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Decentralized Wastewater Management Solutions for Improved Public Health Protection and Reclamation: Optimization and Application

A dissertation submitted in partial satisfaction of the
requirements for the degree Doctor of Philosophy
in Civil Engineering

by

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ABSTRACT OF THE DISSERTATION

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Professor Michael Knudsen Stenstrom, Chair

Centralized wastewater treatment, widely practiced in developed areas, involves transporting wastewater from large urban or industrial areas to a large capacity plant using a single network of sewers. Alternatively, the concept of wastewater collection, treatment and reuse at or near its point of generation is called decentralized wastewater treatment. Smaller decentralized plants with energy-efficient reclaimed water pumping, modularization of expansion and minimum capital investment can meet the increasing need for reclamation and wastewater management accessibility in rapidly developing regions Decentralized treatment can improve access to wastewater infrastructure in developing regions and improve energy-efficiency in reclamation in many rapidly growing developed regions. They can also replace land-intensive and inefficient treatment systems such as septic tanks and leach fields for remote, residential communities. They can reduce the strain on existing central facilities and can be an alternative to expensive collection system upgrades. We demonstrated the applicability of decentralized treatment to two examples in India and an example in Los Angeles.

It is important to study the optimization and implications of decentralization. We formulated design and optimization methodology subject to user-defined constraints for a decentralized configuration of several treatment plants and collection networks. In this dissertation we developed an algorithm, using a constrained multi-objective optimization method (Genetic Algorithm), to obtain feasible decentralized configurations with minimum cost and energy. The applications of this methodology include obtaining the optimal solution for a given scenario, comparing alternative solutions devised by the user, and analyzing capacity expansion. Enabling easier reclamation and a more widespread access to wastewater collection and treatment are the chief motivation behind this study.

The dissertation of Kartiki Shirish Naik is approved.

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University of California, Los Angeles

2014

To the family that became my friends and the friends who became my family.

Table of Contents

List of Tables

List of Figures

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1 Introduction

Sanitation and wastewater collection were developed to protect public health from disease. Urban sewerage systems were developed to collect and remove wastewaters from the sources to a safe disposal point. With the advent of several laws, (in the US, namely the Oil Pollution Act, Water Quality Act and Clean Water Act), wastewater treatment assumed high priority for public health and water resource protections (Viessman, et al., 2008). The Clean Water Act has been revised several times, but in 1972 source standards were created which fundamentally changed the way treatment systems were designed, funded and permitted. Urban wastewater treatment has become mostly centralized using large regional treatment plants and further amendments have tended to increase centralization. Centralized treatment requires conveying wastewater from a large area to one plant of large capacity. Decentralization is defined as the collection, treatment reuse of wastewater at or near its source of generation (Crites & Tchobanoglous, 1998).

Decentralized treatment can be further bifurcated into onsite treatment and offsite treatment. Onsite treatment is employed on a "per household" basis. Offsite treatment is community or cluster based and consists of a small collection system which conveys the wastewater away from the households to a suitable treatment location (Singhirunnusorn, 2009; Metcalf & Eddy Inc., 2002). This framework is similar to that of centralized wastewater treatment, except that it operates on a much smaller scale and proximity to the serviced community. The scale is influenced by various factors, such as location, land use, population density, etc. (Bakir, 2001).

Generally, remote residential communities use household level onsite treatment systems such as septic tanks and leach fields. Community expansion tends to exhaust leach field capacity, due to limited land availability, compromising the effluent quality and the soil, surface and groundwater quality. A public sewerage system connecting to a central wastewater treatment plant is usually constructed to accommodate increased, future demand. This is a typical scenario for wastewater management to accommodate suburban growth.

On the other hand, as urban areas expand further from their core, more suburbs are formed. Though developed urbanized areas generally rely on centralized treatment due to a higher economy of scale in terms of labor and capital cost, there is an increasing need to establish “satellite” treatment plants as cities or towns diverge from the main urban area. Satellite treatment plants are a form of decentralization, which includes wastewater collection, treatment and provides reclaimed water much closer to the point of wastewater generation.

Apart from spread of urbanization, there are several motivating factors behind decentralization. Wastewater reclamation being a relatively new requirement, existing wastewater management seldom incorporates the cost of returning recycled water from the central plant in deciding the plant location. Decentralized systems can reduce the topographically-driven need to pump back reclaimed water to potential users. For instance, in Los Angeles, the smaller D.C. Tillman and Glendale wastewater treatment plants, located upstream of the large Hyperion treatment plant (350 MGD), relieve the trunk sewers and reclaim water near potential users[1]. This arrangement also allows biosolids, grit and screenings to be

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[1] Los Angeles Department of Public Works & Los Angeles Bureau of Sanitation: http://www.lacitysan.org/LASewers/ (Accessed 11/27/2011)

returned to the trunk sewer for processing at Hyperion. Figure 1.1 shows the City of LA Sanitation treatment plant system and the LA County Sanitation District treatment plant system.

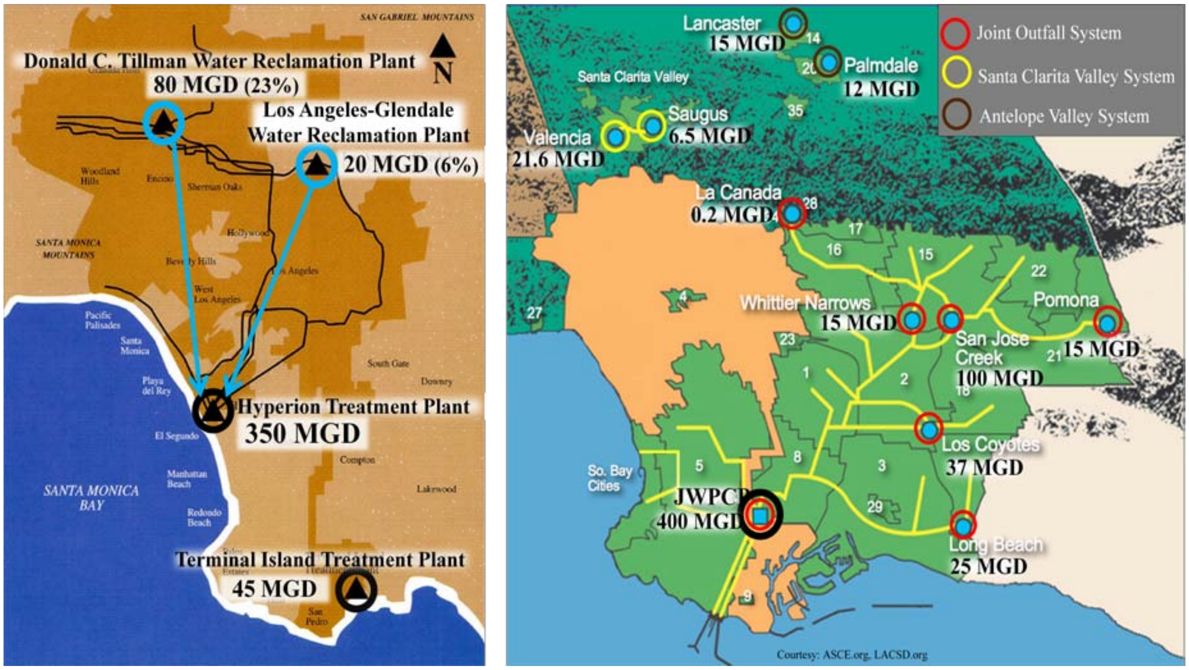


Figure 1.1 Treatment plant system operated by LA City Bureau of Sanitation (left) and LA County Sanitation District (right) (American Society of Civil Engineers, 2012; LA County Sanitation District, 2012).

The LA County also relies on a larger scale distributed system. They have three different cluster systems (Joint Outfall, Santa Clarita Valley and Antelope Valley) consisting of 10 treatment plants of different capacities, ranging from 0.2 MGD to 100 MGD, with the Joint Outfall System flowing to the Joint Water Pollution Control Plant (400 MGD).

Thus, decentralization can also be a local alternative to constructing expensive large trunk collection systems to manage increased flow. Providing wastewater treatment and collection to remote communities can be more achievable with smaller decentralized collection systems and treatment plants due to reduced initial cost. Many developing areas regard wastewater management as a luxury due to higher capital investment and large scale urban planning rather than a basic necessity. In Chapter 3 of this dissertation, we have shown that collection system expansion is usually associated with a very high monetary investment as compared to establishing several smaller collection systems.

Conventional centralized treatment plants are usually designed for a conservative projected capacity. Such a conservative design, though necessary, usually increases capital cost and sometimes dramatically increases cost. Wastewater management in many developing regions is impeded by unreliable financing. Many such regions need to turn to privatized funding and management. Smaller treatment systems can rely on modular biological processes such as Membrane Bioreactors and Rotating Biological Contactors at a relatively lower cost per unit flow than larger plants. These can be modularly expanded for increased capacity, thus dynamically matching the growth rate for a particular area.

To utilize benefits such as public health improvement, energy-efficient reclamation and conveyance and modular expansion, it is necessary to devise an optimization algorithm for a customizable and feasibly minimum cost and energy wastewater collection network and treatment plant location for such regions. There are two aspects to wastewater management and planning: Technology selection and System configuration. Some studies have developed treatment process selection algorithms based on individual cases for small-scaled decentralized treatment systems. In addition to process-based optimization, it is necessary to develop a methodology to obtain a configuration in terms of urban planning to apply this information to improve or optimize the treatment plants.

The main aim of this dissertation is to devise and implement a methodology to determine the configuration of decentralized treatment plants in terms of optimal locations and number, for a set of local constraints and collection network size. The methodology involves dividing the particular area into a grid based on a practicable resolution and determining the least cost collection network and treatment plant solution. This solution is subject to constraints such as feasibility of a location for treatment plant installation, the nature of the road network and connecting the entire service area to the wastewater management system. Fig 1.2 is a schematic of an integrated decentralized wastewater management system.

