

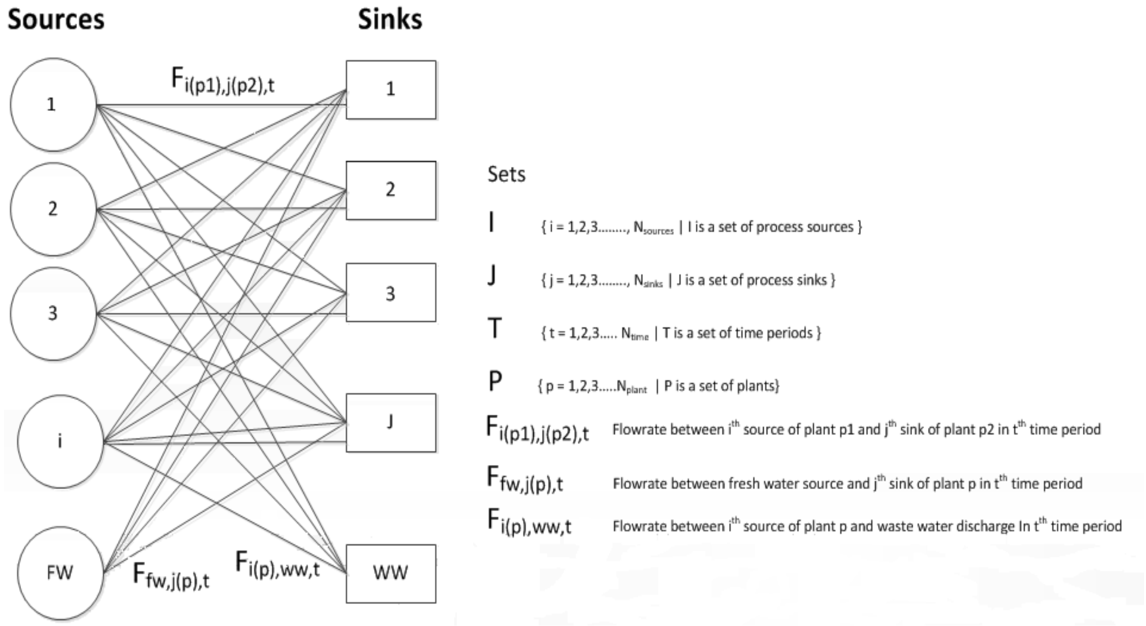

Figure 2- General representation of Source – Sink Mapping

3.2 Problem Formulation

Two multi-period optimization problems for direct water reuse in industrial cities have been formulated: (1) a model to target the direct reuse strategy the requires the minimum amount of water over the planning horizon, and (2) a model to determine the cost-optimal direct reuse network design and its evolution over the planning horizon. Model 1 allows the development of information on the maximum possible water savings in the city over time regardless of cost. Results from Model 1 constitute the minimum water footprint possible for the system using direct reuse. Model 2 allows the development of cost optimal designs that would strike a balance between the value of water saved and the capital investment made in the direct reuse network. For both the cases, it is assumed that a pipe once laid has to be utilized in future periods. The two model formulations are presented in detail below.

3.2.1 Model for Minimum Freshwater Targeting

The optimization formulation developed for targeting of Freshwater used during the planning time horizon is presented below. The objective function involves the minimization of Freshwater used, as described by Equation (1) below:

$$\text{MIN} \quad \sum_{t\epsilon T} \sum_{p\in P} \sum_{j\in J} w_t * F_{fw,j(p),t} \tag{1}$$

Here w_t is the weight assigned to period t and $F_{fw,j(p),t}$ is the freshwater flowrate to sink j of plant p in time period t. The weights are specified by the user in the context of the particular case under investigation. Criteria to decide the setting of the weights might include the relative net water demand in a given period over the maximum demand, the expected continuation of industrial city operation beyond the last planning period, or other criteria the user deems worth exploring during the solution of a case study. The objective function is minimized subject to a number of constraints.

The source and sink mass balance constraints are described by Equations (2) and (3) respectively:

$$F_{i(p1),ww,t} + \sum F_{i(p1),j(p2),t} = F_{i(p1),t} \quad ; \forall \ i \epsilon I, p1,p2 \epsilon P \tag{2}$$

$$F_{fw,j(p2),t} + \sum F_{i(p1),j(p2),t} = F_{j(p2),t} \quad ; \forall \ j \epsilon J, \ p1,p2 \epsilon P \tag{3}$$

Water sources can either be discharged to environment ($F_{i(p1),ww,t}$) or sent to a sink ($F_{i(p1),j(p2),t}$).Here, p1 and p2 can be the same plant or two different plants. Moreover, sinks are able to receive contaminant rich water from sources ($F_{i(p1),j(p2),t}$)

and/or Freshwater ($F_{fw,\ j,\ t}$) . A purity constraint ensuring that the maximum contamination levels tolerable by the sink processes are not exceeded was used, and is provided in Equation (4) below:

$$F_{fw,j(p2),t} * C_{b,fw,t} + \sum F_{i(p1),j(p2),t} * C_{b,i(p1),t} \leq F_{j(p2),t} * C_{b,j(p2),t} \quad ; \forall\ j \epsilon \text{J},\ \ \text{p1}, \text{p2} \epsilon \text{P} \tag{4}$$

where $C_{b,fw}$ is the concentration of contaminant b in freshwater, $C_{b,i(p1),t}$ is the concentration of contaminant b in source i of plant p1 in time period t and $C_{b,j(p2),t}$ is the concentration of contaminant b in sink j of plant p2 in time period t. The number of connections can be limited to a maximum acceptable number, in order to maintain simple designs as necessary. Equation (5) imposes a constraint of number of pipe lines that can be constructed between sources and sinks.

$$\sum_{p \in P} \sum_{i \in I} \sum_{j \in J} X_{i(p1),j(p2),t} \leq \text{N}_\text{t} \tag{5}$$

$X_{i(p1),j(p2),t}$ denotes the existence of flow between source i of plant p1 to sink j of plant p2 in time period t. Interconnections with flowrate ($F_{i(p1),j(p2),t}$) below a minimum threshold (∈)maybe discarded for economic reasons. This constraint is satisfied by the following “if-then” conditions of Equations (6) and (7).

$$\text{if} \quad F_{i(p1),j(p2),t} \leq \in, \text{ then } X_{i(p1),j(p2),t} = 0 \tag{6}$$

$$\text{if } \in \leq F_{i(p1),j(p2),t} \leq U \text{, then } X_{i(p1),j(p2),t} = 1 \tag{7}$$

where U is an upper bound on the acceptable flowrate $F_{i(p1),j(p2),t}$.

The “if-then” conditions of Equations (6) and (7) can be implemented with the help of Equation (8).

$$\in * X_{i(p1),j(p2),t} \leq F_{i(p1),j(p2),t} \leq U * X_{i(p1),j(p2),t} \tag{8}$$

According to this equation, if $F_{i(p1),j(p2),t} < \in$ then $F_{i(p1),j(p2),t}$ and $X_{i(p1),j(p2),t}$ are forced to be zero to satisfy the constraint and if $F_{i(p1),j(p2),t}$ lies between $\in$ and U, then $X_{i(p1),j(p2),t}$ is forced to be 1.Any connection made in a time period t is carried forward into future time periods according to:

$$X_{i(p1),j(p2),(t+1)} - X_{i(p1),j(p2),t} \geq X_{i(p1),j(p2),t} - 1 \tag{9}$$

An alternative formulation to handle the requirement of Equation. (9) that future period connections are enforced is the following expression:

$$X_{i(p1),j(p2),t} = X_{i(p1),j(p2),(t+1)}; \qquad \{t: X_{i(p1),j(p2),t} = 1\} \tag{10}$$

This equation ensures that even a connection is not required in previous period ($X_{i(p1),j(p2),t-1}$=0) and is required in current period, values of all X in future period will be set to 1.

Finally, all flows must be non-negative.

$$F_{fw,j(p2),t} \geq 0, \tag{11}$$

$$F_{i(p1),ww,t} \geq 0, \tag{12}$$

$$F_{i(p1),j(p2),t} \geq 0 \tag{13}$$

Equations (1) through (13) constitute the optimization model for minimum Freshwater targeting. Since a water network would develop over time and run beyond their development horizon, the relative importance of the different time periods may not be considered equal. Therefore, the objective function has weight w_{t} assigned to each time period t. The weights allow for the option to emphasize individual time periods. For instance, the importance of the individual time periods can be rated so that there is more emphasis on water savings in the last time period that would extend beyond the planning horizon. Time periods can be rated in different ways. The weighting could be done on the basis on flowrates in individual periods or on total load being handled. The time periods can also be assigned equal weights if the industrial city is mature and is not going to expand significantly into future. The setting of weights is user dependent and should reflect the specific needs of a given case study. Apart from the minimization of Freshwater, waste water minimization can be set as an alternative objective function for the optimization problem.

3.2.2 Model for Cost-Optimal Network Design

The optimization formulation developed for minimizing the total cost used during the planning time horizon is presented below. The objective is to minimize the total cost of the network, both piping and freshwater cost utilization, as described in Equation (11) below:

$$\text{MIN} \ \sum_{t\in T}\sum_{p1,p2\in P} w_t\Big(\sum_{\mathrm{i}\in \mathrm{I}}\sum_{\mathrm{j}\in \mathrm{J}} \mathrm{a}\big(\mathrm{DI}^{\mathrm{c}}_{\mathrm{i(p1),j(p2)}}\big)^{\mathrm{b}}\, d_{i,j} + \sum_{\mathrm{j}\in \mathrm{J}} a\big(\mathrm{DI}^{\mathrm{c}}_{\mathrm{Fw,j(p2)}}\big)^{\mathrm{b}}\, d_{fw,j} + \sum_{\mathrm{i}\in \mathrm{I}} a\big(\mathrm{DI}^{\mathrm{c}}_{\mathrm{i(p1),WW}}\big)^{\mathrm{b}} d_{i,ww} + \mathrm{Hy}\ \mathrm{C}^{\mathrm{fresh}} \sum_{i\in I}\sum_{t\in T} F_{Fw,j(p2),t}\Big) \qquad (14)$$

where w_t represents the weight associated with time period *t*, d represents distance between two facilities, $\mathrm{DI}^{\mathrm{c}}_{\mathrm{i(p1),j(p2)}}$ is the diameter of the pipe between source i of plant p1 to sink j of plant p2, $\mathrm{DI}^{\mathrm{c}}_{\mathrm{Fw,j(p2)}}$ is the diameter of the pipe between freshwater source and sink j of plant p2, $\mathrm{DI}^{\mathrm{c}}_{\mathrm{i(p1),WW}}$ is the diameter of the pipe between source i of plant p1 and wastewater discharge point, $F_{Fw,j(p2),t}$ is the flowrate between freshwater source (F_w) to sink j of plant p2 in time period t, Hy denotes the hours of operation in a time period, C^{fresh} is cost of freshwater per ton , and a and b are cost parameters. The capital cost is a function of the diameters of interconnecting pipes, which in turn is calculated based on the flow rate through the interconnection as explained below.

The number of connections are limited to a maximum acceptable number, in order to allow the user a control to maintain simple designs as appropriate. Equation (15) imposes a constraint on the number of pipe connections that can be constructed between sources and sinks.

$$\sum_{p\in P}\sum_{i\in I}\sum_{j\in J} X_{i(p1),j(p2),t} \leq \mathrm{N}_{\mathrm{t}} \qquad (15)$$

Equation (16) imposes a constraint on the minimum flow rate requirement enforced on a connection to avoid connections with very small flow rates and therefore diameters:

$$\in * X_{i(p1),j(p2),t} \leq F_{i(p1),j(p2),t} \leq U * X_{i(p1),j(p2),t} \qquad (16)$$

where U is a very large number and ∈ is the minimum value of flowrate. Any connection made in a time period t is carried forward into future time periods according to Equation (17).

$$X_{i(p1),j(p2),(t+1)} - X_{i(p1),j(p2),t} \geq X_{i(p1),j(p2),t} - 1 \qquad (17)$$

Finally, a non-negative constraint was imposed on all flows within the network, described by Equations (18)-(20) below

$$F_{fw,j(p2),t} \geq 0 \qquad (18)$$

$F_{i(p1),ww,t} \geq 0$ (19)

$F_{i(p1),j(p2),t} \geq 0$ (20)

The pipe Size (DI) is calculated as as:

DI = $0.363((M)^{0.45} * \rho^{0.13})$ (21)

This expression has been taken from Peters et al. [75], where M represents the volumetric flowrate given in m^3/s and ρ is density of the stream. The pipe diameter obtained using the expression is rounded off up to one decimal place .The assumption of rounding up to the next highest decimal number is justified as this gives a standard pipe size value(in meters) which satisfies the requirement of the flow and makes selection of the pipe easier.

3.3 Implementation and Case Study Development

The two MINLP formulations for multi-period water minimization and cost-optimal network design have been implemented using "What's Best 9.0,5.0" Lindo[76] Global solver for MS-Excel 2007 using a laptop with Intel Core 2 Duo processor T6400, 2 GHz, 4 GB RAM and a 32-bit Operating System.

In addition to the multi-period solutions developed for the case studies in Section 4, results have also been developed using single-period optimization. In single period optimization, we do not take into consideration future supplies and demands while establishing connections between facilities. Each period is optimized with information for that period only whilst retaining connections made in previous periods. The single period optimization results resemble the use of existing methods, which do not take into consideration a planning horizon in determining water networks. In terms of results for the freshwater minimization model, we expect the amount of freshwater required in both multi-period optimization and single period optimization over all time periods to be identical. This is because the model does not take into account the network cost and therefore can achieve optimal allocations or water in each period with additional connections and adjusted flows that may not be cost effective. On the other hand, we expect the multi-period model for cost optimization to determine lower cost networks as compared to the single-period optimization. The MINLP model formulation given in Chakraborty[18] has been used to solve the Freshwater and total cost minimization problem using single period optimization.

3.4 Case Studies

Two case studies illustrating the advantages of multi-period planning over individual period planning have been presented in the following sections. The case studies have been solved separately for both multi-period and individual period optimization, and the results of which were compared.

In all case studies, the values of a,b and ρ are set to 3114.86 ,1.0532 and 1000 kg/m^3 respectively. H_y is set to a value of 8760 h/y and the cost of Freshwater C^{fresh} is set be $0.13/ton. The lower bound for the flowrate (ϵ) is set to 2 tons/h.

3.4.1 Case Study 1

This example is based on two case studies of Malaysian Textile Company (Ujang et al [77]) and a thermo mechanical pulp and newsprint mill (Jacob et al [78]). The original case study of Textile Company consists of two sources and two sinks. The planning is done for ten years divided into five time periods of. The initial setup consists only of a bleaching section textile plant with two sources and sinks involving one kind of contaminant. This setup expands in capacity for three time periods In the fourth time period, the pulp and news print mill is commissioned, thereby adding another type of contaminant in the system. This system expands in capacity till the fifth period. The data for flow rates and concentrations that has been provided is a mixture of real instances and hypothetical scenarios. The case study input data are presented in the Appendix

3.4.1.1 Freshwater Minimization

The flowrate results of multi-period optimization for this example are provided in Table 1 to 5 and Figures 3 & 4 present a picture of development of water network.

Table 1 - Time Period 1(Case Study 1 – Multi-Period Freshwater Minimization)

	SINKS			
SOURCES		BG	MK	WW
	C12	440.25	209.75	0
	C34	0	490.25	109.75
	FW	559.75	0	

Table 2 - Time Period 2(Case Study 1 – Multi-Period Freshwater Minimization)

	SINKS(j)			
SOURCES		BG	MK	WW
	C12	836.48	463.52	0
	C34	0	1036.48	63.52
	Fw	1063.52	0	

Table 3 - Time Period 3(Case Study 1 – Multi-Period Freshwater Minimization)

	SINKS(j)			
SOURCES		BG	MK	WW
	C12	1540.88	759.12	0
	C34	0	1690.88	409.12
	FW	1959.12	0	

Table 4 - Time Period 4(Case Study 1 – Multi-Period Freshwater Minimization)

	SINKS(j)						
SOURCES		BG	(MK)	D6	D8	D9	WW
	C12	858	2	0	1740	0	0
	C34	0	2400	0	0	0	0
	S1	1668.89	0	2361.1	0	1950	0
	S2	0	0	0	2840	0	0
	FW	1473.11	398	1888.9	0	0	0

Table 5 - Time Period 3(Case Study 1 – Multi-Period Freshwater Minimization)

	SINKS(j)						
		BG	MK	D6	D8	D9	WW
SOURCES	C12	2	2	0	2796	0	0
	C34	0	2600	0	0	0	0
	S1	1822.22	0	2777.8	0	2400	0
	S2	0	0	0	3500	0	0
	FW	2575.78	398	2222.2	204	0	0

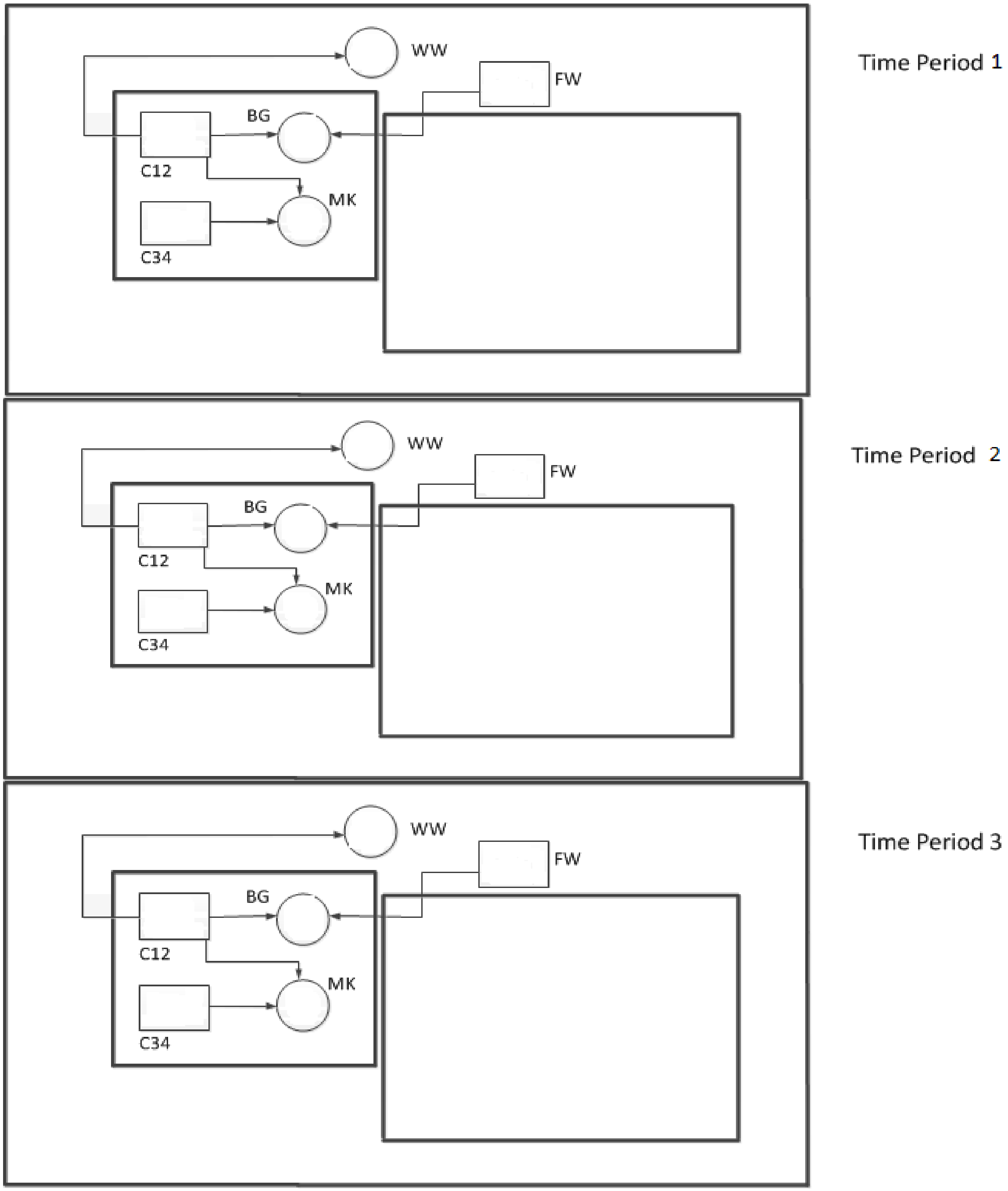

Figure 3 - Multi-Period Optimization minimizing Freshwater usage from tp1 to 3 (Case Study 1)

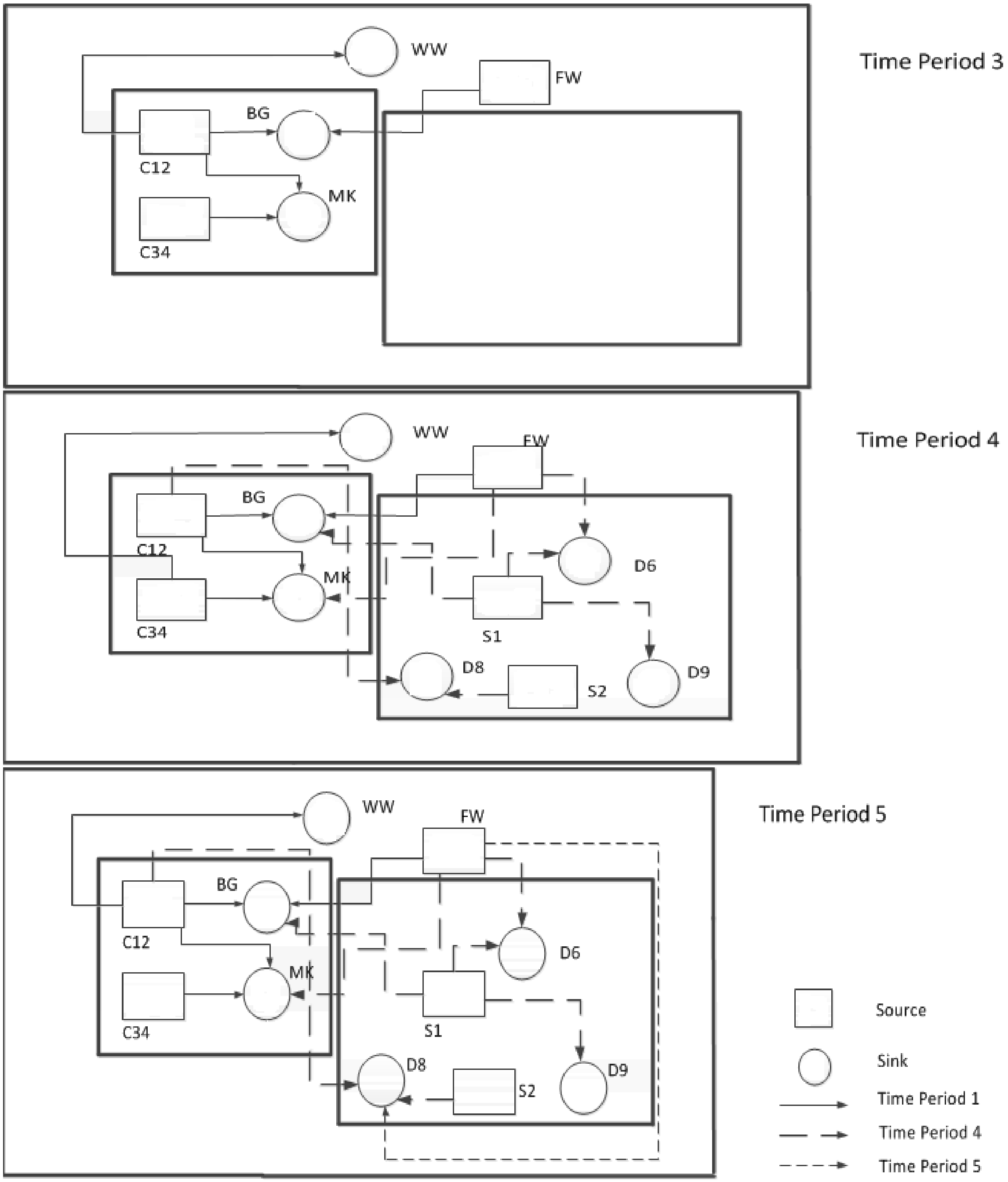

Figure 4 - Multi-Period Optimization minimizing Freshwater usage from tp3 to 5(Case Study 1)

By minimizing the weighted sum of Freshwater flow rates of five time periods, the minimum value obtained was 12742 tons/h. Weights have been assigned on the basis of amount of flowrates handled during a period. Ratio of total flowrate in individual periods to total flowrate handled in all the periods have been made the basis for assigning the weights. Periods 1 to 5 have been assigned 5, 5, 15, 30 and 45 respectively in the scale of 100. Ratio of sum total of the flowrates of all the streams in single period to sum total of flowrates of all the streams in the entire period of planning has been taken as the basis for this rating. The fact that later periods provide a more developed picture of industrial city has also been taken into account. Based on this two facts, the periods have been assigned ratings in multiples of five. Last period has be assigned extra weight as it presents the most developed layout of the city.

The five time periods have also been solved individually for comparison of results. Table 6 to 10 present the results for Case Study 1 from single period optimizations minimizing the Freshwater requirements. Flowrates obtained in a particular period form the basis of selection of pipes without taking into account, the needs of future periods unlike the multi-period planning in which only the existence of the pipe is fixed whereas it's diameter is decided by looking at the entire time period. In this case both the existence of a connection and their size are fixed after solving for a particular period. This approach gives a water network which is more complex.

Table 6 - Time Period 1(Case Study 1 – Individual Period Freshwater Minimization)

	SINKS(j)			
SOURCES		BG	MK	WW
	C12	440.25	100	109.75
	C34	0	600	0
	Fw	559.75	0	

Table 7 - Time Period 2(Case Study 1 – Individual Period Freshwater Minimization)

	SINKS(j)			
SOURCES		BG	MK	WW
	C12	836.48	400	63.52
	C34	0	1100	0
	FW	1063.52	0	

Table 8 - Time Period 3(Case Study 1 – Individual Period Freshwater Minimization)

	SINKS(j)			
SOURCES		BG	MK	WW
	C12	1540.88	431.82	327.29
	C34	0	2018.18	81.82
	FW	1959.12	0	

Table 9 - Time Period 4(Case Study 1 – Individual Period Freshwater Minimization)

	SINKS(j)						
SOURCES		BG	MK	D6	D8	D9	WW
	C12	0	0	0	2600	0	0
	C34	0	2400	0	0	0	0
	S1	3618.89	0	2361.1	0	0	0
	S2	0	0	0	1980	860	0
	FW	381.11	400	1888.9	0	1090	0

Table 10 - Time Period 5(Case Study 1 – Individual Period Freshwater Minimization)

	SINKS(j)						
SOURCES		BG	MK	D6	D8	D9	WW
	C12	0	0	0	1366.04	1433.96	0
	C34	0	2600	49.25	0	0	0
	S1	0	0	1866.04	5133.96	0	0
	S2	3500	0	0	0	0	0
	FW	900	400	3133.96	0	966.04	0

Moreover, the total number of interconnections required from multi-period planning was found to be 8 connections. The sum total of Freshwater flowrates that was obtained by independently optimizing in individual time periods is 12742 tons/h. The total number of interconnections required to achieve this objective was 11. As expected, the amount of freshwater required is equal in both the cases but multi-period planning provides a less complex piping layout.

3.4.1.2 Total Cost Minimization

Table 11 to 15 and Figures 5 & 6 present the flowrate results

Table 11 - Time Period 1(Case Study 1 – Multi- Period Cost Minimization)

	SINKS			
SOURCES(i)		BG	MK	WW
	C12	440	100	109.75
	C34	0	600	0
	FW	559.75	0	

Table 12 - Time Period 2(Case Study 1 – Multi- Period Cost Minimization)

	SINKS			
SOURCES		BG	MK	WW
	C12	836.48	400	63.52
	C34	0	1100	0
	FW	1063.52	0	

Table 13 - Time Period 3(Case Study 1 – Multi- Period Cost Minimization)

	SINKS			
SOURCES		BG	MK	WW
	C12	1540.88	350	409.12
	C34	0	2100	0
	FW	1959.12	0	

Table 14 - Time Period 4(Case Study 1 – Multi- Period Cost Minimization)

	SINKS(j)						
SOURCES		BG	MK	D6	D8	D9	WW
	C12	381.11	478.89	0	1740	0	0
	C34	0	2321.11	0	0	0	78.9
	S1	3618.89	0	2361.1	0	0	0
	S2	0	0	0		0	0
	FW	0	0	1888.9	0	1950	0

Table 15 - Time Period 5(Case Study 1 – Multi- Period Cost Minimization)

		SINKS					
		BG	MK	D6	D8	D9	WW
SOURCES	C12	2	2	0	2796	0	0
	C34	0	2598	2	0	0	0
	S1	4234.58	0	2765.4	0	0	0
	S2	0	0	0	3500	0	0
	FW	163.42	400	2232.6	204	2400	