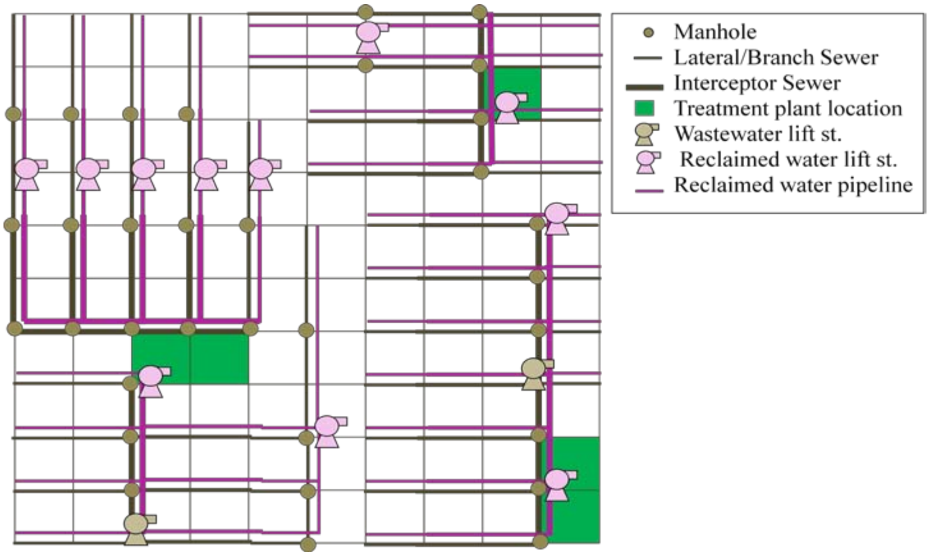


Figure 1.2 Schematic of integrated decentralized wastewater management system

This methodology uses Binary Genetic Algorithm to arrive at the collection network and number of treatment plants. A genetic algorithm is an optimization method which follows modern evolutionary synthesis to arrive at the "fittest" solution. It uses several "generations" of "populations" composed of individual possible solutions known as chromosomes. The advantage of this method is the random selection of elements of a possible solution and adapting mutations introduced in every generation to evolve into an optimal solution. This aspect is applicable to designing a multi-component inter-dependent wastewater management system. Chapter 4 describes Genetic Algorithm and its fundamentals in more detail.

To opt for the decentralization, it is necessary to determine the degree of decentralization which can provide the least-cost, most feasible solution. In addition to arriving at a solution, we determined the favorable degree of decentralization, expressed in number of discrete collection and treatment systems per geographical area for some typical scenarios. We also conducted a sensitivity analysis study based on the resolution of the area, demand, topography and feasible locations.

Understanding decentralized systems demands allied studies to select a suitable methodology to determine their application technique. These studies address various aspects of decentralized systems and their purpose, such as motivation due to public health, local suitability and cost implications.

1.1 Background research

1.1.1 Quantitative evidence of public health benefit by wastewater management

Several studies have established the influence of sanitation or clean drinking water availability on public health and disease outbreaks, but the benefits of wastewater collection and treatment have generally not been quantified. Even though the primary goal of wastewater treatment is public health protection, developing regions often view it as a luxury addressing only aesthetic concerns, not related to drinking water protection. Achieving this research objective emphasizes the need to optimize and install decentralized systems in such regions.

1.1.2 Limiting factors for wastewater management in developing regions and motivation for developing regions

Certain wastewater management measures which are basic to developed regions can be difficult to achieve in developing regions. We conducted some case studies based on two cities in India to study the general and specific hindrances to achieving complete wastewater collection and treatment. We also analyzed the application of decentralized treatment to such cases and possible roadblocks.

1.1.3 Preliminary feasibility analysis methodology for decentralization/Motivation for developed regions

Local scenarios individually determine the feasibility of either decentralized or centralized type of collection and treatment system. Many studies have delved into very specific feasibility or qualitative analyses for different case studies, but none have prescribed a standard preliminary feasibility assessment for the most general scenarios. A preliminary quantitative suitability assessment for each configuration to a locality before exhaustively optimizing any system can direct the planner to a more accurate solution. This is a quantitative test for the applicability of decentralized treatment before performing an exhaustive design and planning exercise.

1.1.4 Capital Investment Estimation Methods

Many studies, surveys and software have estimated the capital investment for wastewater treatment plants using both theoretical and statistical approaches. We reviewed these estimation methods to create cost estimates as part of the model. The user of the optimization algorithm can select a preferred estimate or set his cost parameters. Analyzing these cost estimates for consistency in time for each unit processes is important as many user interface based design and costing software depend on these literature. On performing cost studies for different years we deduced these costs updated to a certain reference time can be inconsistent.

Through this doctoral study, we aim to improve the comprehension of decentralized systems and their purpose, which will in turn refine their application techniques. Decentralized systems have several advantages, which if effectively utilized, can pose as a solution for many upcoming public health and water demand issues stemming from rapid urbanization. Such a study can cultivate awareness of emerging reclamation and wastewater management solutions and their appropriate use, especially in developing regions.

1.2 Literature Review

Decentralization has stemmed from the emerging needs of reclamation and urban expansion. Though most of the previous work suggests that it is more of a recent requirement, the concept has been known to the wastewater community since the 1970s. As mentioned previously in the introduction section, the Donald C. Tillman reclamation plant (built in 1985) and Los-Angeles Glendale reclamation plant (built in 1976) were successful large-scale projects to decentralize the Los Angeles City wastewater treatment system (City of Los Angeles, 2012).

Some older studies focused on the aspect of pollutant dilution for decentralized collection and treatment configurations. Adams et al. (1972) analyzed the diseconomies of scale in collection systems and their trade-off against the economies of scale in treatment plants. They deduced from cost modeling that there is a relation between the quantity of flow and the area of service: low density areas have a smaller minimum cost service area. Some demographical studies indicated that due to a general low density of urban areas (barring the high density core); large scale wastewater management systems can incur higher expenses with larger low density collection systems. Another conclusion was that multiple outfalls or discharge points can mitigate the inconsistency in performance of treatment plants.

Several studies after the Clean Water Act 1972 resulted in models relating the degree of decentralization and the consequent effluent quality. Another study by Adams and Gemmel (1973) estimated the impact of degree of decentralization on the receiving waters using known water quality models such as Dobbins and Streeter Phelps. According to that analysis, decentralization improves receiving water quality at smaller dilution ratios and the water quality improvement tapers off after decentralizing it to more than 8 plants. Yao (1973) studied the effect of centralization of wastewater treatment on receiving waters by applying the Streeter Phelps model to a six treatment plant system and concluded that regionalization is more likely to deplete the downstream waters of dissolved oxygen. A study by Rossman and Liebman (1974) devised a mathematical decision model based on nonlinear programming for the decentralization or regionalization of the wastewater management system for a river with a specified water quality goal and minimum cost. Chapter 4 discusses other previous work on optimization of decentralized collection and treatment systems in more detail. The following sub-sections overview various aspects of research in decentralized treatment.

1.2.1 Feasibility of decentralization

Gawad et al. (1995) formulated a model to determine the optimized size for cluster formation for a number of communities/towns based on construction and operation costs of the facilities, existing infrastructure, the geography of the governorate, environmental impact, alternative treatment technologies and phasing of implementation. Engin and Demir (2006) compared three alternatives for a community of 70 villages in Gebze, Turkey: Centralized, Centralized with a cluster of septic systems and Package plants. They devised a method relying on construction cost for the collection network, septic systems and package plants. Using a per capita cost computation to evaluate the trade-off between collection network and treatment system costs, Deininger and Su (1973) compared the individual and regional treatment systems. They applied it to two scenarios: multiple linearly located communities and seven scattered communities, and concluded that one regional treatment system can achieve more economies of scale than individual systems.

1.2.2 Onsite Treatment (Household)

Several studies suggested onsite treatment for urban development further from the core urban area. Otterpohl et al. (1997) suggested measures such as low water consumption system for wastewater and storm water management based on storm water, black water and grey water separation in Lubeck, Germany for 300 people. They demonstrated some process-related technological advances of onsite treatment by using an anaerobic digester without dewatering for the black water, a biofilter for grey water and trench infiltration and retention for storm water. Babcock et al. (2004) developed a household based aerobic wastewater treatment system called OESIS-750 for secondary treated and disinfected effluent. Kujawa-Roeleveld and Zeeman (2006) discussed the suitability of source separation and various anaerobic treatment processes to onsite and decentralized treatment. Emmerson et al. (1995) conducted a Life Cycle Assessment (LCA) on three small sewage-treatment works serving a population of approximately 1000 (200 m^3/d) and compared the processes used based on energy consumption and emissions. The LCA methodology consists of three components: resource consumption over six stages of the product/process life cycle; significance of the product/process for the environment and impact of the product/process on the environment. Several other studies proposed and tested novel process technologies for onsite treatment (Kegebein, et al., 2007; Bdour, et al., 2009; Sabry, 2010; Liang, et al., 2010).

1.2.3 Degrees and Sophistication of Decentralization

Decentralized systems have not been popular with sanitation authorities due to the record of inadequate treatment performance by available onsite technologies. The necessary factors for a decentralized system to be viable are sufficiently high performance for reclamation and a competent staff to operate and maintain the system. The unit cost for mass produced package treatment plants can be lower than that for a single package treatment cost (Wilderer & Schreff, 2000). Onsite treatment systems such as cesspools and septic tanks have evolved little from since their earliest use for household-based sanitation. Yet, a significant fraction of households rely on these systems without proper performance and monitoring. A history of employing the "lowest common denominator" approach for onsite treatment has resulted in poor public health and environment protection (Bradley, et al., 2002). Bradley et al. (2002) proposed a methodology to evaluate the sustainability of wastewater management systems with varying degree of sophistication. They based this method on several criteria such as public health, community acceptance, development and involvement, aesthetics, affordability, economic development and environmental impact, and provided normalized weighting for each criterion. Gikas and Tchobanoglous (2009) explored the definitions of "centralized", "satellite" (distributed) and "decentralized" (onsite) configurations, their types, requirements, applicability and shortcomings. They also emphasized on the need to move towards decentralization to address the need for indirect potable reuse.

1.2.4 Dependence on geographical location

Bakir (2001) discussed several adaptations of decentralized and onsite wastewater management such as and their geographical prevalence in the Middle Eastern and North African regions. He suggested minimizing water demand especially for waste conveyance, site-specific solutions for a reduced service area per system and minimal transport of waste. Roma and Jeffrey (2010) analyzed the necessity and implications of the level of community participation on the process and configuration selected in the densely populated areas of Indonesia. They emphasized the need for the serviced communities to be "self-sustained" with respect to operation, maintenance and monitoring in the post-installation stage. Brown et al. (2010) evaluated several upcoming concept designs, for both treatment and habitation for onsite and decentralized configurations based on available literature and process characteristics (qualitatively) and the capital, operational, energy and nutrient recovery implications of the technical design (quantitatively) for Melbourne. They concluded that high density multi-storeyed dwelling coupled with cluster systems were most economical in terms of the above mentioned factors. Other configurations were equally capable of achieving sufficient reuse. Urine separation, composting and irrigation improved the scope for nutrient recovery.

2 Evidence of the Influence of Wastewater Treatment on Improved Public Health

2.1 Introduction

Sanitation and wastewater treatment protect human health by conveying wastewaters away from populated areas and converting them to less hazardous or less infective forms. Public sanitation has benefitted from early laws and regulations that often addressed other water-based issues. For instance, in the USA the earliest water laws protected navigation by preventing the introduction of solid wastes into navigable waters (Viessman, et al., 2008).

The history of public sanitation laws in the USA illustrates how regulations have evolved from protecting navigation and public health to protecting the environment. From 1912, when the Public Health Service Act provided a section on the removal of waterborne diseases, to the formation of the Environmental Protection Agency (EPA) in 1970, and the passing of Clean Water Act in 1972 to protect water quality for the environment, water regulations had adapted to technological advancement (Viessman, et al., 2008). Yet, the primary objective of protecting human health cannot be neglected despite the increasing focus on environment protection.

Lately, increased industrial development has introduced many pollutants such as endocrine disrupters, explosives and heavy metals to surface and ground waters (Benotti, et al., 2009). Wastewater treatment can reduce such pollutants, thus eliminating the necessity for an excessively sophisticated and expensive drinking water treatment system (Leu, et al., 2012). Also, as waterborne diseases stem from source water contamination, protecting source water is necessary to reduce disease burden via direct contact or vector breeding. Balancing an efficient drinking water supply and wastewater treatment is the key to eliminating waterborne diseases.

Sanitation is usually considered to be a more fundamental community need relative to wastewater treatment (HDR Engineering Inc., 2001). Our study demonstrates that many nations that have complete sanitation but low wastewater treatment also have high disease mortality. The aim of the paper is to establish that increased wastewater-treatment access reduces waterborne disease mortality. As increased national income implies improved health care services, the effect of wastewater treatment on disease mortality is verified independent of that of economy.

2.2 Literature review

Previous studies have analyzed the relationship between sanitation or water supply and disease mortality or burden extensively by employing various methodologies, sampled data and disease indicators. Table 2.1 reviews previous work based on the relationship of water and public health. A few relevant studies might have been omitted inadvertently.

2.3 Methods

2.3.1 Indicators

There are three indicators in this study: health, environmental and economic. Based on previously encountered methodological problems, the availability and suitability of data, parameters have been chosen for these indicators. The indicators, the bases for their selection and the parent database are described in Table 2.2 and the following section in detail.

The Gross National Income (GNI) per capita, an economic indicator, quantifies the net capita income of a population. It impacts health care, infrastructure and hygiene (United Nations, 2010a). For the human development index (HDI), another economic indicator, the calculations have been described in detail in the Human Development Report (United Nations, 2010b).

Table 2.1 Previous studies relating sanitation, wastewater treatment, water supply and public health

Reference	**Objective/Results**	**Summarized conclusions**
(Blum & Feacham, 1983)	Reviewed previous studies and qualitatively examined methodological problems that can distort or hinder conclusive analyses from such studies	Methodological problems are listed as follows (elaborated in later sections): Inadequate control, One-to-one comparison, Complex variables, Health indicator recall, Health indicator definition, No analysis by age, Lack of facility usage record
(Esrey, et al., 1985)	• Studied pathogen dose–response relationship by also separating mild and severe diarrhea based on incidence rate • Formulated model relating improved water supply and excreta disposal with diarrhea incidence rate • Reviewed: 67 studies from 28 countries based on different infections or different health indicators and calculated median reduction based on different conditions	• Water supply or excreta disposal can reduce ingestion of pathogens by young children, which reduces diarrhea • With increased pathogen dosage mild diarrhea increases to a breakpoint after which severe diarrhea dominates • Significant reduction in both diarrheal morbidity (27%) and mortality observed (30%)
(Soller, et al., 2003)	Formulated hydraulic model on San Joaquin River, CA, USA integrated with a dynamic disease transmission model for diarrhea to assess incremental benefit associated with added tertiary treatment	• Continuous risk to individual with recreational water source • In winter, tertiary treatment lowers risk by 15–50%, though effluent pathogen count below EPA limit (site-specific results)
(Fewtrell, et al., 2005)	Reviewed 46 studies from peer-reviewed articles to pool data and conduct conclusive analysis by random effects test on disease mortality reduction due to interventions like improved water supply, sanitation and hygiene	Relative risks (reduction in frequency of diarrhea) for: • Hygiene: 0.55 (0.52–0.77) 95% • Sanitation: 0.68 (0.53–0.87) 95% • Water supply: 0.75 (0.62–0.91) 95% • Water quality: 0.61 (0.46–0.81)
(Haller, et	Analyzed cost–effectiveness for increasing access to improved	• Piped water supply and sewerage accomplished

al., 2007)	water supply and sanitation facilities, increasing access to in-house piped water and sewerage connection, and providing household water treatment, in ten continental WHO sub-regions	maximum health gains • Disinfection had lowest cost–benefit, but had high health improvements • The highest improvement was in low diarrheal mortality countries of the Eastern Mediterranean Region, the Americas, Europe and South-east Asia
(Nelson & Murray, 2008)	Reviewed current sanitation technologies with respect to long-term performance, user demands, expenses and capacity	• Existing facilities do not suffice in protecting human health and treating waste • Water quality standards should be the deciding factor in the design of sanitation and wastewater treatment infrastructure
(Tsuzuki, 2008)	Conducted a correlation analysis between Pollutant Discharges per Capita (PDC) and GNI, access to safe drinking water, domestic water usage amount, and integrated parameters of water, sanitation and economic indicators for eight international coastal zones and lakeside regions	• PDC-BOD is correlated with GNI per capita with a third-order regression • PDC-TP is correlated with the integrated parameters of water, sanitation, economy with 10% significance • A complex relationship suggested by multiple linear regression analyses between PDC-BOD and safe drinking water availability
(Tsuzuki, 2009)	Conducted linear and log regression analyses on PDC and gross domestic product per capita (GDPC) in seven international lakeside and coastal regions	PDC-BOD, PDC-TN (total nitrogen) and PDC-TP (total phosphorus) have different correlations with GDPC because of prioritizing nutrient removal after a certain economic development
(Mara, 1996)	Reviewed and analyzed benefits and implementation of sanitation	• Inappropriate population target and lack of guidance to users • Situation-specific approach is necessary
(Cairncross,	Analyzed inadequacy of sanitation and suggested tasks for	Tasks at various organizational levels:

et al., 2010)	organizations at different levels	• Local Government: quick response to local needs, effective delivery and cooperation with local providers • Central Government: support local government by regulation and resourcing • External agencies: optimize financing sanitation and obtaining investment from users • Health sector: propagate importance of hygiene, sanitation, water supply and quality; establish by-laws; support at household and community levels

Disease mortality was more reliable than disease burden as a health indicator. Disease burden data, measuring number of cases, was inconsistent and possibly improbable for the low-income countries where health care might receive lesser priority (World Health Organization, 2010). The data are based on tuberculosis, diarrheal diseases and malaria as they differ in geographic susceptibility and are consistently reported. Parasitic diseases were not considered due to inadequate data. Due to the unavailability of data for some countries, they have been excluded from the analysis for collection of wastewater. Water quality was not used as an indicator as a means to avoid complexity.

Table 2.2 Nomenclature for Economic, Environmental and Health indicators

Indicator	**Units**	**Range**	**Definition**	**Reference**
Gross National Income	USD per capita	-	'Income of country' – aggregate balances of gross primary incomes for all sectors	(United Nations Statistics Division, 2010)
Human Development Index (HDI)	-	0 to 1	'Measure of human development' – based on health, education and standard of living	(United Nations, 2010b)
Disease Mortality	Numbers per million	-	Number of deaths by cause	(World Health Organization, 2010)
Access to wastewater treatment	Percent	0 to 100	Percent population connected to facilities	(United Nations, 2010a)
Access to sanitation	Percent	0 to 100		(United Nations, 2010c)
Access to collection	Percent	0 to 100		(United Nations, 2010a)

The following parameters were the environmental indicators. Access to sanitation comprises 'connections to public sewers, septic systems, pour-flush latrines, simple and ventilated improved pit latrines'. Population connected to wastewater collecting systems covers the percentage of population which 'may deliver wastewater via collecting systems either to treatment plants or discharge it directly to the environment'. 'The population connected to urban wastewater treatment denotes the percentage of the resident population whose wastewater is treated at wastewater treatment plants' (United Nations, 2010a)

2.3.2 Dataset

Each point in the sample set corresponds to a country and the corresponding indicators. The dataset is given in Appendix 1 (available online at http://www.iwaponline.com/wst/066/144.pdf). Categorized based on HDI, the 'developed', 'moderately developed' and 'underdeveloped' country categories have almost an equal number of national statistics. Figure 2.1 shows a global variation of these indicators.

The overall disease rate is low in North America, Australia, Europe, Mexico and Argentina. Sanitation is mostly high or at least moderately developed globally except in India and Chad. Wastewater treatment access is more randomly distributed. Thus, barring a few extremes, disease mortality and wastewater treatment individually do not follow a prominent geographical pattern.

Our study resolves many previously encountered methodological problems. Table 2.3 describes those and our approach towards them.

2.4 Results and Discussion

2.4.1 Interdependence

Figure 2.2 shows the effect of GNI on disease mortality, wastewater treatment and sanitation accessibility respectively. Disease mortality decreases with increased national income due to improvements in health care. Also, GNI indirectly affects disease mortality due to its effect on wastewater treatment. Thus, extricating the influence of wastewater treatment from that of GNI is necessary.

2.4.2 Wastewater and disease variation

The indicators being interdependent, analyzing the impact of wastewater treatment access on disease mortality at constant human development is necessary. We conducted a paired regression of disease mortality and lack of wastewater treatment access for small