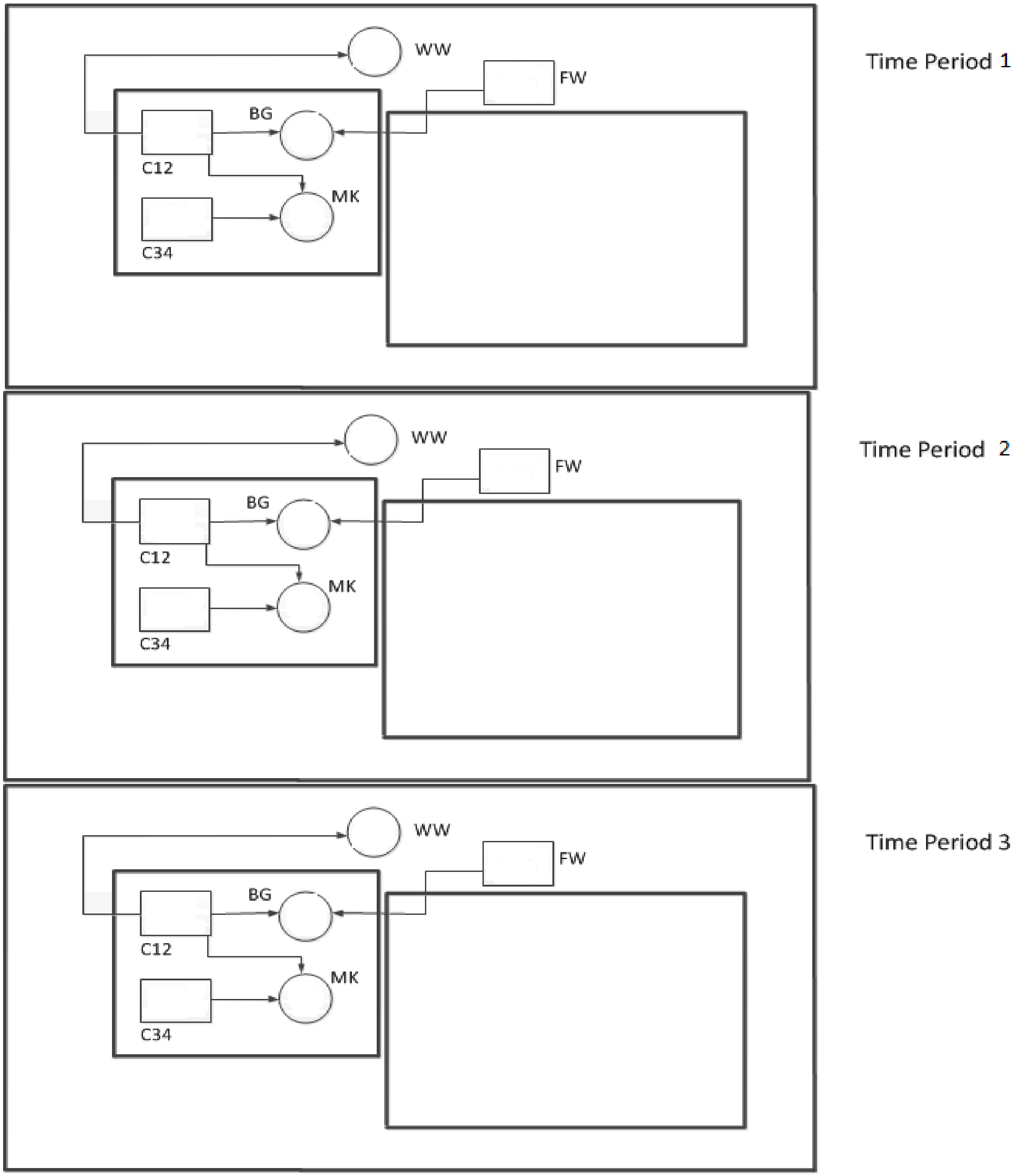

Figure 5 - Multi-Period Optimization minimizing Cost from tp1 to 3 (Case Study 1)

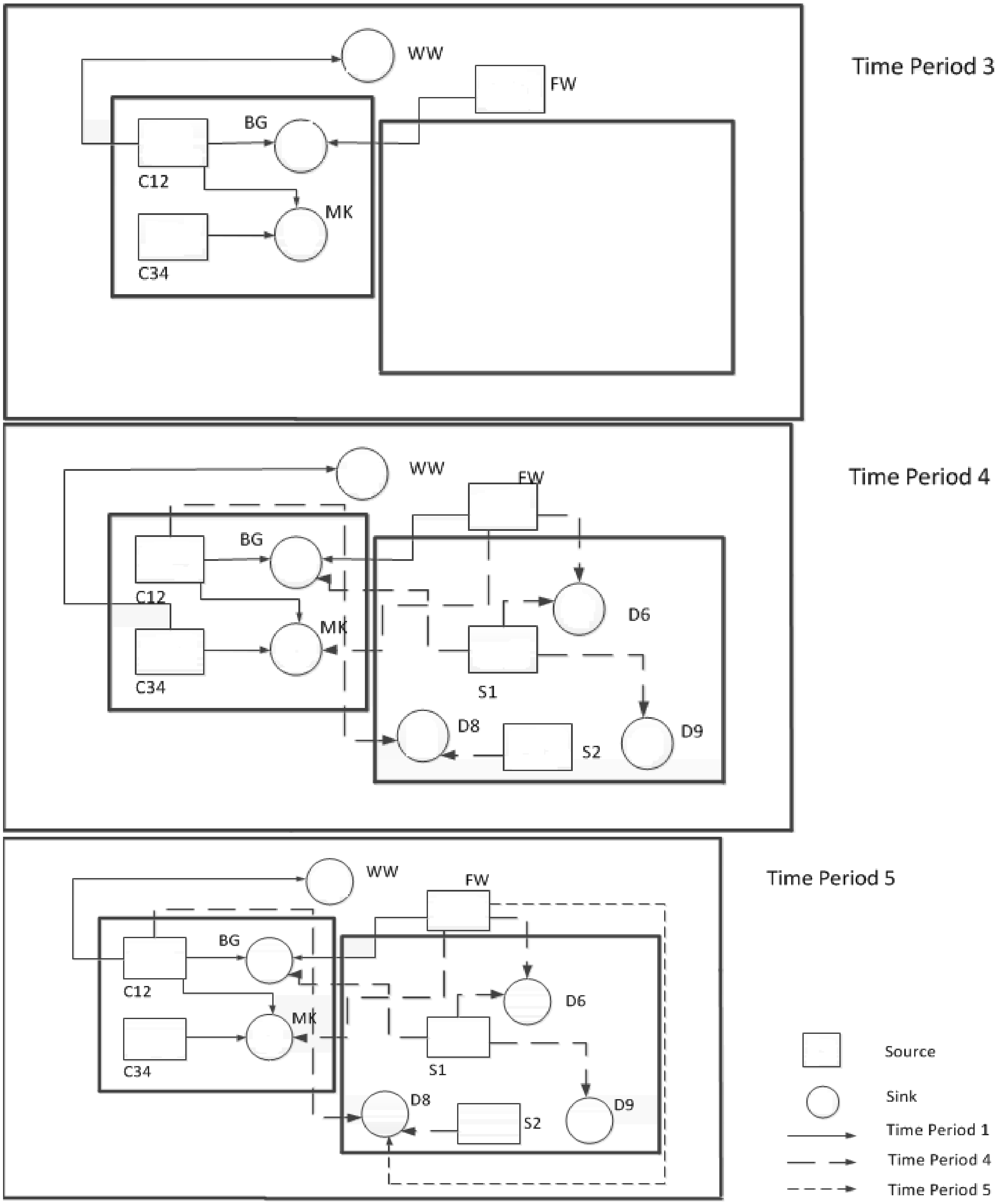

Figure 6 - Multi-Period Optimization minimizing Cost from tp3 to 5 (Case Study 1)

Table 16 provides the cost chart which gives the capital cost for piping.

Table 16 - Cost Chart of Multi-period Optimization for Case Study 1(x 10^7 $)

	SINKS						
SOURCES		BG	MK	D6	D8	D9	WW
	C12	1.15	0.59	0	2.46	0	0.37
	C34	0	0.78	0.17	0.72	0	0.20
	S1	2.99	0	1.03	0	0	0
	S2	0	1.05	0	1.56	0	0
	FW	2.48	1.23	2.12	0.65	1.82	

This example has also been solved while considering the periods independently. Tables 17 to 21 present the flowrate. Cost data for Case Study 1 from single period optimizations minimizing the total network cost is presented in Table 22.

Table 17 - Time Period 1(Case Study 1 – Individual Period Cost Minimization)

	SINKS			
SOURCES		BG	MK	WW
	C12	440	100	109.75
	C34	0	600	0
	FW	559.75	0	

Table 18 - Time Period 2(Case Study 1 – Individual Period Cost Minimization)

	SINKS			
		BG	MK	WW
SOURCES	C12	836.48	463.52	0
	C34	0	1036.48	63.52
	FW	1063.52	0	

Table 19 - Time Period 3(Case Study 1 – Individual Period Cost Minimization)

	SINKS(j)			
		BG	MK	WW
SOURCES	C12	1540.88	350	409.12
	C34	0	2100	0
	FW	1959.12	0	

Table 20 - Time Period 4(Case Study 1 – Individual Period Cost Minimization)

	SINKS(j)						
		BG	MK	D6	D8	D9	WW
SOURCE	C12	2	0	0	2598	0	0
	C34	0	2400	0	0	0	0
	S1	3998	0	0	1982	0	0
	S2	0	0	1634.61	0	1205.38	0
	FW	0	400	2615.38	0	744.61	

Table 21 - Time Period 5(Case Study 1 – Individual Period Cost Minimization)

		SINKS					
SOURCES		BG	MK	D6	D8	D9	WW
	C12	0	0	0	2800	0	0
	C34	0	2079.78	0	520.22	0	0
	S1	900	920.22	2777.78	2	2400	0
	S2	3500	0	0	0	0	0
	FW	0	400	2222.22	3177.78	0	

Table 22 - Cost Chart of Individual period optimization for Case Study 1(x 107)

		SINKS					
SOURCES		BG	MK	D6	D8	D9	WW
	C12	2.09	1.47	0	3.34	0	0.37
	C34	0	1.34	0	0.97	0	0.20
	S1	2.99	0.6	1.03	1.67	2.31	0
	S2	2.28	0	1.02	0	1.3	0
	FW	4.49	1.23	2.11	2.06	1.11	

The capital cost of the network obtained, using multi-period planning was found to be \$ 21.33 x10^7, and the total cost of Freshwater required within the fifth time period was \$5.33 x 10^7. When the periods are solved independently, the capital cost of the network was increased to \$34.03 x10^7, and the cost of freshwater calculated was \$ 5.46 x10^7.Comparing the two results, the total cost calculated using multi-period planning is 35% cheaper when compared to individual period planning. The cost of Freshwater is almost same in both cases. The total number of connections required was found to be 15 in multi-period planning, and 30 for individual period planning.

Water network in multi-period and single period optimization develop through time differently. In multi-period optimization, five connections are made in time period 1, seven connections are made in time period 4 and three connections are made in time period five. Since the connections are made keeping in mind the future plan of the city, only single connections are required between two facilities. When single period optimization is considered, four connections are made in time period 1, five connections are made in time period 2, four connections are made in time period 3, 10 connections in time period 4 and seven connections in time period 5. Since the periods are optimized independently, pipes are laid whenever the capacity increases.

A multi-period scenario allows for the flexibility of choosing the flowrates between two facilities, by looking into the entire period of planning, then selecting the maximum flowrates that can be handled. Selecting the maximum value of flowrate ensures that the pipe diameter satisfies the need in all time periods, hence ensures a single time pipe installation. Conversely, future periods are not taken into consideration in individual period optimization. The flowrate in the pipe is decided as the optimization is done for a single period. This flowrate provides a pipe diameter which may fulfill the need for the current time period but probably will not be able to satisfy the need in future time periods. Therefore, extra pipes need to be installed between the facilities, and this has resulted in increases in cost and complexity of the water network.

3.4.2 Case Study 2

This case study considers planning of an industrial setup for five time periods of two years each. The initial setup consists of two sources and two sinks. This number increases to four sources and four sinks in the second time period, while keeping the flowrates and concentration values of the previous two sinks the same. In the third time period the number of sources and sinks become six by addition of two more sources and sinks with the flowrate, while having the concentration data associated with the previous four facilities remain constant. In the fourth period, capacities of sources and sinks expand but the concentrations of the contaminants remain the same. In the fifth time period, the flowrate from the fourth time period is carried on, but the concentration of contaminants change. Three different contaminants were assumed to be present in the streams. The input data for Case Study 2 is presented in the Appendix.

3.4.2.1 Freshwater Minimization

The total amount of Freshwater required in multi-period planning was found to be 1089 tons/h and the number of connections required is 27. The results for multi-period optimization are provided in Tables 23 to 27 and Figures 7 to 9. Tables 28 to 32 present the results for Case Study 2 from single period optimizations minimizing the Freshwater requirements. For individual period planning the total flowrate required was 1089 tons/h, with 33 pipeline connections required. Therefore, as expected the water requirement in both the cases are identical, but the number of required connections is lower in case of multi-period optimization.

Table 23 - Time Period 1(Case Study 2 - Multi-Period Freshwater Minimization)

	SINKS			
SOURCES		P1D1	P1D2	WW
	P2S2	43.71	39.18	37.1
	P2S1	2	0	78
	FW	74.28	40.82	

Table 24 - Time Period 2(Case Study 2 - Multi-Period Freshwater Minimization)

	SINKS(j)					
SOURCES		P1D1	P1D2	P3D1	P5D1	WW
	P2S2	10.82	39.18	0	70	0
	P2S1	25.36	0	27.83	0	26.81
	P3S1	0	0	0	70	70
	P6S2	0	0	0	0	80
	FW	83.82	40.82	52.17	0	

Table 25 - Time Period 3(Case Study 2 - Multi-Period Freshwater Minimization)

		SINKS(j)						
SOURCES		P1D1	P1D2	P3D1	P5D1	P5D2	P4D1	WW
	P2S2	2	26.06	0	57.36	34.61	0	0
	P2S1	27.55	0	12.38	0	0	40	0
	P3S1	0	0	0	73.92	18.36	47.71	0
	P6S2	0	0	0	0	2	78	0
	P6S1	0	0	0	0	0	0	195
	P4S1	5.76	13.12	21.75	0	25	0	34.34
	FW	84.7	40.82	45.87	8.72	0	29.22	

Table 26 - Time Period 4(Case Study 2 - Multi-Period Freshwater Minimization)

		SINKS(j)						
SOURCES		P1D1	P1D2	P3D1	P5D1	P5D2	P4D1	WW
	P2S2	2	65.16	0	95	37.9	0	0
	P2S1	27.53	0	20.89	0	0	51.53	0
	P3S1	0	0	0	95	36.4	3.6	0
	P6S2	0	0	0	0	23.73	108.34	57.93
	P6S1	0	0	0	0	0	0	195
	P4S1	5.76	32.79	36.7	0	2	0	42.78
	FW	84.70	102	77.4	0	0	31.54	0

Table 27 - Time Period 5(Case Study 2 - Multi-Period Freshwater Minimization)

		SINKS						
		P1D1	P1D2	P3D1	P5D1	P5D2	P4D1	WW
SOURCES	P2S2	2	65.16	0	95	38	0	0
	P2S1	27.53	0	18.58	0	0	53.76	0
	P3S1	0	0	0	95	36	4	0
	P6S2	0	0	0	0	24	107.63	58.36
	P6S1	0	0	0	0	0	0	195
	P4S1	5.76	32.8	39.96	0	2	0	39.5
	FW	84.75	102	76.46	0	0	29.6	

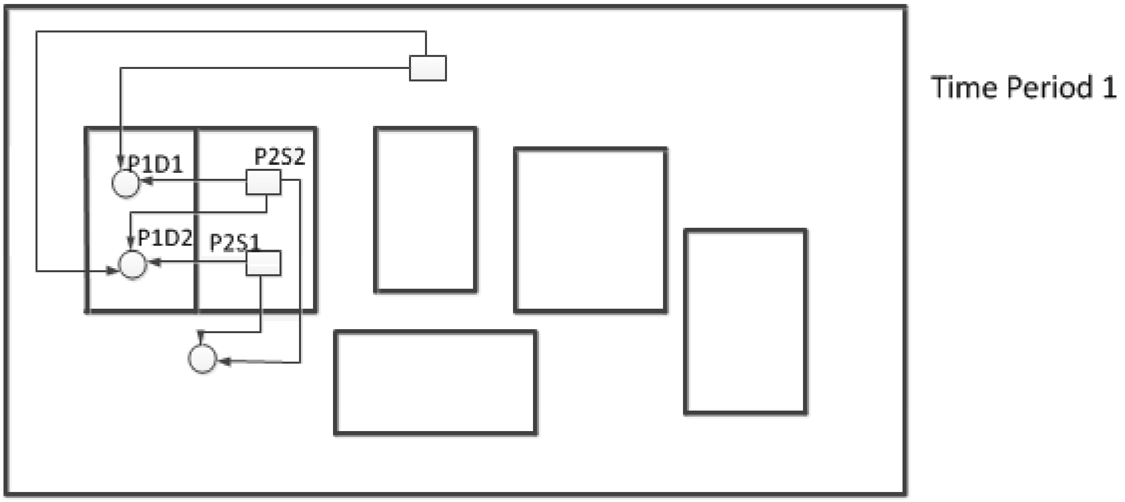

Figure 7: Multi-Period Optimization minimizing Freshwater usage in tp 1(Case Study 2)