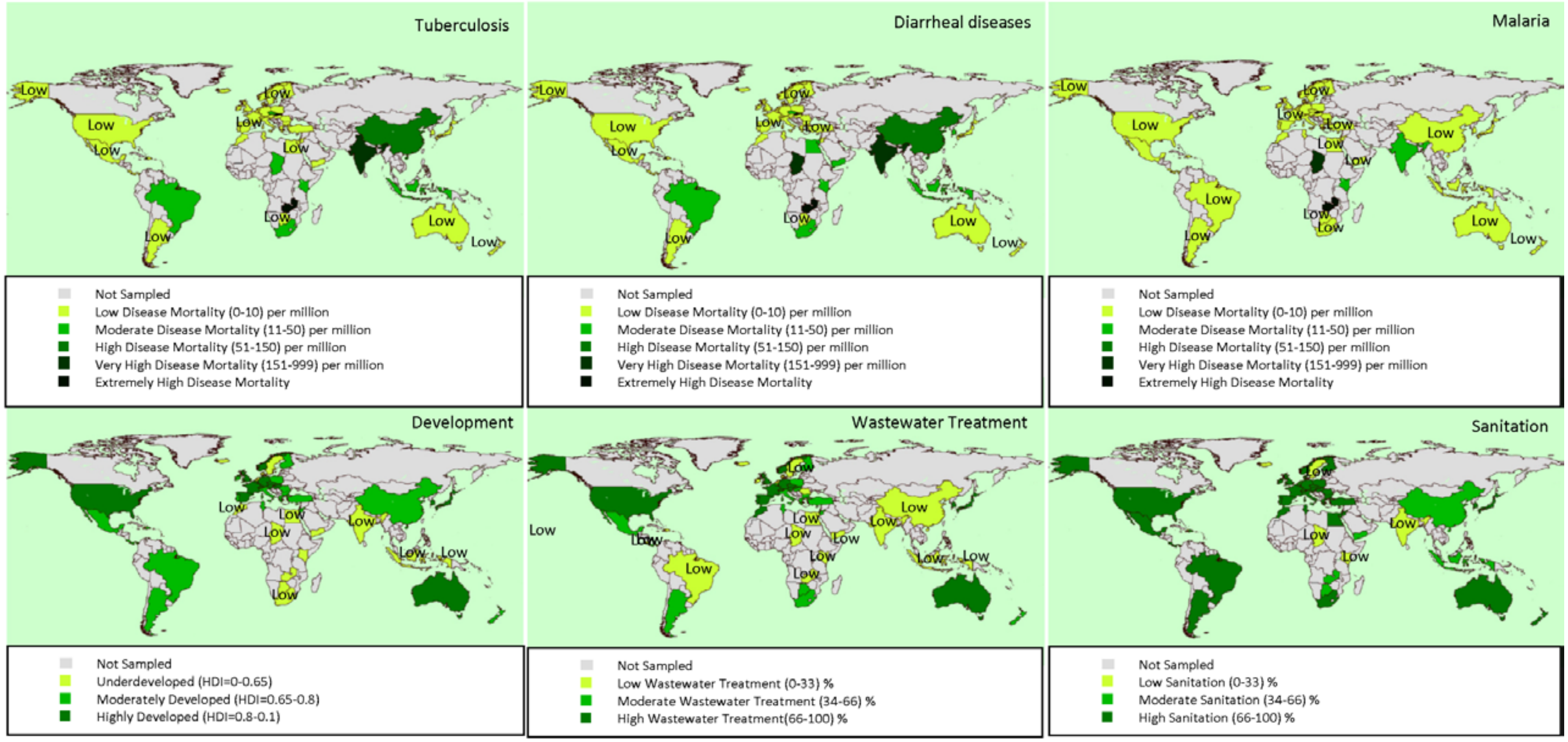


Figure 2.1 Global variation of disease mortality, human development, and access to wastewater treatment and sanitation (United Nations Statistics Division, 2010; United Nations, 2010b; World Health Organization, 2010; United Nations, 2010a)

The ranges of the HDI (range 0 to 0.1) to approximate constant human development in those ranges. The parameter ‘population not connected to wastewater treatment’ was more suitable for a paired analysis with disease mortality. Figure 2.3 denotes the variation in disease mortality with lack of access of wastewater treatment in every small range of HDI.

The plots show that disease mortality increases with lack of access to wastewater treatment (both parameters of corresponding pairs appear close together). Though not a linear variation, more wastewater treatment access indicates low disease mortality and vice versa. The public health benefit can also be observed for all degrees of development and countries having 100% sanitation. Therefore, the relationship between disease and availability of wastewater treatment is independent of national income, development and sanitation. In the paired analysis, there were a greater number of supporting pairs for diarrheal diseases than for malaria or tuberculosis (diarrhea: 28, tuberculosis: 27, malaria: 22).

2.4.3 Correlation

A linear fit of wastewater treatment access with logarithm of disease mortality gives correlation coefficients (r^2) of 0.319 for diarrheal diseases, 0.436 for tuberculosis and 0.484 for malaria. The correlations are significant as they have a probability value of less than 0.001. Malaria has a higher correlation coefficient than tuberculosis and diarrheal diseases. This result was initially counterintuitive to the authors’ expected result of diarrheal diseases being more closely related to wastewater treatment. Upon reflection it was expected, as areas with more stagnant water accumulation have greater opportunity for waterborne diseases. Tuberculosis is an opportunistic disease more prominently affecting individuals with compromised immune systems due to diseases (e.g. diarrhea) (Winthrop, 2006). The magnitude of these effects cannot be tested with the existing datasets, but provided are previously documented reasons for the correlations

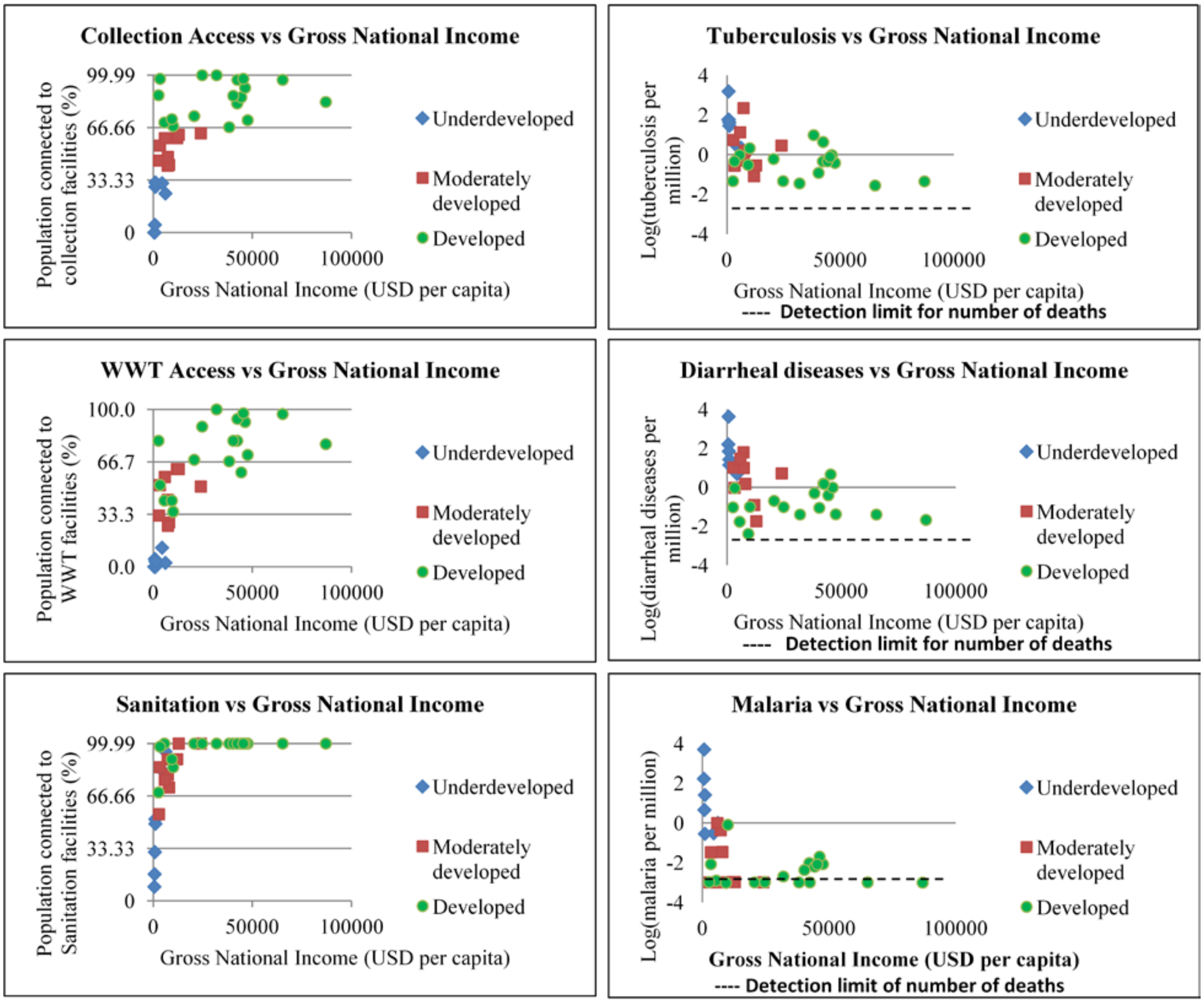


Figure 2.2 Dependence of environmental and health indicators on Gross National Income **(United Nations Statistics Division, 2010; United Nations, 2010b; World Health Organization, 2010; United Nations, 2010a; United Nations, 2010c)**

The low correlation coefficients can be explained by the possible nonlinearity of the relations. Also, the diarrheal disease data pertains to parasitic, viral or bacterial diarrhea. It is necessary to pursue a single diarrheal disease like cholera which is tracked exhaustively by organizations like the World Health Organization. In future studies, we would observe the variation of mortality due to cholera with wastewater treatment access.

Table 2.3 Previously encountered methodological problems and solutions **(Blum & Feacham, 1983)**

Observed Problem	**Description**	**Approach in study**
Lack of control group	No distinction between health improvements due to water supply/excreta disposal accessibility and that due to social or economic factors.	By dividing the dataset into very small increments of human development index, we approximated constant human development: observed disease trends were purely based on wastewater treatment access.
One-to-one comparison	Comparison of a single control community to a single intervention community: this would be just one data point as such interventions are a community-wide movement.	Thirty-nine different nations have been considered as data points. The degree of intervention changes in irregular increments.
Complex parameters	Controlling a number of intricate variables is complicated. Groups to be compared should be similar with respect to some variables.	In studying the trend between disease mortality and access to wastewater treatment, we analyzed groups which had approximately the same human development index.
Health indicator recall	Incomplete information on recurrence or family history of diarrhea.	This study uses disease mortality which is better recorded than disease burden.
Health indicator definition	Misinterpretation due to lack of definition of indicators.	In this study, all indicators used have been very well defined in Table 3.
Lack of facility usage record	Assumption that existence of a facility implies complete usage.	To denote wastewater treatment, sanitation or collection access, this study uses percent population connected to each of the facilities.

2.4.4 Role of wastewater treatment in the human development index

Figure 2.4 shows the variation of HDI with the environmental indicators. HDI has individual dependence on access to wastewater collection, treatment and sanitation. In the lower row of Figure 2.4, HDI does not correlate with the fraction of treated wastewater from collection systems and the fraction of collected wastewater from sanitation facilities. We suggest that this facet of development be integrated in such a prominently used development index, to emphasize the need for wastewater treatment.

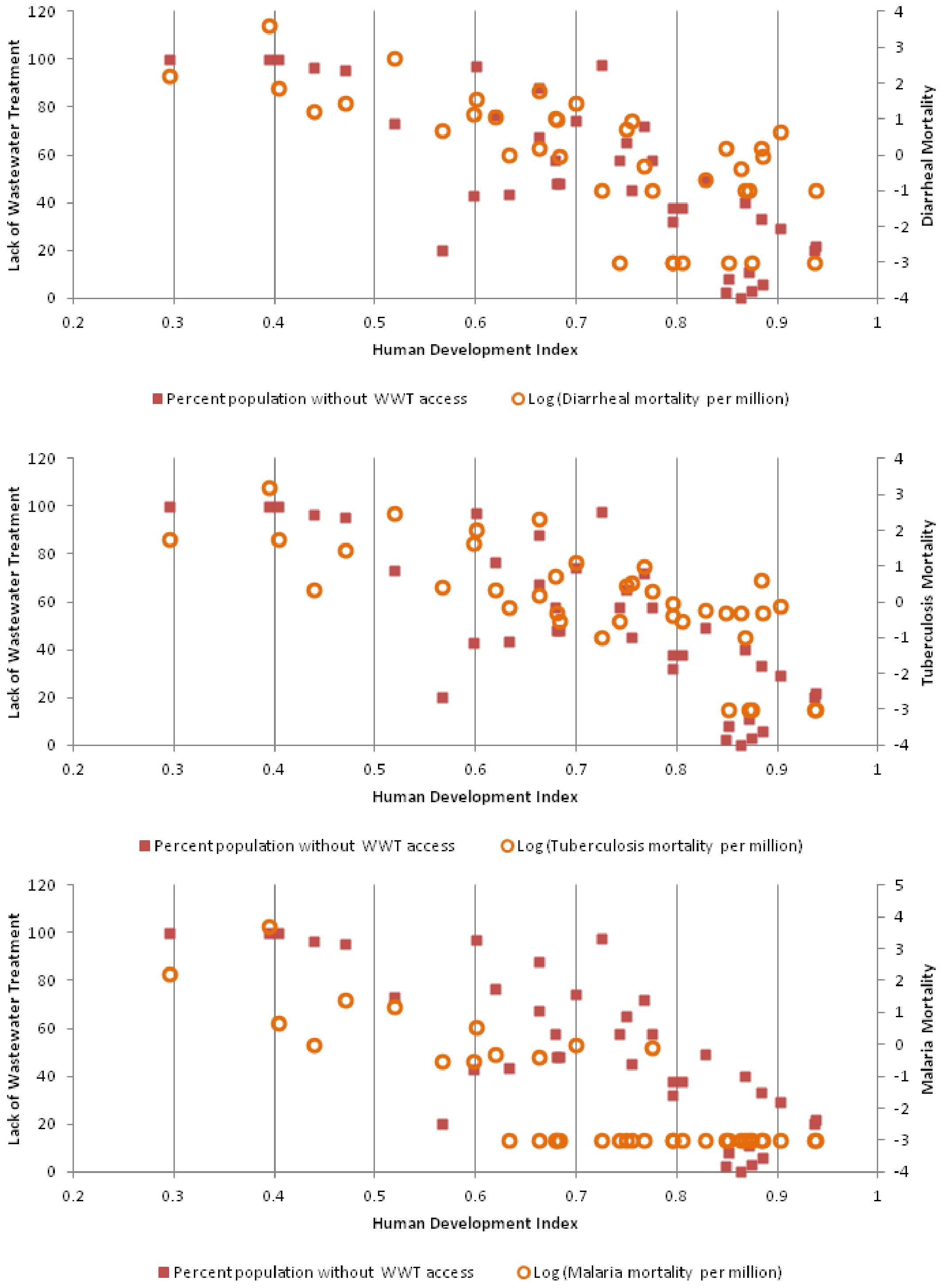


Figure 2.3 Paired analysis for wastewater treatment and diarrheal disease, tuberculosis and malaria respectively at constant HDI **(United Nations, 2010b; World Health Organization, 2010; United Nations, 2010a; United Nations, 2010c)**

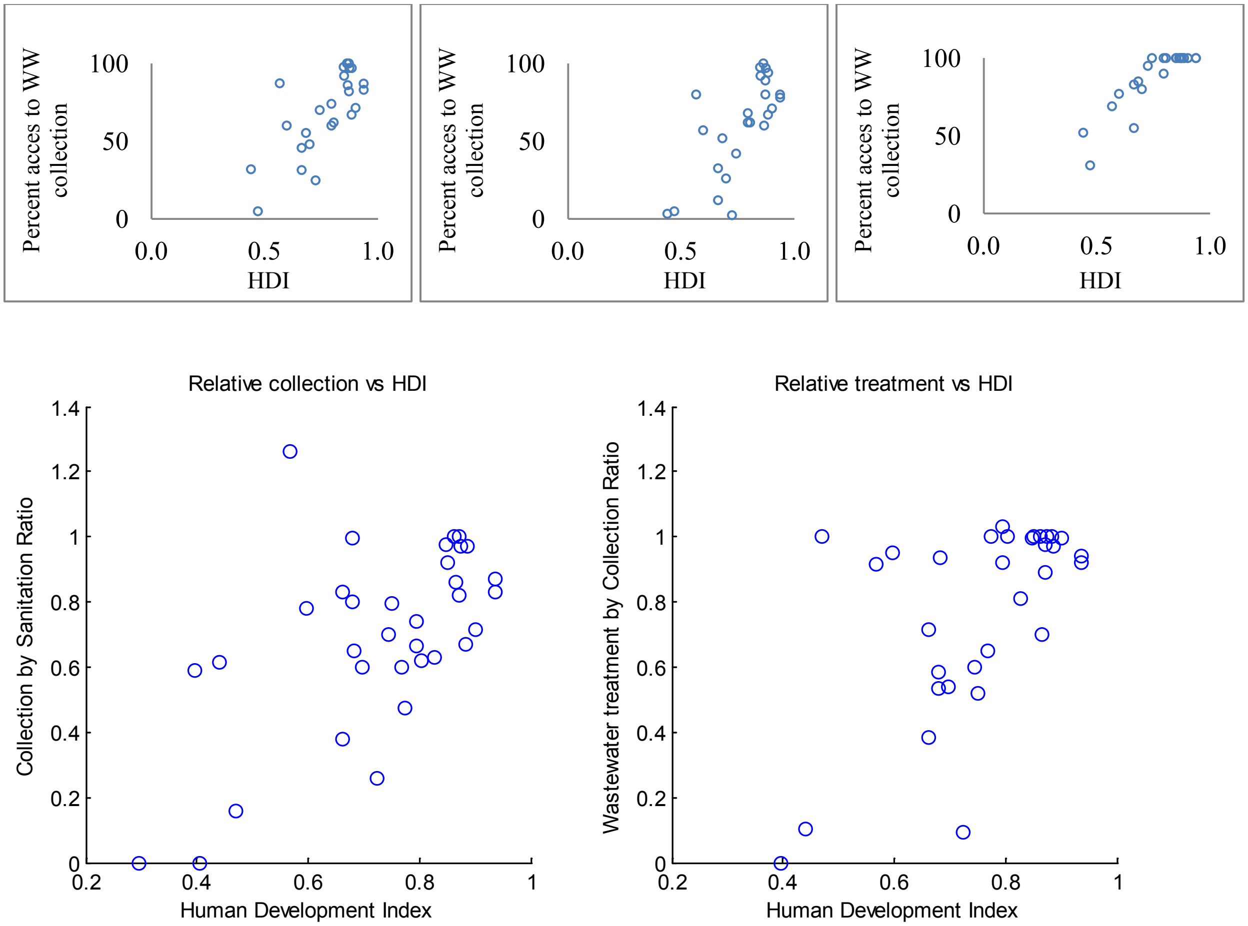


Figure 2.4 Dependence of HDI on wastewater collection, sanitation and wastewater treatment and relative wastewater collection and relative wastewater treatment respectively **(United Nations, 2010b; World Health Organization, 2010; United Nations, 2010a; United Nations, 2010c)**

2.5 Conclusions

This study analyzes the influence of wastewater treatment access on public health independent of national economic growth or other development. Environmental, economic and health indicators corresponding to a set of 39 nations were used for this study. The availability of wastewater treatment significantly benefits public health, independent of increase in health care or national income. This variation is observed at all levels of human development and even conditions of complete sanitation. Also, a prominently used development indicator, the HDI, depends on access to wastewater treatment, collection and sanitation individually, but does not show dependence on their relationships. Overall, this study implies that wastewater treatment is not an extravagance for developed nations but a basic necessity for public health protection irrespective of the income of a nation. Hence it should be considered an integral part of planning the development of a nation. Future work would involve studying the impact of wastewater treatment access on cholera mortality and age specific analysis owing to different age susceptibilities for all these diseases.

3 Cost, Energy, Health and Environmental Incentives for Decentralized Wastewater Management

3.1 Introduction

In Chapter 2 we evaluated the benefits of managing wastewater on public health. We showed that wastewater collection and treatment can improve public health irrespective of the economy or standard of living. Local water resources are an integral part of civilizations, not only for potable but also for recreational and transportation purposes. Disease can infect populations easily through proximate water resources in developing areas due to inadequate wastewater management. Areas that have witnessed greater progress in wastewater management face different issues such as energy efficient and cost-effective reclamation and protection of sensitive water bodies.

Water demands, effluent quality standards and reclamation needs vary across different regions, and depend on factors such as climate, water resources, population density, economy and agricultural intensity. In this chapter, we analyzed key factors that interfere with the effectiveness and efficiency of conventional wastewater management for developing and developed areas. These factors can be categorized as energy-related, financial, political or policy-related. We qualitatively assessed the applicability of decentralized treatment to developing areas to address these issues and suggested typical measures. We quantitatively evaluated the effect of decentralization on reclaimed water pumping energy consumption (pump-back) and capital cost. These studies formed the methodology for a preliminary feasibility assessment for applying decentralization to various scenarios.

3.2 Methodology

Prior to applying a general feasibility assessment methodology to a particular scenario, it is necessary to gauge local features and their significance as constraints in addition to effluent quality requirements. Certain local situations demand specific characteristics in their biological process. Since process selection can affect the cost and energy implications of treatment, it is necessary to choose a biological process suitable to the particular situation.

3.2.1 Biological Process Suitability

We considered a few hypothetical scenarios to understand the suitability of some biological unit processes to typically encountered constraints: Low land availability, high energy cost and lack of skilled labor. We analyzed different biological processes for these criteria: activated sludge process, trickling filter, oxidation ditch, anaerobic, aerobic, facultative lagoons, rotating biological contactors (RBC), upflow anaerobic sludge blanket reactors (UASBR) and septic tanks and leach fields. We theoretically designed each of the unit processes for a given flowrate and obtained the energy and land area requirement. Fig. 1 shows their suitability to different scenarios (Naik & Stenstrom, 2011).