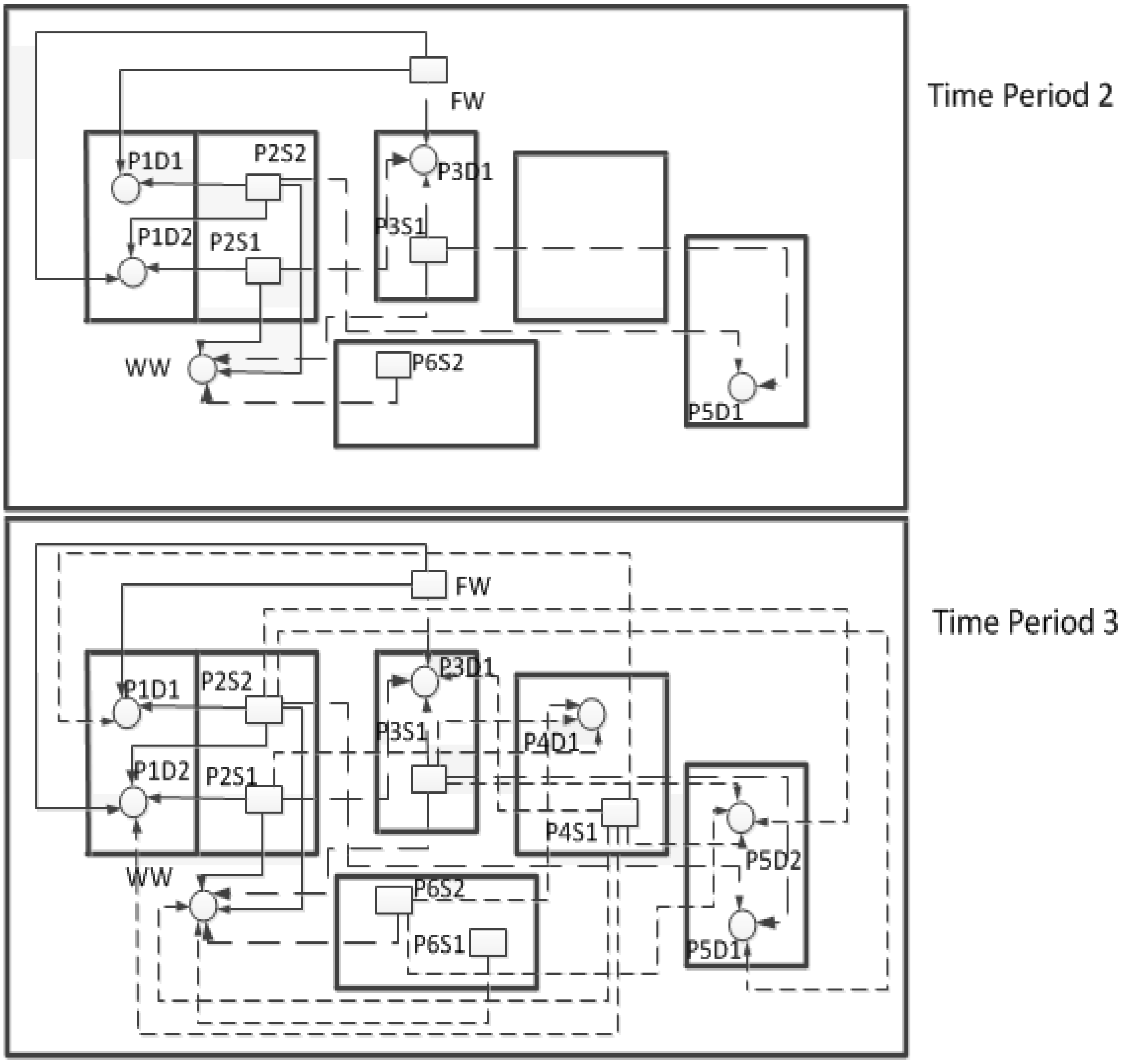

Figure 8: Multi-Period Optimization minimizing Freshwater usage from tp 2 & 3(Case Study 2)

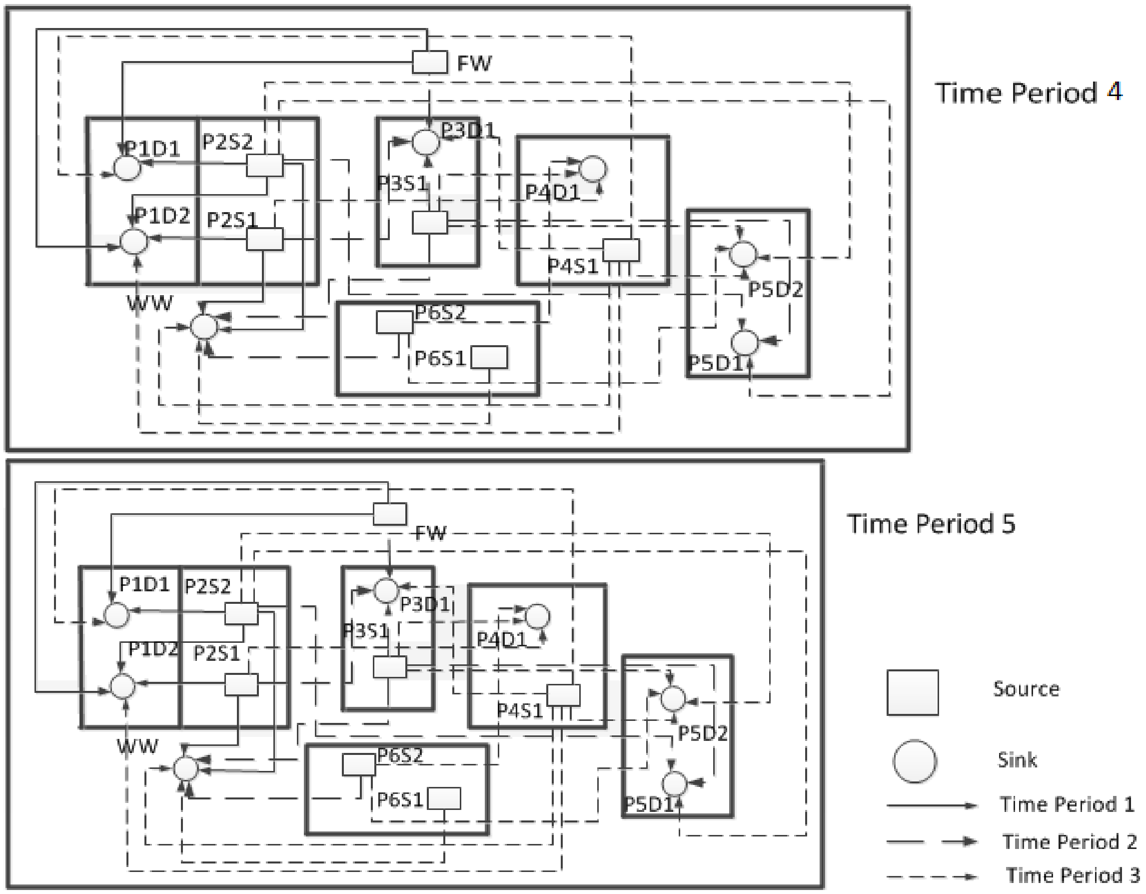

Figure 9: Multi-Period Optimization minimizing Freshwater usage from tp4 & 5(Case Study 2)

Table 28 - Time Period 1(Case Study 2 - Individual Period Freshwater Minimization)

	SINKS(j)			
SOURCES		P1D1	P1D2	WW
	P2S2	46.53	36.37	37.1
	P2S1	0	2	78
	FW	73.47	41.63	

Table 29 - Time Period 2(Case Study 2 - Individual Period Freshwater Minimization)

	SINKS(j)					
SOURCES		P1D1	P1D2	P3D1	P5D5	WW
	P2S2	46.53	0	0	73.47	0
	P2S1	0	27.82	27.83	0	24.35
	P3S1	0	0	0	66.53	73.47
	P6S2	0	0	0	0	80
	FW	73.47	52.18	52.17	0	

Table 30 - Time Period 3(Case Study 2 - Individual Period Freshwater Minimization)

	SINKS							
SOURCES		P1D1	P1D2	P3D1	P5D5	P5D2	P4D1	WW
	P2S2	0	23.1	14.63	50.59	7.26	24.4	0
	P2S1	29.09	0	0	0	50.92	0	0
	P3S1	0	0	0	0	0	140	0
	P6S2	0	0	0	63	0	17	0
	P6S1	0	0	0	0	21.81	0	173.19
	P4S1	5.58	13.84	24.54	0	0	0	56.03
	FW	85.33	43.06	40.82	26.42	0	13.58	

Table 31 - Time Period 4(Case Study 2 - Individual Period Freshwater Minimization)

	SINKS(j)							
SOURCES		P1D1	P1D2	P3D1	P5D5	P5D2	P4D1	WW
	P2S2	0	0	0	85.62	39.38	75	0
	P2S1	29.08	55.12	0	15.8	0	0	0
	P3S1	0	0	18.1	87.56	29.34	0	0
	P6S2	0	0	0	0	31.28	120	38.72
	P6S1	0	0	0	0	0	0	195
	P4S1	5.58	20.35	33.25	0	0	0	60.83
	FW	85.34	124.54	83.65	1	0	0	

Table 32 - Time Period 5(Case Study 2 - Individual Period Freshwater Minimization)

	SINKS(j)							
SOURCES		P1D1	P1D2	P3D1	P5D5	P5D2	P4D1	WW
	P2S2	0	59.32	0	95	0	45.68	0
	P2S1	29.08	5	0	0	65.98	0	0
	P3S1	0	0	15.96	95	24.04	0	0
	P6S2	0	0	0	0	10	128.15	51.88
	P6S1	5.58	0	0	0	0	0	195
	P4S1	85.34	31.68	37.14	0	0	0	45.59
	FW	0	104	81.9	0	0	21.17	

3.4.2.2 Total Cost Minimization

Similar to the previous case study, artificial data for an industrial city layout has been generated and utilized for this example. Table 33 to 37 present the flowrates from period 1 to period 5 and table 38 present the capital cost chart. Figures 10 & 11 show the pipe network over the time periods for multi-period optimization.

Table 33 - Time Period 1(Case Study 2 - Multi-Period Cost Minimization)

	SINKS(j)			
SOURCES		P1D1	P1D2	WW
	P2S2	46.53	39.18	34.29
	P2S1	0	0	80
	FW	73.47	40.82	

Table 34 - Time Period 2(Case Study 2 - Multi-Period Cost Minimization)

	SINKS(j)					
SOURCES		P1D1	P1D2	P3D1	P5D1	WW
	P2S2	46.53	39.18	0	2	32.29
	P2S1	0	0	0	0	80
	P3S1	0	0	21.57	2	116.48
	P6S2	0	0	0	0	80
	FW	73.47	40.82	58.42	136	

Table 35 - Time Period 3(Case Study 2 - Multi-Period Cost Minimization)

		SINKS(j)						
SOURCES		P1D1	P1D2	P3D1	P5D1	P5D2	P4D1	WW
	P2S2	37.55	26.06	0	9.73	0	46.65	0
	P2S1	0	0	0	0	31.23	48.76	0
	P3S1	0	0	10.73	88.7	40.57	0	0
	P6S2	0	0	0	0	2	78	0
	P6S1	0	0	0	0	0	21.58	173.42
	P4S1	8.98	13.11	19.7	0	0	0	58.2
	FW	73.47	40.82	49.57	41.56	6.19	0	

Table 36 - Time Period 4(Case Study 2 - Multi-Period Cost Minimization)

		SINKS(j)						
SOURCES		P1D1	P1D2	P3D1	P5D1	P5D2	P4D1	WW
	P2S2	37.55	65.16	0	82.44	0	14.84	0
	P2S1	0	0	0	0	2	98	0
	P3S1	0	0	18.1	98.89	18	0	0
	P6S2	0	0	0	0	49.71	80.15	60.13
	P6S1	0	0	0	0	0	2	193
	P4S1	8.98	32.8	33.24	0	0	0	44.97
	FW	73.47	102.04	83.65	8.66	30.28	0	

Table 37 - Time Period 5(Case Study 2 - Multi-Period Cost Minimization)

		SINKS						
SOURCES		P1D1	P1D2	P3D1	P5D1	P5D2	P4D1	WW
	P2S2	37.55	65.16	0	95	0	2.28	0
	P2S1	0	0	15.95	0	65.98	34	0
	P3S1	0	0	0	95	24	0	0
	P6S2	0	0	0	0	9.97	119.19	60.13
	P6S1	0	0	0	0	0	2	193
	P4S1	8.98	32.8	37.14	0	0	0	41.08
	FW	73.47	102.04	81.9	0	0	37.5	

Table 38 - Cost Chart of Multi-period optimization for Case study 2(x 10^7 $)

		SINKS(j)						
SOURCES		P1D1	P1D2	P3D1	P5D5	P5D2	P4D1	WW
	P2S2	0.31	0.28	0	0.57	0	0.23	0.15
	P2S1	0.21	0	0	0	0.56	0.29	0.2
	P3S1	0	0	0.12	0.45	0.54	0	0.53
	P6S2	0	0	0	0	0.41	0.25	0.42
	P6S1	0	0	0	0	0	0.13	0.66
	P4S1	0.35	0.63	0.55	0	0	0	0.49
	FW	0.66	0.59	0.49	0.65	0.42	0	