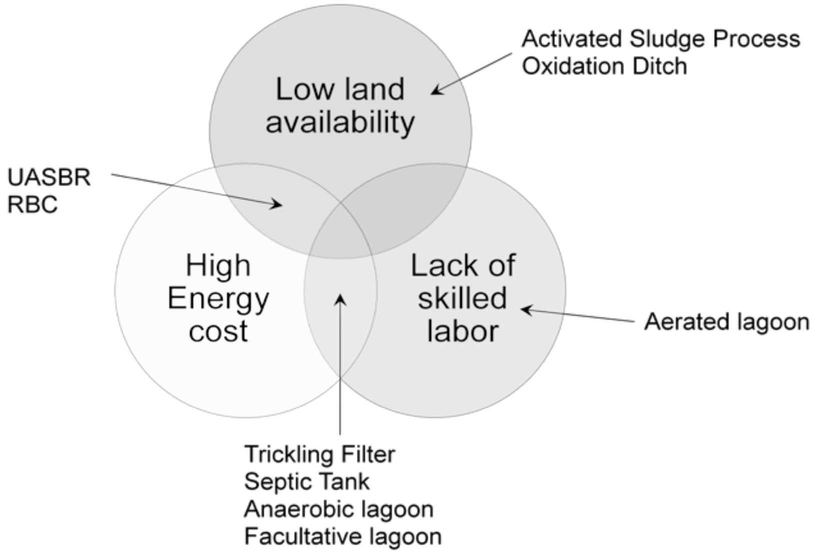


Figure 3.1 Suitability of biological processes to different local scenarios **(Naik & Stenstrom, 2011)**

The UASBR and RBC can be more cost-effective for densely populated regions with high electricity cost. Examples of such regions are small densely populated remote land forms, such as Singapore, Sri Lanka, Puerto Rico, Taiwan, etc. Due to the UASBR's complex operation, skilled labor is necessary. Facultative or anaerobic lagoons do not require skilled labor or electrical supply but need adequate land area. Regions that are not likely to urbanize with available lands can utilize the economy of these unit processes.

Such low density regions with a mostly residential demographic can rely on septic tanks and leach fields owing to the underground treatment of raw wastewater. Septic tanks are household based treatment systems and can be land-intensive due to their requirement of leach fields. Trickling filters are a better alternative for more urbanized, yet low density areas. Trickling filters if not operated properly produce odors and filter flies due to stagnant biofilm growth. This makes it cumbersome to use trickling filters in decentralized plants, which can be in close proximity to residential areas. Aerated lagoons and oxidation ditches are less land-intensive than other types of lagoons, and are simpler to operate than any of the activated sludge process variations. Oxidation ditches are a variant of the activated sludge process and have efficiencies and resilience to shock loadings comparable to the conventional activated sludge process. These advantages with the simplicity of operation make the oxidation ditch a suitable alternative for smaller flows. Variations of the activated sludge process are the most common choice for most urban settings. Conventional centralized wastewater facilities rely on this process for its higher efficiency in carbonaceous and nutrient removal. Figure 3.2 summarizes the characteristics of all these processes.

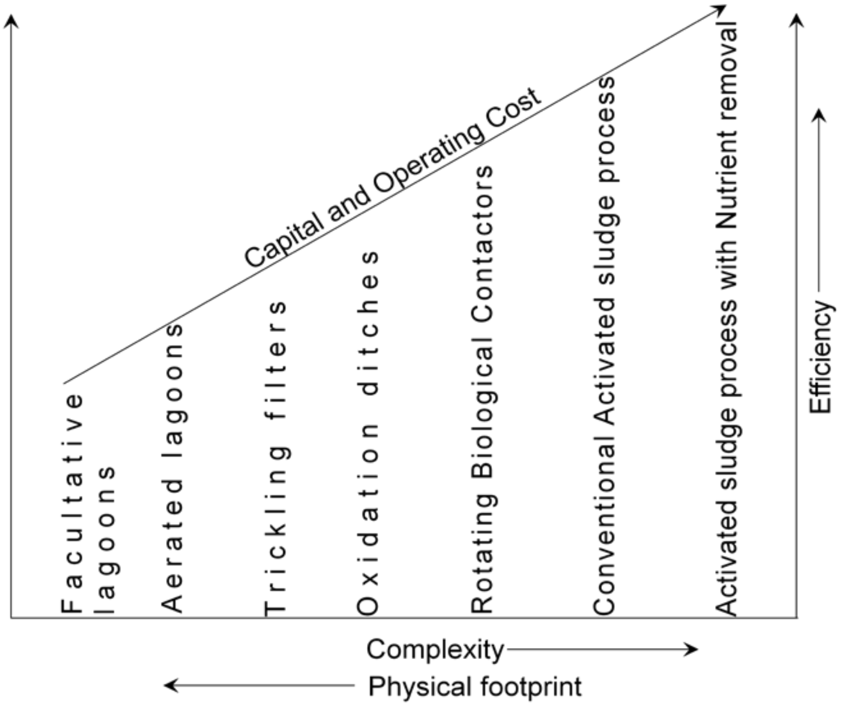


Figure 3.2 Complexity, physical footprint, efficiency, capital and operating cost for various biological processes

Apart from process selection and design, the implementation of a planned system can encounter several obstacles depending on endemic economic, political and water resource situations. Many of these hindrances require an alternative form of wastewater management which can provide more incentives for the investment. We considered existing situations where decentralizing wastewater management can be applied and utilized effectively. We considered three cities (two developing and one developed) to demonstrate the applicability of decentralization.

3.2.2 Case studies – Developing Areas

Many Indian urban areas are developing rapidly, straining existing resources especially due to increased water demand. Also, land is especially scarce in these densely populated urban areas. About 31 % of the Indian population lives in urban areas which form only 2 % of the total political area. The population density of Indian megacities ranges from 3300 to 7200 persons per sq. km (2050-4500 per sq. mile) (Ministry of Home Affairs, India, 2011). We qualitatively analyzed the scenarios of two cities in India.

3.2.2.1 Example 1 (Nagpur, India - Nag River)

Nagpur is a metropolitan area in the state of Maharashtra in western India. It has urbanized rapidly in the past decade. It has three major source waters: Gorewada Tank, Kanhan River and Pench Canal (Nagpur Municipal Corporation, 2013). The Nag River is an indirect tributary of the Kanhan River and flows adjacent to a University Campus, and it is essential that it be free of pathogenic contamination. Being central to urbanized Nagpur, if maintained poorly, this river is a potential breeding ground for disease.

Figure 3.3 Map of Nagpur showing Nag River and the University

A large part of the land adjoining the region where the River crosses Nagpur belongs to the campus of Vishweshwariya National Institute of Technology (VNIT). Figure 3.3 is a map of Nagpur showing Nag River and the University. Also, most of the contamination of the river occurs in this region. Despite the vulnerability of the city dwellers to the quality of the Nag River, a university campus directly disposes its domestic waste into the Nag River (Khadse, et al., 2008).

The Nagpur Municipal Corporation (NMC) plans to install a wastewater treatment plant of 5000 m^3/day each (6.5 MGD) to clean up Nag River. About 5000 ft^2 of land with a 5000 ft^2 buffer zone is required for this plant. The open, vegetated land within the university campus could be used as a buffer zone for the plant. In a high density urban area such as Nagpur, buffer zones are essential. The NMC suggested locating the plant on university properly but the university refused to yield, forcing the project to a standstill (Times of India, 2013a). The university has neglected notices from the NMC demanding a response regarding their wastewater disposal policies.

To further address water quality issues for the Nag River, the NMC plans to install 3 other wastewater treatment plants in other parts of Nagpur, along the river. Figure 3.4 shows the locations, demographics and the problems associated with each of these plants. Of the 3 mini wastewater treatment plants, only one has been installed in a residential area, due to political and corporate support for its construction. The other 2 plants have been either opposed by residents or encountered land disputes. Also, despite privatizing wastewater treatment, the financing depends on the Government. The funding from the Government has been inconsistent for other treatment plants for the same river system.

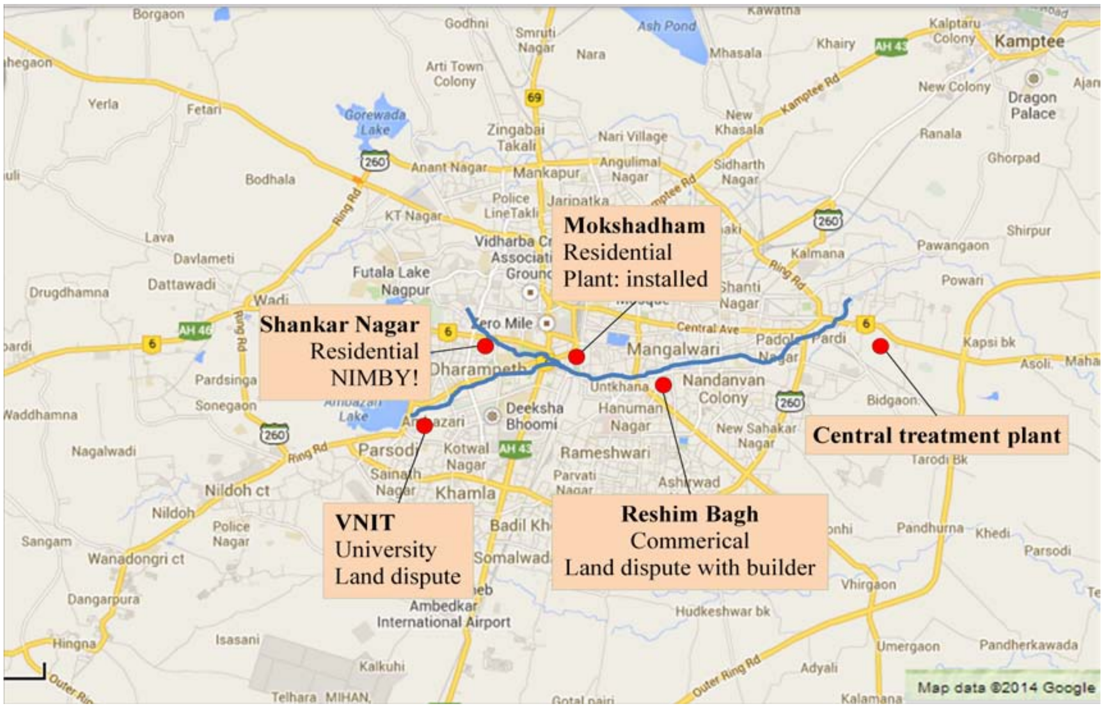


Figure 3.4 Locations of potential treatment plants along Nag River

3.2.2.2 Example 2 - Gurgaon, and Noida, India - Yamuna River

Gurgaon is a city 30 km (18.75 miles) south of New Delhi, the capital of India. Noida (New Okhla Industrial Development Authority) is a relatively newer city 20 km southeast of New Delhi. Noida is adjacent to the Yamuna and Hindon Rivers. Gurgaon is connected to both these rivers via a small channel. Both cities were rapidly industrialized in the past decade. Figure 3.5 is a map showing both cities and their connections to the Yamuna and Hindon Rivers.

Figure 3.5 Map of Northern India showing Gurgaon, Noida, Yamuna and Hindon Rivers

The planning and installation of utilities did not keep current with the rapid industrialization of these cities. The existing wastewater treatment plants for Gurgaon have a total capacity of 148,000 m3/day (39 MGD), whereas the current demand is 225,000 m3/day (59.5 MGD). The untreated wastewater bypasses the plants to the Yamuna River. Noida generates about 150,000 m3/day (40 MGD) of wastewater but has a total treatment capacity of only 70,000 m3/day (18.5 MGD). The remaining 80,000 m3/day (21.5 MGD) flows directly into the Hindon River, a tributary of the Yamuna River (Times of India, 2013c).

The State Govt. installed a 35,000 m3/day (9.2 MGD) for both the cities, 8 years after the capacity exhausted (The Hindu, 2013). The cities had to depend on the Government funds for the treatment plant. The State Government also upgraded two existing plants for better treatment and will complete the installation of a large treatment plant with a capacity of 50,000 m3/day (13.2 MGD) (Times of India[b], 2013). Though the State Govt. claims to have a buffer capacity of 18,000 m3/day (4.8 MGD), the deficit from previous reports is not equal to the capacity increase from the recent reports. Fig. 3 shows the capacity tallies for these two cities.

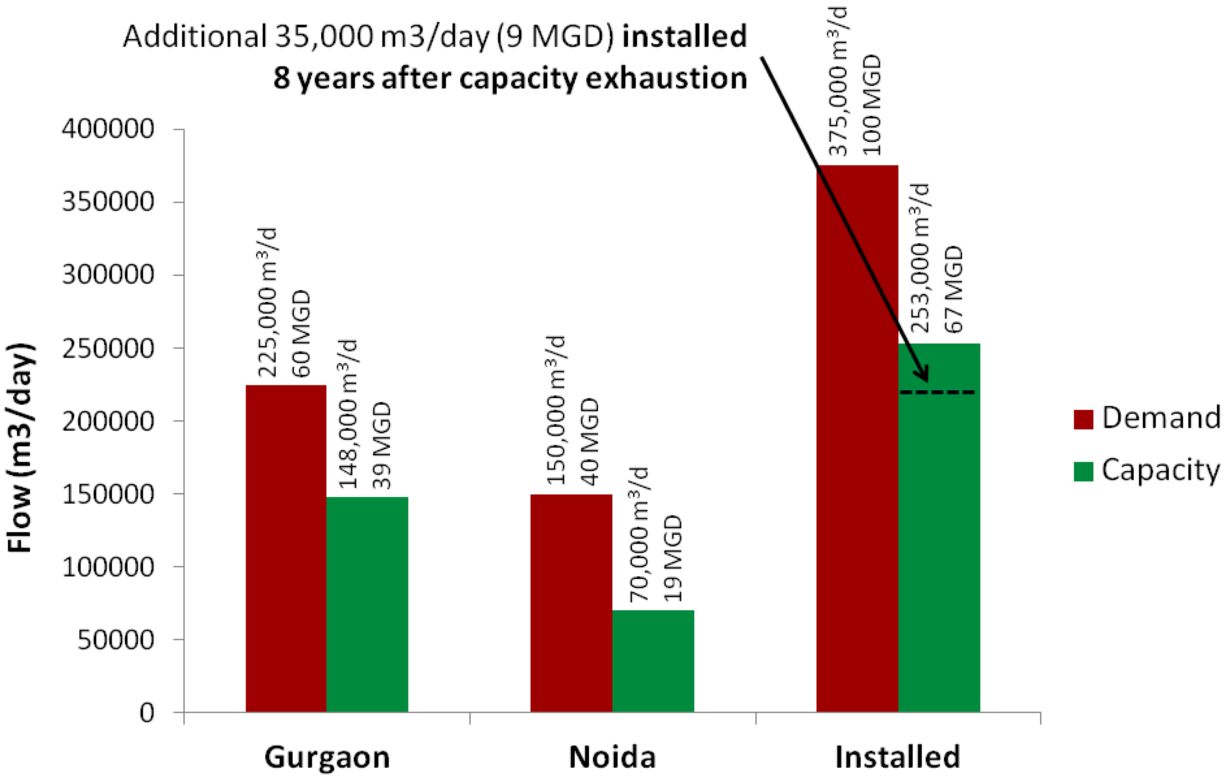


Figure 3.6 Treatment capacity deficit for Gurgaon and Noida

3.2.3 Developed Areas – Los Angeles Example

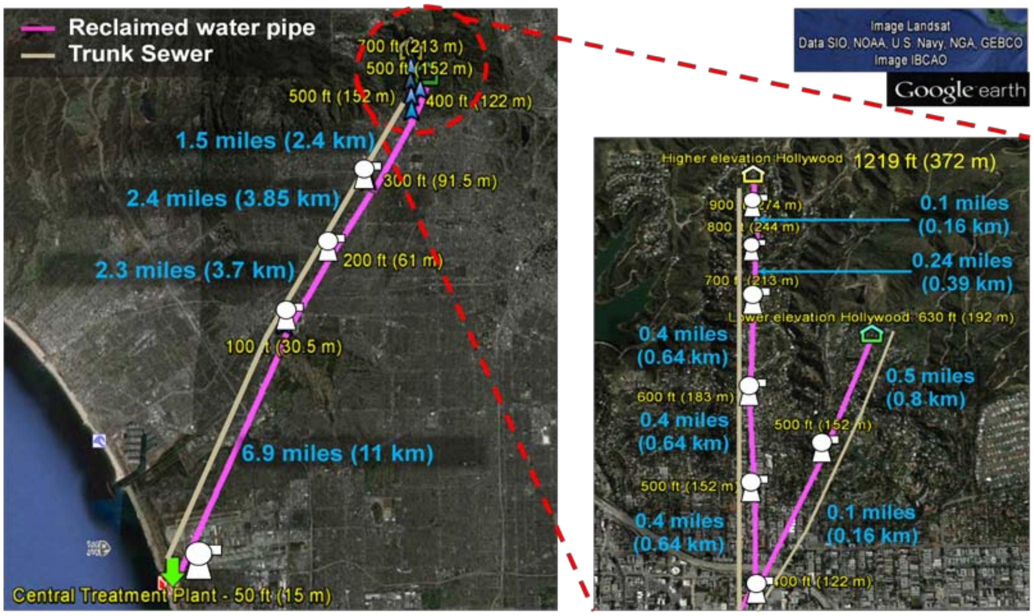
Since most urban areas in developed regions have existing collection and treatment systems, goals for wastewater management often include nutrient removal, energy recovery from solids and reclamation. Certain regions with arid and semi-arid climates are water-starved due to high urban growth. Southern California receives about 15 inches of rain every year in non-drought years. The demand for about 3,687,303 acre-feet (about 1200 billion gallons) is met mostly by imports and groundwater supplies (MWD, 2013). Metropolitan Water District imports water from the Colorado River and the Sacramento-San Joaquin River Delta. The City of Los Angeles imports water from the Owens River Valley (Freeman, 2008)

The City of LA and MWD are inclining emphasizing water conservation to reduce water demands. Though, these efforts have been successful, resulting savings are expected to approach a maximum value, short of our anticipated needs.. Hence these two authorities are also emphasizing water reclamation. In 2012, only 1% of the water demand was met by water reclamation, and efforts are being made to increase this fraction (Metropolitan Water District, 2012). It is necessary to improve reclamation techniques in terms of treatment and conveyance as well as reduce costs.

Wastewater collection networks are designed to use gravity flow and generally flow down gradient, with as few pump stations as possible. Reclaimed water supply networks are required supply water to consumers and are opposite to gravity sewer flow. Thus, they need to overcome elevations differences to distribute reclaimed water to the serviced area. This can be a hindrance in augmenting reclaimed water production and supply. Decentralized collection and reclamation can shorten conveyance distances and reduce the overall pumpback energy costs.

3.2.3.1 Local and treatment process characteristics

We analyzed the energy cost that centralized reclamation can incur in area of Hollywood in the City of Los Angeles, CA. Figure 3.7 shows the geographical location and extent of this area. To assess the preliminary feasibility of a decentralized system, we quantified its benefits and compare them with those of a centralized system. The trunks of the sewer and reclaimed water lines that we designed for this study bifurcated based on topography. Fig. 2 shows the reclamation pipeline direction and the bifurcation. It also shows the pipe lengths and the elevations at different points.



Lift station markers do not depict capacity

Figure 3.7 Locations of lift stations and reclaimed water pipeline direction

Table 3.1 describes the relevant demographics and flow characteristics. The distance from the central treatment plant is equivalent to the maximum distance of Hollywood's most distant borders. We assumed a uniform population distribution. (United State Census Bureau, 2012; Metcalf & Eddy Inc., 2002; Google Earth, 2012)

Table 3.1 Regional characteristics and assumptions for case study

Regional characteristics	**Value**
Population of Hollywood	123,000
Flow rate per capita	225 Liters/day (0.225 m^3/day)
Distance from central treatment plant	15.8 miles (25260 km)

Percent wastewater recycled	90%
Population density	7540 per sq. mile (2950 per sq. km)
Average Elevation for Hollywood	1219 ft (372 m)
Average Elevation for Central Treatment Plant	50 ft (15 m)
Central Plant: Flow treated	45 MGD (1.97 m^3/s)

Figure 3.8 shows the typical treatment train for which the treatment energy was calculated. We selected this treatment plant configuration to avoid skewing of the relation between the pump-back and treatment energy consumption because of expensive treatment. We sized each process according to required standards and calculated the cumulative energy consumption.

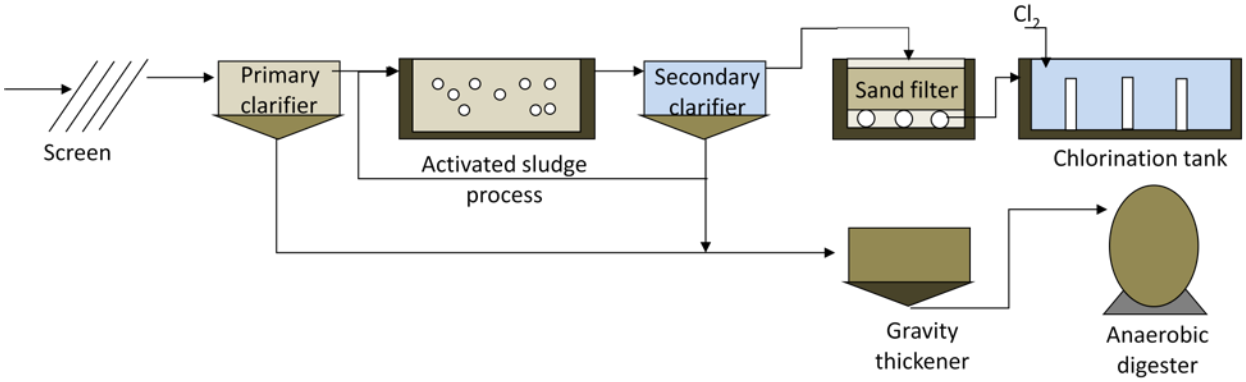


Figure 3.8 Hypothetical wastewater treatment configuration for analysis

We also compared it with the expected capital cost of a decentralized treatment plant. Aeration energy is usually 45-75% of the entire treatment energy consumption (Stenstrom, et al., 2008). Hence we analyzed the pump back energy consumption as a fraction of the aeration energy consumption. Using theoretical process design, we calculated the minimum area required for each plant. Fig. shows the centralized and decentralized scenarios for comparison.