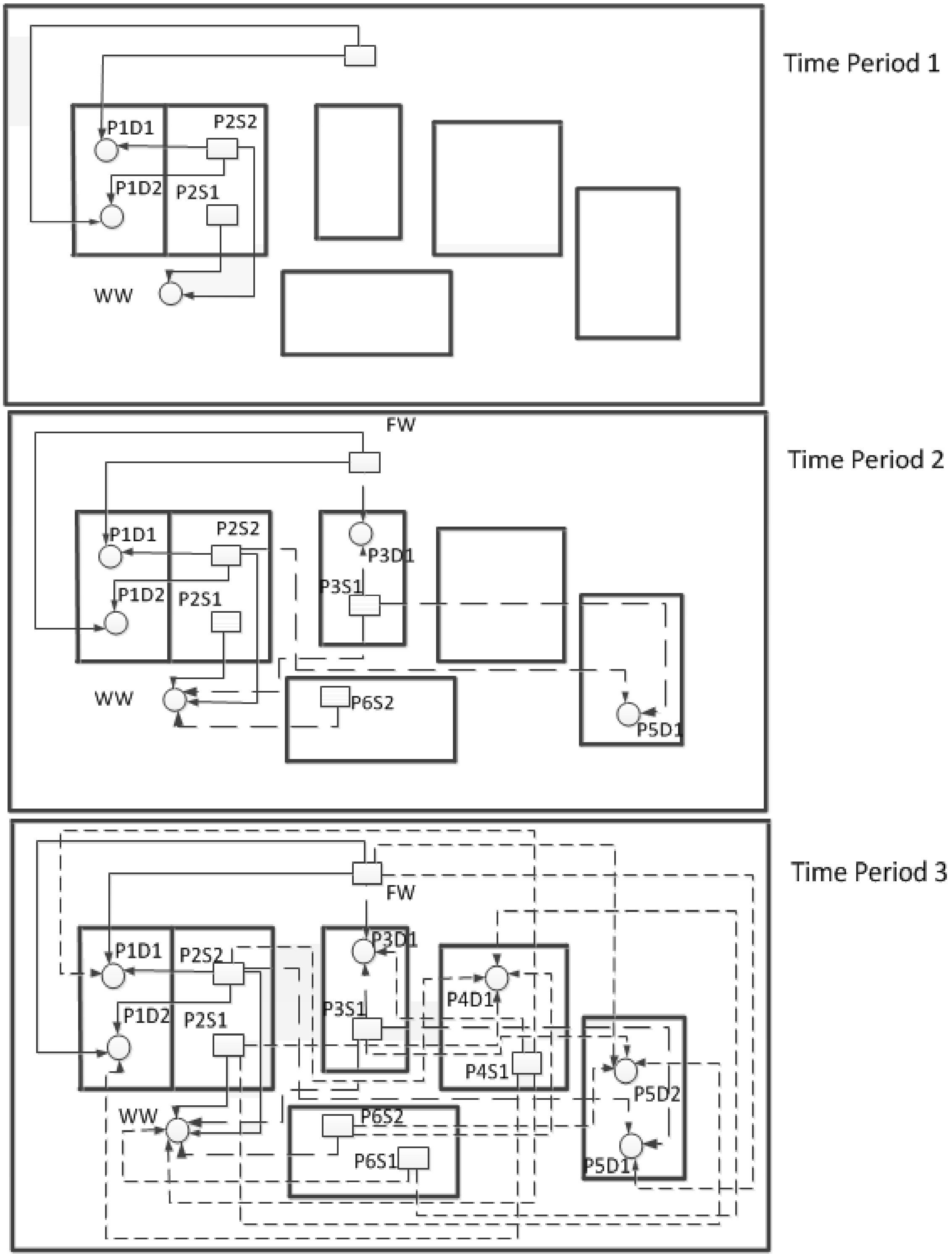

Figure 10 - Multi-Period Optimization minimizing Cost from tp1 to 3 (Case Study 2)

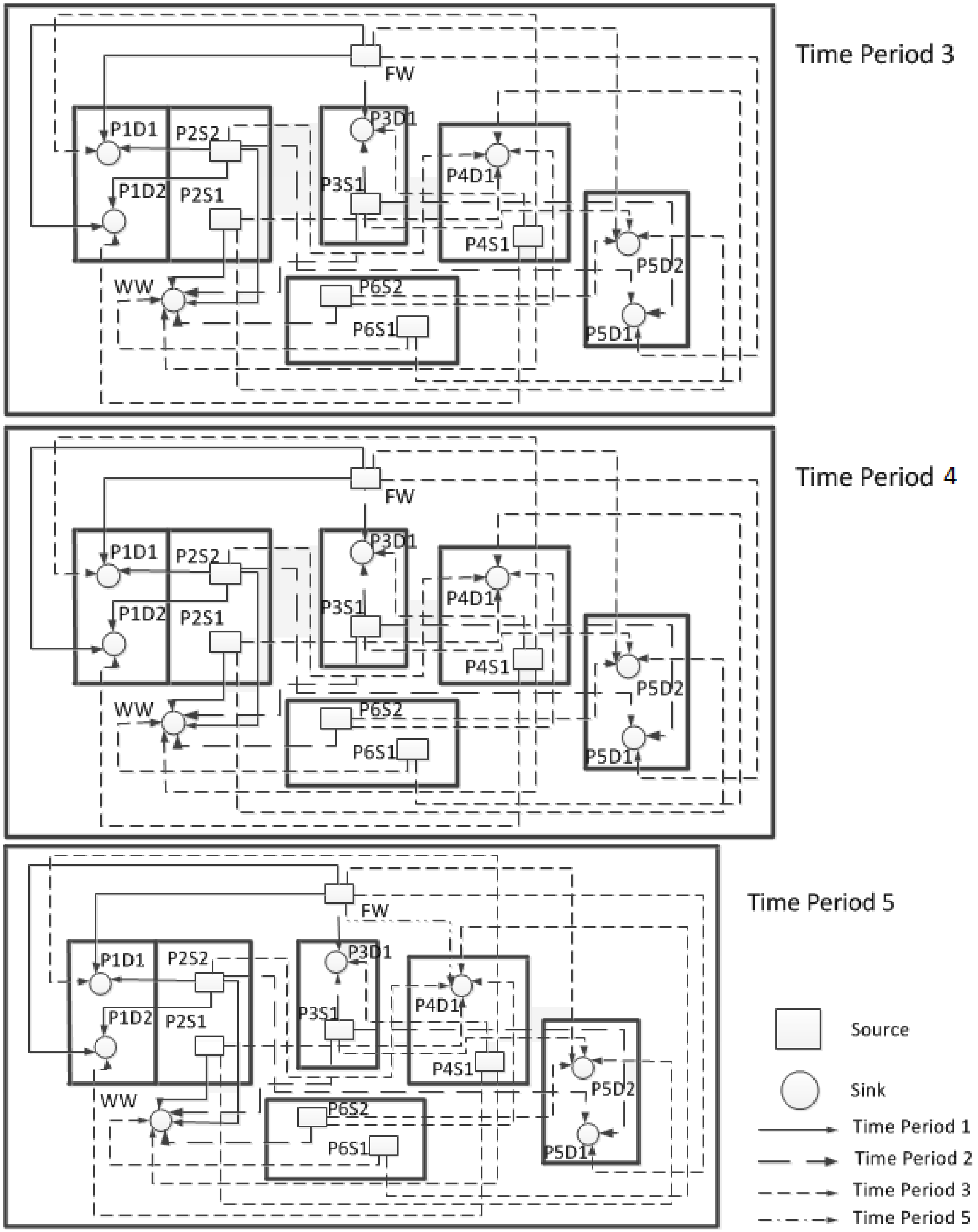

Figure 11 - Multi-Period Optimization minimizing Cost from tp3 to 5 (Case Study 2)

Tables 39 to 43 present the flowrate and Table 44 contains the piping cost data for Case Study 2 from single period optimizations minimizing the total network cost.

Table 39 - Time Period 1(Case Study 2 - Individual Period Cost Minimization)

	SINKS			
		P1D1	P1D2	WW
SOURCES	P2S2	46.53	39.18	34.29
	P2S1	0	0	80
	FW	73.47	40.82	

Table 40 - Time Period 2(Case Study 2 - Individual Period Cost Minimization)

	SINKS					
		P1D1	P1D2	P3D1	P5D5	WW
SOURCES	P2S2	46.53	39.18	0	0	34.29
	P2S1	0	0	0	32.69	44.33
	P3S1	0	0	0	59.06	80.94
	P6S2	0	0	0	0	80
	FW	73.47	40.82	80	48.27	

Table 41 - Time Period 3(Case Study 2 - Individual Period Cost Minimization)

	SINKS							
SOURCES		P1D1	P1D2	P3D1	P5D5	P5D2	P4D1	WW
	P2S2	0	24.05	14.63	0	32.82	48.49	0
	P2S1	29.08	0	0	50.92	0	0	0
	P3S1	0	0	0	0	25.14	114.86	0
	P6S2	0	0	0	48.36	0	31.64	0
	P6S1	0	0	0	0	22.04	0	172.95
	P4S1	5.58	13.61	24.55	0	0	0	56.25
	FW	85.34	42.33	40.81	40.72	0	0	

Table 42 - Time Period 4(Case Study 2 - Individual Period Cost Minimization)

	SINKS(j)							
SOURCES		P1D1	P1D2	P3D1	P5D5	P5D2	P4D1	WW
	P2S2	0	0	0	85.44	42.25	72.3	0
	P2S1	29.08	38.93	12.87	19.11	0	0	0
	P3S1	0	14.02	6.94	85.44	16.9	11.68	0
	P6S2	0	0	0	0	40.84	111.01	38.14
	P6S1	0	0	0	0	0	0	195
	P4S1	5.58	17.66	35.38	0	0	0	61.37
	FW	85.34	129.38	79.8	0	0	0	

Table 43 - Time Period 5(Case Study 2 - Individual Period Cost Minimization)

		SINKS(j)						
		P1D1	P1D2	P3D1	P5D1	P5D2	P4D1	WW
SOURCES	P2S2	0	46.09	0	95	5.25	53.65	0
	P2S1	29.08	12.19	0	0	58.73	0	0
	P3S1	0	3.4	15.96	95	20.64	0	0
	P6S2	0	0	0	0	15.38	125.93	48.68
	P6S1	0	0	0	0	0	0	195
	P4S1	5.58	28.5	37.14	0	0	0	48.77
	FW	85.34	109.8	81.9	0	0	15.42	

Table 44 - Cost Chart of Individual Period Optimization for Case Study2(x 10^7)

		SINKS						
		P1D1	P1D2	P3D1	P5D1	P5D2	P4D1	WW
SOURCES	P2S2	0.31	0.28	0.22	0.57	0.66	0.23	0.15
	P2S1	0.21	0.18	0	0.47	0.56	0	0.2
	P3S1	0	0.11	0.12	0.45	0.54	0.58	0.53
	P6S2	0	0	0	0.32	0.41	0.25	0.42
	P6S1	0	0	0	0	0.17	0	0.66
	P4S1	0.35	0.63	0.53	0	0	0	0.49
	FW	0.66	0.59	0.49	0.42	0	0.13	

The capital cost of the network obtained, using multi-period planning is found to be \$ 10.63 x 10^7, and the total of the cost of Freshwater required in all the period is \$0.24x10^7. When the periods are solved independently, the capital cost calculated was found to be \$ 12.91 x 10^7 and the cost of freshwater calculated was \$ 0.26 x10^7. Comparing the two results, the total cost calculated using multi-period planning is 17.68 % cheaper when compared to individual period planning. A total of 26 connections were required for the multi-period planning case, as opposed to 36 connections for individual period planning case.

In case of multi-period optimization, six connections are made in time period 1, four connections are made in time period 2 and sixteen connections are made in time period 3. Only single connection is established between the facilities and these satisfy the requirements in all the time periods. When the periods are optimized independently six connections are made in time period 1, six connections are made in time period 2, fourteen connections in time period 3, eight connection in time period 4 and two connections in time period 5. These connections are not necessarily single connection and multiple connections have been needed while connecting Freshwater source to P1D2 and source P6S2 to P4D1.

This result indicates that there is not much saving of water by laying new pipes and may not be a viable option to implement if infrastructure for a linear system(all wastewater discharged to environment and requirements of sinks met by use of freshwater only) is already in place. However this option can be implemented when the network is not present.

4. REGENERATION AND REUSE

4.1 Problem Statement

The section addresses the problem of mapping of water sources and sinks existing in an industrial city over a planning time horizon, via regeneration and reuse . The problem solved in this work is an extension of the problem handled in Castro et al [79] which solved the problem of inter-plant piping network for single time period. The problem consists of an industrial city which consists of several plants and grows with time. Information about number of plants, wastewater streams(sources) and water using operation(sinks), the contaminant present in those streams and constraints on the flowrate in various connections have been provided.

Apart from this there is presence of treatment units in two stages, which have specific removal ratios. An additional fictitious interceptor has been included in both the stages for modelling the bypass stream when no treatment is required. A known expansion schedule detailing the addition of new plants and associated sources and sinks and alterations in existing plants the corresponding sources and sinks in each time period. Lengths of the shortest connections between various facilities together with known topological constraints have also been provided.

The main objective is to determine the cost-optimal direct water reuse network that connects various facilities within the industrial city together with its evolution over the time periods. A number of sets are defined as a basis for our problem formulation:

I $\{i = 1, 2, \ldots N_{sources} \mid I \text{ is a set of process sources}\}$

J {j = 1, 2, … N $_{sinks}$ | J is a set of process sinks}

T {t = 1, 2, … N $_{time}$ | T is a set of time periods}

S {s = 1,2, … N $_{stage}$ | S is a set of treatment stages}

R {r = 1,2,…N $_{unit}$ | R is a set of treatment units in each stage}

P {p = 1, 2, … N $_{plant}$ | P is a set of plant}

B {b = 1, 2, …N $_{contaminants}$ | B is a set of contaminants}

Figure 2 illustrates a source-sink mapping for regeneration and reuse water reuse in a single time period, showing p Plants with i sources and j sinks, a source of Freshwater and a waste water discharge. Each source can be split into several streams: (1) Source-to-Sink flows ($F_{i(p1),j(p2),t}$) representing the flow from ith source of plant p1 to jth sink of plant p2 in time period t (p1,p2 ϵ P) , (2) Source-to-Interceptor flows ($F_{i(p1), r(s1) ,t}$) which represents the flow from each source to treatment units of stage 1 and (3) Source-to-Environment flows ($F_{i(p1), env ,t}$) which represents the flow from each source of plant p1 to environment for discharge. The freshwater source is split and allocated to different sinks as($F_{fw,j(p2), t}$) . Water from treatment units ($F_{r(s2),env, t}$) and sources ($F_{i(p1), env ,t}$) is discharged into environment with a constraint on the concentration level of each contaminant.

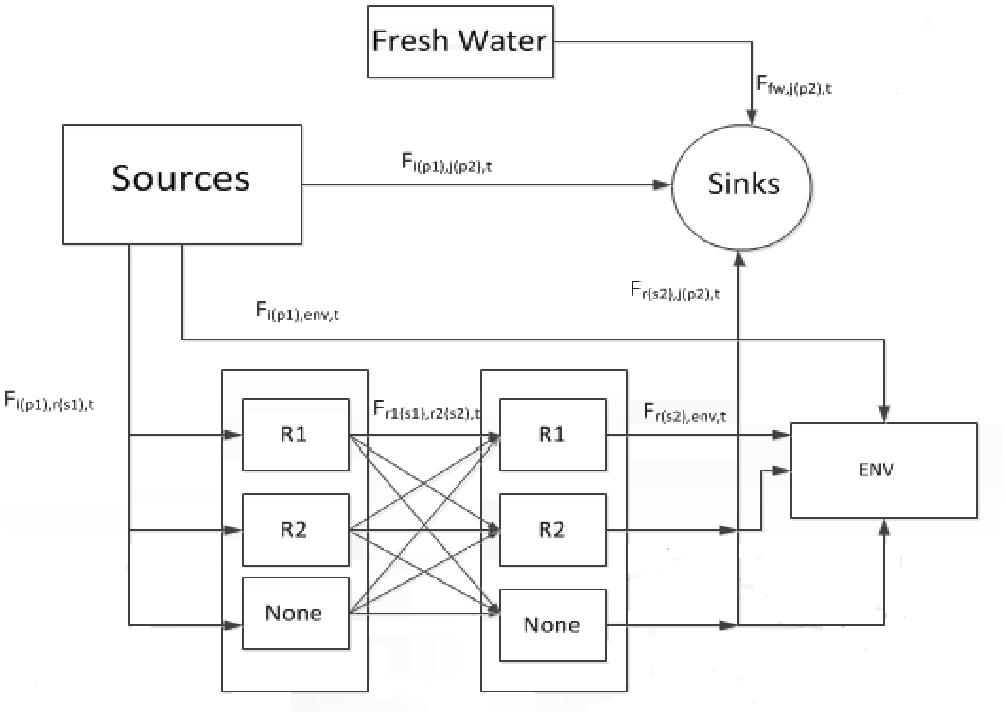

Figure 12 – Superstructure representing various interconnections

4.2 Problem Formulation

The optimization formulation developed for minimizing the total cost used during the planning time horizon is presented below. It has been built upon the superstructure given in Castro et al[79].The objective is to minimize the total cost of the network, both piping and freshwater cost utilization, as described in Equation (1) below:

$$\textbf{MIN} \quad \sum_{t\in T}\sum_{p1,p2\in P} w_t\Big(\sum_{\mathrm{i\in I}}\sum_{\mathrm{j\in J}} \mathrm{a}\big(\mathrm{DI}^{\mathrm{c}}_{\mathrm{i(p1),j(p2)}}\big)^{\mathrm{b}}\, d_{i,j} + \sum_{\mathrm{j\in J}} a\big(\mathrm{DI}^{\mathrm{c}}_{\mathrm{Fw,j(p2)}}\big)^{\mathrm{b}}\, d_{fw,j} + \sum_{\mathrm{i\in I}} a\big(\mathrm{DI}^{\mathrm{c}}_{\mathrm{i(p1),env}}\big)^{\mathrm{b}} d_{i,env} + \sum_{\mathrm{i\in I}}\sum_{\mathrm{r1\in R}} \mathrm{a}\big(\mathrm{DI}^{\mathrm{c}}_{\mathrm{i(p1),r1(s1)}}\big)^{\mathrm{b}}\, d_{i,s1} +$$

$$\sum_{\mathrm{r2} \in \mathrm{R}} a\left(\mathrm{DI}^{\mathrm{c}}_{\mathrm{r2(s2),env}}\right)^{\mathrm{b}} d_{fw,j} + \sum_{\mathrm{r2} \in \mathrm{R}} \sum_{\mathrm{j} \in \mathrm{J}} \mathrm{a}(\mathrm{DI}^{\mathrm{c}}_{\mathrm{r2(s2),j(p2)}})^{\mathrm{b}} d_{r2,s2} + \quad +$$

$$\mathrm{Hy}\ \mathrm{C}^{\mathrm{fresh}} \sum_{i \in I} \sum_{t \in T} F_{Fw,j(p2),t} + \sum_{s \in S} \sum_{r \in R} x_r^5\, CUI_r + H_y \sum_{s \in S} \sum_{r \in R} CUM_r\, cim_{r,b} \qquad (1)$$

where w_t represents the weight associated with time period *t*, d represents distance between two facilities, $\mathrm{DI}^{\mathrm{c}}_{\mathrm{i(p1),j(p2)}}$ is the diameter of the pipe between source i of plant p1 to sink j of plant p2, $\mathrm{DI}^{\mathrm{c}}_{\mathrm{Fw,j(p2)}}$ is the diameter of the pipe between freshwater source and sink j of plant p2, $\mathrm{DI}^{\mathrm{c}}_{\mathrm{i(p1),env}}$ is the diameter of the pipe between source i of plant p1 and wastewater discharge point, $\mathrm{DI}^{\mathrm{c}}_{\mathrm{r2(s2),env}}$ is the diameter of the pipe between interceptor r2 of stage 2 and wastewater discharge point, $\mathrm{DI}^{\mathrm{c}}_{\mathrm{i(p1),r1(s1)}}$ is the diameter of the pipe between sink i of plant p1 to interceptor r1 of stage 1 , $\mathrm{DI}^{\mathrm{c}}_{\mathrm{r2(s2),j(p2)}})^{\mathrm{b}}$is the diameter of the pipe between interceptor r2 of stage 2 to sink j of plant p2, $F_{Fw,j(p2),t}$ is the flowrate between freshwater source ($\mathrm{F_w}$) to sink j of plant p2 in time period t, Hy denotes the hours of operation in a time period, $\mathrm{C}^{\mathrm{fresh}}$ is cost of freshwater per ton , and a and b are cost parameters. $\mathrm{CUI_r}$ is the capital cost of setting up an interceptor ,$\mathrm{CUM}_{\mathrm{r}}$ is the unit cost for mass removed in each interceptor and $\mathrm{cim_{r,b}}$ is the amount of contaminant b removed by interceptor r. The capital cost is a function of the diameters of interconnecting pipes, which in turn is calculated based on the flow rate through the interconnection.

The source and sink mass balance constraints are described by Equations (2) and (3) respectively:

$F_{i(p1),ww,t} + \sum F_{i(p1),j(p2),t} + \sum F_{i(p1),r(s1),t} = F_{i(p1),t}$; $\forall$ i ϵ I , p1,p2 ϵ P , s1 ϵ S (2)

$F_{fw,j(p2),t} + \sum F_{i(p1),j(p2),t} + \sum F_{r(s2),j(p2),t} = F_{j(p2),t}$; $\forall$ j ϵ J, p1,p2 ϵ P, s1 ϵ S (3)

Water sources can either be discharged to environment ($F_{i(p1),\, ww,\, t}$) ,sent to a sink ($F_{i(p1),j(p2),t}$) or sent to inceptors of first stage for treatment(s1). Here, p1 and p2 can be the same plant or two different plants. Moreover, sinks may receive contaminant rich water from sources ($F_{i(p1),j(p2),t}$), Freshwater ($F_{fw,\, j,\, t}$) and treated water from the interceptor units of stage 2 ($F_{r(s2),j(p2),t}$) . A purity constraint ensuring that the maximum contamination levels tolerable by the sink processes are not exceeded was used, and is provided in Equation (4) below:

$F_{fw,j(p2),t} * C_{b,fw,t} + \sum F_{i(p1),j(p2),t} * C_{b,i(p1),t} + \sum F_{r(s2),j(p2),t} * C_{b,r(s2),t} + F_{j(p2),t}$ $*C_{b,j(p2),t}$; $\forall$ j ϵ J, p1, p2 ϵ P (4)

where $C_{b,fw}$ is the concentration of contaminant b in freshwater, $C_{b,i(p1),t}$ is the concentration of contaminant b in source i of plant p1 in time period t , $C_{b,r(s2),t}$ is the concentration of contaminant b in streams originating from interceptor r in treatment stage 2 during time period t $C_{b,j(p2),t}$ is the concentration of contaminant b in sink j of plant p2 in time period t.

Mass balances for first stage of interceptors are described by equations (5)-(6).

$\sum_{i \in I} F_{i(p1),r(s1),t} = F_{r(s1),t}$ $\forall$ i $\in$ I, r $\in$ s1 (5)

$\sum_{i \in I} F_{i(p1),r(s1),t} * C_{b,i(p1),t} = F_{r1(s1),t} * C^{in}_{b,r1(s1),t}$ $\forall$ i $\in$ I, r1 $\in$ s1 (6)

Here $F_{i(p1),r(s1),t}$ represent flows from various source to interceptors in treatment stage 1 and $F_{r(s1),t}$ is the amount of water that will be regenerated by each interceptor.

Equation 5 accounts the mass balance and equation 6 represents the component balance at the inlet of each treatment unit. In equation 6, $C_{b,i(p1),t}$ is the concentration of contaminant b in source i of plant p1 in time period t and $C_{b,r1(s1),t}^{in}$ is the inlet concentration of contaminant b in interceptor r1 of stage 1 in time period t. The inlet concentration at each treatment unit is unknown and is determined by optimizing the cost function.

Equation (7) and (8) account for the mass and component balances for the flows between interceptors of stage 1 and 2 respectively.

$$F_{r1(s1),t} = \sum_{r1 \in s1, r2 \in s2} F_{r1(s1),r2(s2),t} \qquad \forall \ r1 \in s1, r2 \in s2 \qquad (7)$$

$$F_{r2(s2),t} * C_{b,r2(s2),t}^{in} = \sum_{r1 \in s1, r2 \in s2} F_{r1(s1),r2(s2),t} * C_{b,r1(s1),t}^{out} \quad \forall \ r1 \in s1, r2 \in s2 \quad (8)$$

$F_{r1(s1),r2(s2),t}$ represents the flow between interceptors r1 of stage 1 to interceptors r2 of stage 2 in time period t and $F_{r2(s2),t}$ represents the amount of water to be treated by treatment unit r2 of stage 2 in time period t. $C_{b,r1(s1),t}^{out}$ is the outlet concentration of contaminant b from treatment unit of stage 1 in time period t and $C_{b,r2(s2),t}^{in}$ is the inlet concentration of contaminant b in treatment units r2 of stage 2 during time period t.

Inlet and outlet concentrations in interceptors of both stages are related by removal ratio. Removal ratio is a constant which accounts for the percentage of contaminant removed from a stream. Equations (9) and (10) correlate the inlet and outlet concentrations of the interceptors in both the stages.

$$C_{b,r1(s1),t}^{out} = (1 - RR_{r1(s1)}) * C_{b,r1(s1),t}^{in} \qquad \forall \ r1 \in s1 \qquad (9)$$

$C^{out}_{b,r2(s2),t}$ = (1 - $RR_{r2(s2)}$) $*$ $C^{in}_{b,r2(s2),t}$ $\forall$ r2 $\in$ s2 (10)

Mass balances for interceptors in stage 2 and of environment discharge is given by equations (11) and (12) and component balance for environment discharge is given by equation (13).

$F_{r2(s2),t}$ = $\sum_{r2\in s2,j\in J,p2\in P} F_{r2(s2),j(p2),t}$ + $\sum_{r2\in s2} F_{r2(s2),env,t}$ $\forall$ r2 $\in$ s2, j $\in$ J, p2 $\in$ P (11)

$F_{env,t}$ = $\sum_{r2\,\in\,s2} F_{r2(s2),env,t}$ + $\sum_{i\in I} F_{i(p1),env,t}$ $\forall$ r2 $\in$ s2, i $\in$, p2 $\in$ P (12)

$F_{env,t}$ $*$ $C_{b,env,t}$= $\sum_{r2\,\in\,s2} F_{r2(s2),env,t}$ $*$ $C^{out}_{b,r2(s2),t}$ + $\sum_{i\in I} F_{i(p1),env,t}$ $*$ $C_{b,i(p1),t}$ $\forall$ r2 $\in$ s2, i $\in$, p2 $\in$ P (13)

Flows from interceptors r2 can either be directed to various sinks($F_{r2(s2),j(p2),t}$) or to environment($F_{r2(s2),j(p2),t}$).Water can be discharged into the environment from various sources($F_{i(p1),env,t}$) or from treatment units of stage 2 ($F_{r2(s2),env,t}$). $C_{b,env,t}$ is the concentration of contaminant b in the environment discharge and waste has been assumed to be discharged at maximum threshold level.

Calculation of load of contaminant removed is given by the equation (14)

$Cim_{b,r}$ = ($C^{in}_{b,r,t}$ - $C^{out}_{b,r,t}$) $*$ $F_{r(s),t}$ (14)

Equations (15), (16), (17) and 18 defines the existence of various streams from sources to sinks, sources to interceptors, interceptors to sinks and interceptors to environment. Equation (19) defines the existence of treatment units . In all these equations , the flowrates have been constrained to stay below a maximum value (M^{max}). Here X are binary variables which indicate the presence of a stream.

$F_{i(p1),j(p2),t}$ - $M^{max}_{F_{i(p1),j(p2),t}}$$*$ $X_{i(p1),j(p2),t}$ ≤ 0 (15)

$F_{i(p1),r(s1),t}$ - $M^{max}_{F_{i(p1),r(s1),t}}$ * $X_{i(p1),r(s1),t} \leq 0$ (16)

$F_{r2(s2),j(p2),t}$ - $M^{max}_{F_{r2(s2),j(p2),t}}$ * $X_{r2(s2),j(p2),t} \leq 0$ (17)

$F_{r2(s2),env,t}$ - $M^{max}_{F_{r2(s2),env,t}}$ * $X_{r2(s2),env,t} \leq 0$ (18)

$F_{r(s),t}$ - $M^{max}_{F_{F_{r(s),t}}}$ * $X_{r(s),t} \leq 0$ (19)

The pipe Size (DI) is calculated as as:

DI = $0.363((M)^{0.45} * \rho^{0.13})$ (20)

This expression has been taken from Peters et al. [67], where M represents the volumetric flowrate given in m^3/s and ρ is density of the stream. The pipe diameter obtained using the expression is rounded off up to one decimal place .The assumption of rounding up to the next highest decimal number is justified as this gives a standard pipe size value(in meters) which satisfies the requirement of the flow and makes selection of the pipe easier.

4.3 Implementation and Case Study Development

MINLP formulation for multi-period cost-optimal network design have been implemented using "What's Best 12.0" Lindo[68] Global solver for MS-Excel 2010 using a laptop with Intel Core i7 Duo processor , 8 GB RAM and a 64-bit Operating System.

In addition to the multi-period solutions developed for the case studies in Section 4, results have also been developed using single-period optimization. In single period optimization, we do not take into consideration future supplies and demands while establishing connections between facilities. Each period is optimized with information for that period only whilst retaining connections made in previous periods. The single period optimization results resemble the use of existing methods, which do not take into consideration a planning horizon in determining water networks. In terms of results we expect the multi-period model for cost optimization to determine lower cost networks as compared to the single-period optimization. The MINLP model formulation given in Castro et al[79] has been used to solve the total cost minimization problem using single period optimization.

4.4 Case Study

A case study illustrating the advantages of multi-period planning over individual period planning have been presented in the following sections. The case study have been solved separately for both multi-period and individual period optimization, and the results of which were compared. In all case studies, the values of a,b and ρ are set to 3114.86 ,1.0532 and 1000 kg/m^3 respectively. H_y is set to a value of 8760 h/y and the cost of Freshwater C^{fresh} is set be \$0.13/ton. Flowrate, Concentration and removal ratios data has been taken from Castro et al [79] . Though the data available in the original case studies is used only for the instances of commissioning of plants, the expansion plan data is an artificial data and has been generated with assumptions that the contaminant level in the streams of the individual plants is constant for all the time period. Planning has been done for five time periods with a new plant being added in the first three periods. During the last two time periods, the existing sinks and sources undergo expansion in their capacities. Each time period is of four years and the entire planning has been done for twenty years. The case study input data are presented in the Appendix.

4.4.1 Cost Minimization for Regeneration and Reuse Case

Artificial data for an industrial city layout has been generated and utilized for this example. Table 45 to Table 64 below present the flowrate results.

Table 45 - Time Period 1(Multi-Period Optimization - Sources to Sinks)

		SINKS		
SOURCES		P1SI1	P1SI1	WW
	P1SO1	0	0	34.29
	P1SO2	0	0	80
	FW	0	0	

Table 46 - Time Period 2(Multi-Period Optimization - Sources to Sinks)

	SINKS					
SOURCES		P1SI1	P1SI2	P2SI1	P2SI2	WW
	P1SO1	0	0	0	0	0
	P1SO2	31.86	0	27.89	0	10.26
	P2SO1	0	0	0	0	10
	P2SO2	0	0	0	0	0
	FW	0	0	0	24.89	

Table 47 - Time Period 3(Multi-Period Optimization - Sources to Sinks)

	SINKS(j)							
SOURCES		P1SI1	P1SI2	P2SI1	P2SI2	P3SI1	P3SI2	WW
	P1SO1	0	0	0	0	0	0	50
	P1SO2	0	0	0	0	0	0	70
	P2SO1	0	0	0	0	0	0	86.43
	P2SO2	0	0	25.24	0	0	0	0
	P3SO1	0	0	18.71	0	0	0	36.29
	P3SO2	0	0	0	0	0	0	0
	FW	50	70	0	70	55	70	

Table 48 - Time Period 4(Multi-Period Optimization - Sources to Sinks)

	SINKS(j)							
SOURCES		P1SI1	P1SI2	P2SI1	P2SI2	P3SI1	P3SI2	WW
	P1SO1	0	0	0	0	0	0	70
	P1SO2	0	0	0	0	0	0	100
	P2SO1	0	0	0	0	0	0	0
	P2SO2	0	0	0	0	0	0	120
	P3SO1	0	0	0	0	0	0	0
	P3SO2	0	0	0	0	0	0	0
	FW	0	71.98	110	120	0	75	

Table 49 - Time Period 5(Multi-Period Optimization - Sources to Sinks)

	SINKS(j)							
SOURCES		P1SI1	P1SI2	P2SI1	P2SI2	P3SI1	P3SI2	WW
	P1SO1	0	0	0	100	0	0	0
	P1SO2	0	0	0	0	0	0	140
	P2SO1	0	0	0	46.57	0	0	0
	P2SO2	0	0	0	0	0	0	167.8
	P3SO1	0	70	0	8.12	0	0	21.88
	P3SO2	0	0	0	0	0	0	125
	FW	100	70	160	35.31	100	125	

Table 50 - Time Period 1(Multi-Period Optimization - Sources to Interceptors)

	Treatment Units			
SOURCES		R1	R2	None
	P1SO1	0	0	50
	P1SO2	0	0	70

Table 51 - Time Period 2(Multi-Period Optimization - Sources to Interceptors)

	Treatment Units			
SOURCES		R1	R2	None
	P1SO1	0	50	0
	P1SO2	0	0	0
	P2SO1	0	80	0
	P3SO2	0	70	0

Table 52 -Time Period 3(Multi-Period Optimization - Sources to Interceptors)

	Treatment Units			
SOURCES		R1	R2	None
	P1SO1	0	0	0
	P1SO2	0	0	0
	P2SO1	3.57	0	0
	P2SO2	44.76	0	0
	P3SO1	0	0	0
	P3SO2	70	0	0

Table 53 -Time Period 4(Multi-Period Optimization - Sources to Interceptors)

	Treatment Units			
SOURCES		R1	R2	None
	P1SO1	0	0	0
	P1SO2	0	0	0
	P2SO1	110	0	0
	P2SO2	0	0	0
	P3SO1	60	0	0
	P3SO2	0	0	0

Table 54 - Time Period 5(Multi-Period Optimization - Source to Interceptors)

	Treatment Units			
SOURCES		R1	R2	None
	P1SO1	0	0	0
	P1SO2	0	0	0
	P2SO1	113.43	0	0
	P2SO2	22.2	0	0
	P3SO1	0	0	0
	P3SO2	0	0	0

Table 55 - Time Period 1(Multi-Period Optimization - Ts1 to Ts2)

		Ts2		
Ts1		R1	R2	None
	R1	0	0	0
	R2	0	0	0
	None	0	120	0

Table 56 - Time Period 2(Multi-Period Optimization - Ts1 to Ts2)

		Ts2		
Ts1		R1	R2	None
	R1	0	0	0
	R2	19.29	0	180.71
	None	0	0	0

Table 57 - Time Period 3(Multi-Period Optimization - Ts1 to Ts2)

		Ts2		
Ts1		R1	R2	None
	R1	72.28	0	46.04
	R2	0	0	0
	None	0	0	0

Table 58 - Time Period 4(Multi-Period Optimization - Ts1 to Ts2)

	Ts2			
Ts1		R1	R2	None
	R1	0	55.59	114.41
	R2	0	0	0
	None	0	31.39	43.61

Table 59 - Time Period 5(Multi-Period Optimization - Ts1 to Ts2)

	Ts2			
Ts1		R1	R2	None
	R1	0	0	135.62
	R2	0	0	0
	None	0	0	0

Table 60 - Time Period 1(Multi-Period Optimization - Interceptors to Sinks)

	SINKS(j)		
TS2		P1SI1	P1SI2
	R1	0	0
	R2	50	70
	None	0	0

Table 61 - Time Period 2(Multi-Period Optimization - Interceptors to Sinks)

	SINKS(				
TS2		P1SI1	P1SI2	P2SI1	P2SI2
	R1	14.65	0	0	0
	R2	0	0	0	0
	None	3.49	70	62.11	45.1

Table 62 - Time Period 3(Multi-Period Optimization - Interceptors to Sinks)

	SINKS						
TS2		P1SI1	P1SI2	P2SI1	P2SI2	P3SI1	P3SI2
	R1	0	0	0	0	0	0
	R2	0	0	0	0	0	0
	None	0	0	46.05	0	0	0

Table 63 - Time Period 4(Multi-Period Optimization - Interceptors to Sinks)

	SINKS						
TS2		P1SI1	P1SI2	P2SI1	P2SI2	P3SI1	P3SI2
	R1	0	0	0	0	0	0
	R2	0	0	0	0	0	0
	None	70	28.02	0	0	60	0

Table 64 - Time Period 5(Multi-Period Optimization - Interceptors to Sinks)

	SINKS						
		P1SI1	P1SI2	P2SI1	P2SI2	P3SI1	P3SI2
TS2	R1	0	0	0	0	0	0
	R2	0	0	0	0	0	0
	None	0	0	0	0	0	0

Tables 65 to 69 & Tables 70 to 74 provide concentration of the contaminants at the inlet of interceptors in treatment stage 1 & 2. Table 75 provide the cost chart.

Table 65 - Time Period 1(Concentration - Ts1-Multi-Period Optimization)

	Contaminants		
		C1	C2
Interceptors	R1	0	0
	R2	0	0
	None	115.83	98.33

Table 66 - Time Period 2(Concentration - Ts1-Multi-Period Optimization)

	Contaminants		
Interceptors		C1	C2
	R1	0	0
	R2	94.75	115.5
	None	0	0

Table 67 - Time Period 3(Concentration - Ts1-Multi-Period Optimization)

	Contaminants		
Interceptors		C1	C2
	R1	85.8	90.27
	R2	0	0
	None	0	0

Table 68 - Time Period 4(Concentration - Ts1-Multi-Period Optimization)

	Contaminants		
Interceptors		C1	C2
	R1	99.18	113.24
	R2	0	1100
	None	80	70

Table 69 - Time Period 5(Concentration - Ts1-Multi-Period Optimization)

	Contaminants		
Interceptors		C1	C2
	R1	86.64	115.82
	R2	0	0
	None	0	0

Tables 70 to 74 present the inlet concentration at Interceptor Units in Stage 2

Table 70 - Time Period 1(Concentration - Ts2 –Multi-Period Optimization)

	Contaminants		
Interceptors		C1	C2
	R1	0	0
	R2	115.83	98.33
	None	0	0

Table 71 - Time Period 2(Concentration - Ts2 -Multi-Period Optimization)

	Contaminants		
Interceptors		C1	C2
	R1	19	23.1
	R2	0	0
	None	19	23.1

Table 72 - Time Period 3(Concentration - Ts2 -Multi-Period Optimization)

	Contaminants		
Interceptors		C1	C2
	R1	34.3	36.1
	R2	0	0
	None	34	36.1

Table 73 - Time Period 4(Concentration - Ts2 -Multi-Period Optimization)

	Contaminants		
Interceptors		C1	C2
	R1	0	0
	R2	54.21	54
	None	50.78	52.11

Table 74 - Time Period 5(Concentration - Ts2 -Multi-Period Optimization)

	Contaminants		
		C1	C2
Interceptors	R1	0	0
	R2	0	0
	None	34.65	46.33

Table 75 - Cost Chart of Piping- Multi-Period optimization –Source to Sink(x 10^6)

	SINKS							
		P1SI1	P1SI2	P2SI1	P2SI2	P3SI1	P3SI2	WW
SOURCES	P1SO1	0	0	0	6.23	0	0	1.62
	P1SO2	2.24	0.99	1.93	0	0	0	3.36
	P2SO1	0	0	0	4.86	0	0	5.73
	P2SO2	0	0	1.49	0	0	0	6.91
	P3SO1	0	3.98	1.43	1.07	0	0	4.17
	P3SO2	0	0	0	0	0	0	4.85
	FW	7.22	6.47	8.03	4.6	4.6	4.73	

Table 76 - Cost Chart of Piping- Multi-Period Optimization –Source to Interceptor(x 10^6)

	Treatment Units			
		R1	R2	None
SOURCES	P1SO1	0	3.43	3.43
	P1SO2	0	0	1.77
	P2SO1	4.14	4.14	0
	P2SO2	2.16	2.16	0
	P3SO1	2.42	0	0
	P3SO2	2.84	0	0

Table 77 - Cost Chart of Piping- Multi-Period Optimization –Interceptor to Sink(x 10^6)

	SINKS(j)						
		P1SI1	P1SI2	P2SI1	P2SI2	P3SI1	P3SI2
TS2	R1	1.71	0	0	0	0	0
	R2	0	3.49	0	0	3.11	0
	None	0	3.49	2.93	4.05	0	0

This example has also been solved while considering the periods independently. Tables 77 to Table 97 provide the flowrate in connections between different facilities.

Table 78 -Time Period 1(Individual Period Optimization - Sources to Sinks)

	SINKS			
		P1SI1	P1SI2	WW
SOURCES	P1SO1	0	0	0
	P1SO2	0	0	0
	FW	0	0	

Table 79 - Time Period 2(Individual Period Optimization - Sources to Sinks)

	SINKS					
		P1SI1	P1SI2	P2SI1	P2SI2	WW
SOURCES	P1SO1	0	0	0	0	50
	P1SO2	0	0	0	0	70
	P2SO1	0	0	0	0	0
	P2SO2	0	0	0	0	45.63
	FW	18.51	70	90	70	

Table 80 - Time Period 3(Individual Period Optimization - Sources to Sinks)

	SINKS(j)							
		P1SI1	P1SI2	P2SI1	P2SI2	P3SI1	P3SI2	WW
SOURCES	P1SO1	0	0	0	0	0	0	50
	P1SO2	0	0	0	0	0	3	0
	P2SO1	0	0	0	0	0	0	0
	P2SO2	0	0	0	0	0	0	0
	P3SO1	0	33.38	0	0	21.62	0	0
	P3SO2	0	0	0	0	0	0	0
	FW	0	0	0	0	0	67	

Table 81 - Time Period 4(Individual Period Optimization - Sources to Sinks)

	SINKS(j)							
		P1SI1	P1SI2	P2SI1	P2SI2	P3SI1	P3SI2	WW
SOURCES	P1SO1	0	0	0	70	0	0	0
	P1SO2	0	0	55.1	0	0	0	0
	P2SO1	0	44.64	0	0	0	0	0
	P2SO2	0	0	0	0	37.75	23.34	0
	P3SO1	34.23	0	0	0	0	0	0
	P3SO2	0	0	0	0	0	0	0
	FW	0	0	0	0	0	0	

Table 82 - Time Period 5(Individual Period Optimization - Sources to Sinks)

		SINKS(j)						
		P1SI1	P1SI2	P2SI1	P2SI2	P3SI1	P3SI2	WW
SOURCES	P1SO1	0	0	0	0	0	100	0
	P1SO2	0	0	0	0	0	140	0
	P2SO1	0	0	0	0	0	160	0
	P2SO2	0	0	0	0	28.46	11.54	0
	P3SO1	0	0	0	0	0	0	0
	P3SO2	0	0	0	0	0	125	0
	FW	140	78.83	190	100	96.54		

Table 83 - Time Period 1(Individual Period Optimization - Sources to Interceptor)

		Treatment Units		
		R1	R2	None
SOURCES	P1SO1	12.42	0	37.58
	P1SO2	70	0	0

Table 84 - Time Period 2(Individual Period Optimization - Sources to Interceptor)

	Treatment Units			
SOURCES		R1	R2	None
	P1SO1	0	0	0
	P1SO2	0	0	0
	P2SO1	0	0	90
	P2SO2	0	0	24.37

Table 85 - Time Period 3(Individual Period Optimization - Sources to Interceptor)

	Treatment Units			
SOURCES		R1	R2	None
	P1SO1	0	0	0
	P1SO2	0	66.98	0
	P2SO1	0	0	90
	P2SO2	0	0	70
	P3SO1	0	0	0
	P3SO2	0	70	0

Table 86 - Time Period 4(Individual Period Optimization - Sources to Interceptor)

	Treatment Units			
		R1	R2	None
SOURCES	P1SO1	0	0	0
	P1SO2	44.89	0	0
	P2SO1	65.36	0	0
	P2SO2	58.91	0	0
	P3SO1	0	0	0
	P3SO2	75	0	0

Table 87 - Time Period 5(Individual Period Optimization - Sources to Interceptor)

	Treatment Units			
		R1	R2	None
SOURCES	P1SO1	0	0	0
	P1SO2	0	0	0
	P2SO1	0	0	0
	P2SO2	0	0	150
	P3SO1	0	0	37.5
	P3SO2	0	0	0

Table 88 - Time Period 1(Individual Period Optimization - Ts1 to Ts2)

	Ts2			
Ts1		R1	R2	None
	R1	0	0	82.42
	R2	0	0	0
	None	0	0	37.58

Table 89 - Time Period 2(Individual Period Optimization - Ts1 to Ts2)

	Ts2			
Ts1		R1	R2	None
	R1	0	0	0
	R2	0	0	0
	None	114.37	0	0

Table 90 - Time Period 3(Individual Period Optimization - Ts1 to Ts2)

	Ts2			
Ts1		R1	R2	None
	R1	0	0	0
	R2	14.87	84.6	37.5
	None	2.11	105.39	52.49

Table 91 - Time Period 4(Individual Period Optimization - Ts1 to Ts2)

		Ts2		
Ts1		R1	R2	None
	R1	84.48	0	159.68
	R2	0	0	0
	None	0	0	0

Table 92 - Time Period 5(Individual Period Optimization - Ts1 to Ts2)

		Ts2		
Ts1		R1	R2	None
	R1	0	0	0
	R2	0	0	0
	None	0	187.5	0

Table 93 - Time Period 1(Individual Period Optimization - Interceptor to Sink)

		SINKS(j)	
TS2		P1SI1	P1SI2
	R1	0	0
	R2	0	0
	None	50	70

Table 94 - Time Period 2(Individual Period Optimization - Interceptor to Sink)

		SINKS(j)			
		P1SI1	P1SI2	P2SI1	P2SI2
TS2	R1	31.49	0	0	0
	R2	0	0	0	0
	None	0	0	0	0

Table 95 - Time Period 3(Individual Period Optimization - Interceptor to Sink)

		SINKS					
		P1SI1	P1SI2	P2SI1	P2SI2	P3SI1	P3SI2
TS2	R1	0	0	0	0	0	0
	R2	50	36.62	0	70	33.38	0
	None	0	0	90	0	0	0

Table 96 - Time Period 4(Individual Period Optimization - Interceptor to Sink)

		SINKS					
		P1SI1	P1SI2	P2SI1	P2SI2	P3SI1	P3SI2
TS2	R1	0	55.36	29.12	0	0	0
	R2	0	0	0	0	0	0
	None	35.76	0	0	50	22.25	51.66

Table 97 - Time Period 5(Individual Period Optimization - Interceptor to Sink)

	SINKS						
		P1SI1	P1SI2	P2SI1	P2SI2	P3SI1	P3SI2
TS2	R1	0	0	0	0	0	0
	R2	0	0	81.17	0	0	0
	None	0	0	0	0	0	0

Table 98 to and 107 provide the concentration of contaminants at the inlet of interceptors.

Table 98 - Time Period 1(Concentration -Ts1- Individual Period Optimization)

	Contaminants		
		C1	C2
Interceptors	R1	118.49	93
	R2	0	0
	None	110	110

Table 99 - Time Period 2(Concentration -Ts1- Individual Period Optimization)

	Contaminants		
Interceptors		C1	C2
	R1	0	0
	R2	0	0
	None	87.13	116

Table 100 - Time Period 3(Concentration -Ts1- Individual Period Optimization)

	Contaminants		
Interceptors		C1	C2
	R1	0	0
	R2	99.56	79.78
	None	89.37	117.19

Table 101 - Time Period 4(Concentration -Ts1- Individual Period Optimization)

	Contaminants		
Interceptors		C1	C2
	R1	92.31	97.78
	R2	0	0
	None	0	0

Table 102 - Time Period 5(Concentration -Ts1- Individual Period Optimization)

	Contaminants		
Interceptors		C1	C2
	R1	0	0
	R2	0	0
	None	101	118

Table 103 to 107 present inlet concentrations in treatment stage 2.

Table 103 - Time Period 1(Concentration -Ts2- Individual Period Optimization)

	Contaminants		
Interceptors		C1	C2
	R1	0	0
	R2	0	0
	None	67	60

Table 104 - Time Period 2(Concentration -Ts2- Individual Period Optimization)

	Contaminants		
Interceptors		C1	C2
	R1	87.13	116
	R2	0	0
	None	0	0

Table 105 - Time Period 3(Concentration -Ts2- Individual Period Optimization)

	Contaminants		
Interceptors		C1	C2
	R1	0	0
	R2	58.44	72.1
	None	60.43	75

Table 106 - Time Period 4(Concentration -Ts2- Individual Period Optimization)

	Contaminants		
Interceptors		C1	C2
	R1	36.92	39.11
	R2	0	0
	None	36.92	39.11

Table 107 - Time Period 5(Concentration -Ts2- Individual Period Optimization)

		Contaminants	
		C1	C2
Interceptors	R1	0	0
	R2	101	118
	None	0	0

Tables 108 –110 present cost data for case study from single period optimizations minimizing the total network cost.

Table 108 - Cost Chart of Piping- Individual-Period Optimization –Source to Sink(x 10^6)

		SINKS						
		P1SI1	P1SI2	P2SI1	P2SI2	P3SI1	P3SI2	WW
SOURCES	P1SO1	0	0	0	6.23	0	0	1.62
	P1SO2	2.24	0.99	1.93	0	0	0	3.36
	P2SO1	0	0	0	4.86	0	0	5.73
	P2SO2	0	0	1.49	0	0	0	6.91
	P3SO1	0	3.98	1.43	1.07	0	0	4.17
	P3SO2	0	0	0	0	0	0	4.85
	FW	7.22	6.47	8.03	4.6	4.6	4.73	

Table 109 - Cost Chart of Piping- Individual-Period Optimization –Source to Interceptor(x 10^6)

	Treatment Units			
SOURCES		R1	R2	None
	P1SO1	0	3.43	3.43
	P1SO2	0	0	1.77
	P2SO1	4.14	4.14	0
	P2SO2	2.16	2.16	0
	P3SO1	2.42	0	0
	P3SO2	2.84	0	0

Table 110 - Cost Chart of Piping- Individual-Period Optimization – Ts1 to Ts2(x 106)

	SINKS						
TS2		P1SI1	P1SI2	P2SI1	P2SI2	P3SI1	P3SI2
	R1	1.71	0	0	0	0	0
	R2	0	3.49	0	0	3.11	0
	None	0	3.49	2.93	4.05	0	0

4.4.2 Results

The total cost of the network obtained using multi-period planning was found to be $ 15.94 x10^7, with the cost of Freshwater required and treatment within the five time period was $5.43 x 10^6 and $7.58 x 10^6 respectively . When the periods are solved independently, the total cost of the network was increased to \$19.39 x10^7, and the cost of freshwater and waste treatment calculated was \$ 3.98 x 10^6 & 8.42 x 10^6. Comparing the two results, the total cost calculated using multi-period planning is 17.8% cheaper when compared to individual period planning. The total number of connections required was found to be 40 in multi-period planning, and 53 for individual period planning.

Water network in multi-period and single period optimization develop through time differently. In multi-period optimization, four connections are made in time period 1, fourteen connections are made in time period 2, eleven in period 3 and five connections are made in time period 4 and six in time period 5. Since the connections are made keeping in mind the future plan of the city, only single connections are required between two facilities.

When single period optimization is considered, five connections are made in time period 1, eleven connections are made in time period 2, twelve connections are made in time period 3, fourteen connections in time period 4 and ten connections were made in period 5. Since the periods are optimized independently, pipes are laid whenever the capacity increases.

5. CONCLUSION

This work involves the use of direct recycle and regeneration & recycling water integration strategies for obtaining an optimal network for an industrial city considering the fact that its layout changes with time. The shortest source-to-sink distances that are associated with the provided layout and arrangement of the different plants within the industrial city have been provided. The results indicate that network design planning for an entire time period (Multi-period) yields enhanced performance compared to the solutions obtained from solving individual time periods, for most of the cases that have been illustrated. The former method shows that either the number of connections, total cost or both can be reduced. A reduction in the number of connection means a less complex water network. This work clearly shows the deficiencies of individual period optimization without considering the future periods. Besides this, multi-period optimization helps in determining the best way of setting up new plants and to recognize the best of the potential site for setting up of new plants.

Moreover, multi period planning enables rating of time periods, for which the last time period in any case gives the most developed water network. The ratings can be done on several basis. In this work, the periods have been rated according to the flowrates handled in them. They can also be rated on the basis of load that is handled in a particular period. Thus, water resources were found to be utilized more often during the planning phase for a given city.

Since this work only involves centralized treatment system as a water integration option, the multi-period planning methodology can certainly be expanded to further look into other treatment scenarios. This includes use of decentralized treatment systems and water mains concept which will also try to address the management issues which arise in due course of planning. Also more component of costs like operation cost will be analyzed . Therefore, future work will certainly look into investigating the impact of the presence of other kind of treatment options on the cost and number of connections within the network design, from a multi-period planning perspective.

Apart from the inclusion of other kind of treatment options more water consuming sinks like irrigation and demand of potable water will also be included in future works. Inclusion of these water consuming avenues describe the industrial city in a better way. This will be coupled with the development of multi-period approaches for industrial city energy and cogeneration integration (Stijepovic, M.Z. and P. Linke [80], Stijepovic V.Z et al [81])towards energy-water nexus integration.

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APPENDIX

Table 111 - Flowrate and Contaminant Data for Sources for Case Study 1

Time Periods	**Source**	**Flowrate (tons/hr)**	**Contaminant 1 (kΩcm)-^{1}**	**Contaminant2 %**
TP 1	**Class 1-2(C12)**	650	7.14E-05	-
	Class 3-4(C34)	600	8.33E-05	-
TP 2	**Class 1-2(C12)**	1300	7.14E-05	-
	Class 3-4(C34)	1100	8.33E-05	-
TP 3	**Class 1-2(C12)**	2300	7.14E-05	-
	Class 3-4(C34)	2100	8.33E-05	-
TP 4	**Class 1-2(C12)**	2600	7.14E-05	-
	Class 3-4(C34)	2400	8.33E-05	-
	S1	5980	-	0.5%
	S2	2840	-	0.49%
TP 5	**Class 1-2(C12)**	2800	7.14E-05	-
	Class 3-4(C34)	2600	8.33E-05	-
	S1	7000	-	0.5%
	S2	3500	-	0.49%

Table 112 - Flowrate and Contaminant Data of Sinks for Case Study 1

Time period	**Sink**	**Flowrate (tons/hr)**	**Contaminant 1 (kΩcm)-^{1}**	**Contaminant 2 %**
TP1				
	Back grinding(BG)	1000	6.25E-05	-
	Marking(MK)	700	1.00E-04	-
TP 2	**Back grinding(BG)**	1900	6.25E-05	-
	Marking(MK)	1500	1.00E-04	-
TP 3	**Back grinding(BG)**	3500	6.25E-05	-
	Marking(MK)	2450	1.00E-04	-
TP 4	**Back grinding(BG)**	4000	6.25E-05	-
	Marking(MK)	2800	1.00E-04	-
	D1	4250	-	1%
	D2	4580	-	1%
	D3	1950	-	1%
TP 5	**Back grinding(BG)**	4400	6.25E-05	-
	Marking(MK)	3000	1.00E-04	-
	D1	4600	-	1%
	D2	5000	-	1%
	D3	2300	-	1%

Table 113 - Industrial City Layout for Case study 1

Distance(km)	**SINKS(j)**					
SOURCE(i)	**Back grinding**	**Marking**	**D6**	**D8**	**D9**	**Waste Water**
Class 1-2	5.4	5	8	10	11.6	2.6
Class 3-4	3.6	3.2	6.2	8.2	9.8	3.6
S1	9.6	4	4.2	7.8	9.4	9.2
S2	8.2	7	4.8	5.6	7.2	7.4
Freshwater	11.6	10.4	8.6	7.4	7.4	7.6

Table 114 - Industrial City Layout for Case study 2

Distance(km)	**SINKS(j)**						
SOURCE(i)	**P1D1**	**P1D2**	**P3D1**	**P5D1**	**P5D2**	**P4D1**	**Waste Water**
P2S2	5.4	5	8	10	11.6	4	2.6
P2S1	3.6	3.2	6.2	8.2	9.8	5	3.6
P3S1	9.6	4	4.2	7.8	9.4	10.2	9.2
P6S2	8.2	7	4.8	5.6	7.2	4.4	7.4
P6S1	8	6.8	3.8	4.6	6.2	4.6	7.6
P4S1	12.6	11.4	9.6	10.4	11.2	5.6	8.6
Freshwater	11.6	10.4	8.6	7.4	7.4	4.6	7.6

Table 115 - Flowrate and Concentration Data of Sources for Case Study 2

Time Period	Sources	Flowrate(tons/hr)	C1(ppm)	C2(ppm)	C3(ppm)
TP 1	**P2S2**	120	100	50	30
	P2S1	80	140	100	60
TP 2	**P2S2**	120	100	50	30
	P2S1	80	140	100	60
	P3S1	140	180	150	130
	P6S2	80	230	180	180
TP 3	**P2S2**	120	100	50	30
	P2S1	80	140	100	60
	P3S1	140	180	150	130
	P6S2	80	230	180	180
	P6S1	195	250	190	200
	P4S1	100	100	190	210
TP 4	**P2S2**	200	100	50	30
	P2S1	100	140	100	60
	P3S1	135	180	150	130
	P6S2	190	230	180	180
	P6S1	195	250	190	200
	P4S1	120	100	190	210
TP 5	**P2S2**	200	100	50	30
	P2S1	100	160	120	60
	P3S1	135	180	150	160
	P6S2	190	210	210	180
	P6S1	195	270	190	210
	P4S1	120	120	180	210

Table 116 - Flowrate and Contaminant Data of Sinks for Case Study 2

Time Period	Sinks	Flowrate(tons/hr)	C1(ppm)	C2(ppm)	C3(ppm)
TP 1	**P1D1**	120	40	60	30
	P1D2	80	50	50	80
TP 2	**P1D1**	120	40	60	30
	P1D2	80	50	50	80
	P3D1	80	50	70	100
	P5D1	140	140	100	100
TP 3	**P1D1**	120	40	60	30
	P1D2	80	50	50	80
	P3D1	80	50	70	100
	P5D1	140	140	100	100
	P5D2	80	170	120	130
	P4D1	195	240	130	150
TP 4	**P1D1**	120	40	60	30
	P1D2	200	50	50	80
	P3D1	135	50	70	100
	P5D1	190	140	100	100
	P5D2	100	170	120	130
	P4D1	195	240	130	150
TP 5	**P1D1**	120	40	60	30
	P1D2	200	50	50	80
	P3D1	135	50	85	120
	P5D1	190	140	100	100
	P5D2	100	160	120	140
	P4D1	195	240	145	150

Table 117 - Flowrate and Concentration Data of Sources(Regeneration and Reuse)

Time Period	Sources	Flowrate(tons/hr)	C1(ppm)	C2(ppm)
TP 1	**P1SO1**	50	110	110
	P1SO2	70	120	90
TP 2	**P1SO1**	50	110	110
	P1SO2	70	120	90
	P2SO1	90	85	115
	P2SO2	70	95	120
TP 3	**P1SO1**	50	110	110
	P1SO2	70	120	90
	P2SO1	90	85	115
	P2SO2	70	95	120
	P3SO1	55	125	110
	P3SO2	70	80	70
TP 4	**P1SO1**	70	110	110
	P1SO2	100	120	90
	P2SO1	110	85	115
	P2SO2	120	95	120
	P3SO1	60	125	110
	P3SO2	75	80	70
TP 5	**P1SO1**	100	110	110
	P1SO2	140	120	90
	P2SO1	160	85	115
	P2SO2	190	95	120
	P3SO1	100	125	110
	P3SO2	125	80	70

Table 118 - Flowrate and Concentration data of Sinks (Regeneration and Reuse)

Time Period	**Sources**	**Flowrate(tons/hr)**	**C1(ppm)**	**C2(ppm)**
TP 1	**P1SI1**	50	80	90
	P1SI2	70	70	60
TP 2	**P1SI1**	50	80	90
	P1SI2	70	70	60
	P2SI1	90	100	75
	P2SI2	70	85	95
TP 3	**P1SI1**	50	80	90
	P1SI2	70	70	60
	P2SI1	90	100	75
	P2SI2	70	85	95
	P3SI1	55	110	90
	P3SI2	70	55	70
TP 4	**P1SI1**	70	80	90
	P1SI2	100	70	60
	P2SI1	110	100	75
	P2SI2	120	85	95
	P3SI1	60	110	90
	P3SI2	75	55	70
TP 5	**P1SI1**	100	80	90
	P1SI2	140	70	60
	P2SI1	160	100	75
	P2SI2	190	85	95
	P3SI1	100	110	90
	P3SI2	125	55	70

Table 119 - Distance between Sources and Sinks(Regeneration and Reuse Case)

Distance(km)	**SINKS(j)**							
		P1SI1	**P1SI2**	**P2SI1**	**P2SI2**	**P3SI1**	**P3SI2**	**Waste Water**
SOURCES(i)	**P1SO1**	5.4	5	8	10	11.6	3.8	2.6
	P1SO2	3.6	3.2	6.2	8.2	9.8	2.2	3.6
	P2SO1	9.6	4	4.2	7.8	9.4	3.6	9.2
	P2SO2	8.2	7	4.8	5.6	7.2	4.4	7.4
	P3SO1	5.9	6.4	4.6	3.45	6.5	4.8	6.7
	P3SO2	3.5	5.2	7.2	4.3	5.48	8	7.8
	Freshwater	11.6	10.4	8.6	7.4	7.4	7.6	

Table 120 - Distance between Sources and Interceptors(Regeneration and Reuse Case)

	Treatment Units			
		R1	**R2**	**None**
SOURCES(i)	**P1SO1**	5.5	5.5	5.5
	P1SO2	5.674	5.674	5.674
	P2SO1	6.645	6.645	6.645
	P2SO2	3.467	3.467	3.467
	P3SO1	7.786	7.786	7.786
	P3SO2	4.563	4.563	4.563

Table 121 - Distance between Interceptors and Sinks(Regeneration and Reuse Case)

	SINKS(j)						
		P1SI1	**P1SI2**	**P2SI1**	**P2SI2**	**P3SI1**	**P3SI2**
TS2	**R1**	3.4	5.6	4.7	6.5	5	4.8
	R2	3.4	5.6	4.7	6.5	5	4.8
	None	3.4	5.6	4.7	6.5	5	4.8

Table 122 - Removal Ratios and Regeneration Cost($ per kg of Waste removed)of treatment units

		Removal Ratio	**Regeneration Cost**
Interceptor	**R1**	0.6	1.46
	R2	0.8	2.06
	None	0	-