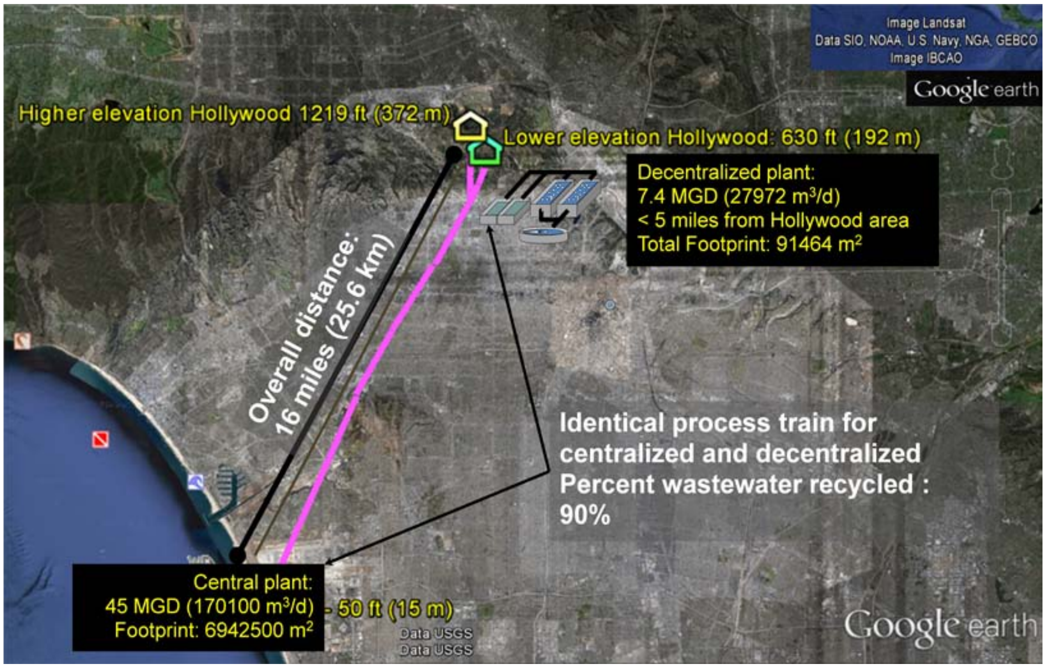


Figure 3.9 Hypothetical central and decentralized scenarios for Hollywood

3.2.3.2 Sewer Design

To design the trunk sewer, we computed the flow generated at every mile along the sewer direction. We estimated the wastewater generation per mile by calculating the flow on a per capita per unit length (miles) basis and designed each unit length for that flow. Sewers are commonly designed using empirical curves relating the depth of flow ratio (partial to full flow) to other ratios such as discharge, velocity, wetted area, wetted perimeter and hydraulic radius (Bizier, 2007). Such curves are tedious to use in a sewer design model without a large amount of interpolation and assuming linearity. Hence, we designed the sewer pipe for this distance, using two methods: iteration and theoretical design (Ott & Jones, 1988). For the iteration method, we used a suitable depth of flow and velocity of flow ratios (for partial to full flow) to iterate among different solutions. This takes several manual trials and an approximate estimate of the sewer size as an initial guess. The theoretical design involves calculating the sewer size and depth of flow from theoretical equations relating the sewer diameter and depth of flow.

For the iteration method, we used sewer design curves to determine the velocity of flow ratio from the maximum diameter ratio. We adjusted the sewer size to meet the constraints for velocity of flow and depth of flow ratios. After obtaining the desired pipe size and depth of flow ratio, we sized the pipe for that section. We applied this iteration technique to sections of entire sewer trunk at every mile.

For the theoretical design, we used explicit equations derived by (Ott & Jones, 1988). We created a routine in Matlab® to assume a sewer size, running in a loop to iterate the size as the flow depth ratio and velocity ratio requirement changes. Figure 4.8 describes the algorithm for designing an entire trunk sewer.

To design each link we used the theoretical equations derived by Ott and Jones (1988). This is one of the few published techniques that uses explicit theoretical equations to relate hydraulic parameters and ratios. The theoretical model considers two cases of flow: (1) Depth of flow ≤ Radius of pipe (2) Depth of flow > Radius of pipe. Figure 3.10 considers both these cases and show corresponding schematics of the sewer pipe.

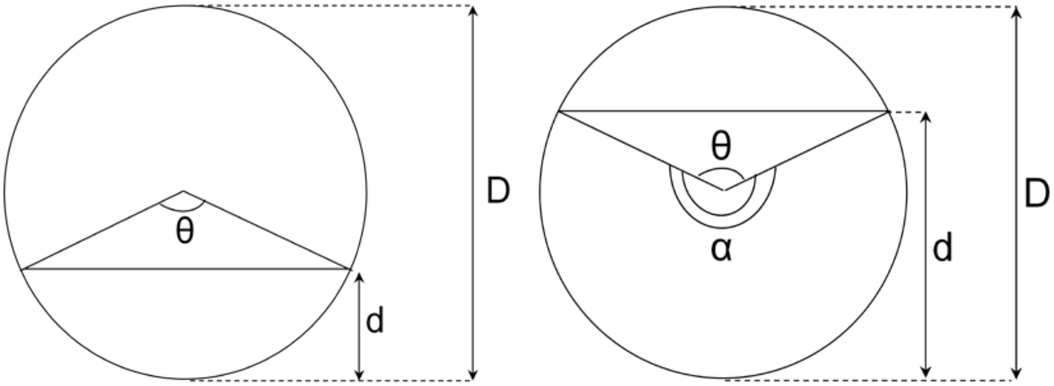


Figure 3.10 Sewer with partial flow (d/D ≤ 0.5) (left); Sewer with partial flow (d/D ≤ 0.5) (right)

Table 4.4 describes the theoretical equations and the corresponding variables for the two cases of flow. The equations for the higher depth of flow have been simplified by changing the use of the subtended angle. These equations were used in the iteration part of the model after choosing a potentially suitable pipe size using the hydraulic parameter constraints.

3.2.3.3 Pump-back energy consumption

We calculated the pump-back energy based on the topography of the region. As shown in Table 3.1, the distance from the Hollywood area to the central treatment plant is 16 miles (25.6 km). The Hollywood area is at an elevation about 360 meters higher than the location of the central plant. We used a preliminarily defined maximum static design head of 100 ft (30.5 m) for lift stations for the reclaimed water. From elevation data of the points in the direction of the reclaimed water pipeline from the central plant to Hollywood, we determined the positions of the pumping stations and the distances of the sections. We had to design each section of the reclaimed water pipe for full flow. We divided the reclaimed water pipeline into sections based on the initial placement of the pumping stations (100 m elevation gain).

We analyzed the sensitivity of the required pipe size and the power consumption due to head losses to change in flow velocity. Figure 3.11 shows the sensitivity analysis results. We assumed a design velocity of 0.9 m/s (Asano, 1998) for minimum frictional losses. We calculated the pipe size for each section for the flow in each pipe section and computed the total pump-back energy consumption for each section.

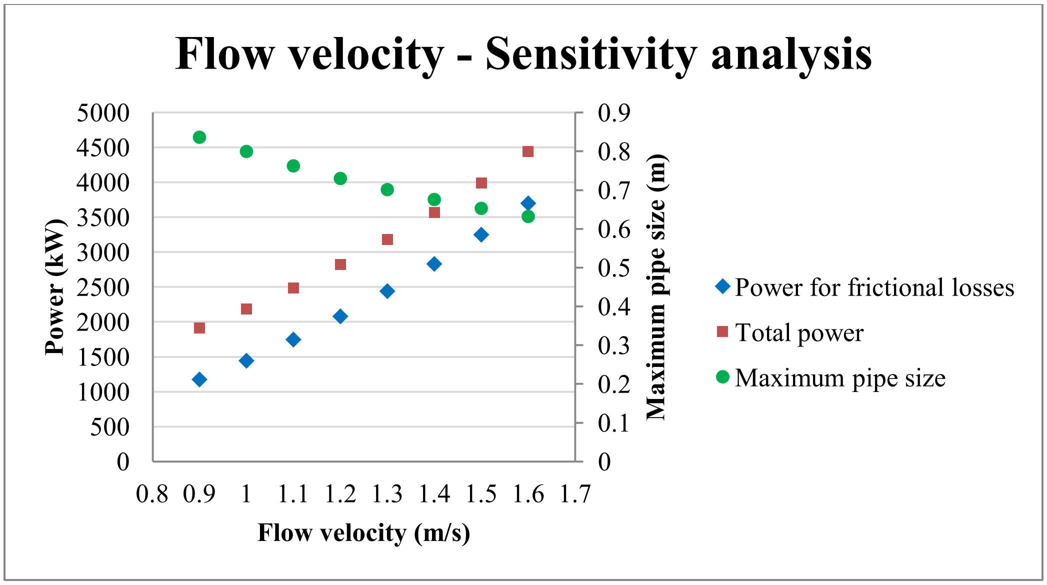


Figure 3.11 Sensitivity of full flow pipe size and energy losses to flow velocity

We surveyed pressure ratings for HDPE pipes and arrived at a desired working pressure of 150 psi (Polk County Utilities, 2010). We calculated the pumping head using the power equation given by Equation 3.1. To account from deviations from the assumed direction, we assumed that the actual length of each section of the pipe was 20% more than the straight line measurement. Fig. 3 shows the placement of pumping stations and trunk pipeline for reclaimed water supply.

Equation 3.1

$$P = \frac{\rho g Q h}{\eta}$$

P: Power (kW),

ρ: Density of water (N/m^3);

Q: Discharge in pipe (m^3/s);

h: Head (m);

η: Pump efficiency

3.2.3.4 Capital investment

We considered the capital cost of the decentralized treatment plant assuming the same treatment configuration. This cost was calculated based on capacity of the plant, using literature cost relationships that include economies of scale. This assumption simplified the determination of the capital cost of two plants of different capacities and identical treatment configuration. We conducted a literature review establishing and describing relations of cost with the capacity of the plant corresponding to various years. Table 3.2 summarizes these relations from different sources.

The entire set of equations was assessed for consistency by projecting the values from one year to the rest of the years. We used Producer Price Indices calculated by the Bureau of Labor Statistics (U.S.A) to project the values (US Department of Labor, 2012). The projected costs were not consistent with the reported values over the time period of the references. The most exhaustive data was reported in the 1978 and 1980 reports. Hence we computed a construction cost relation from the correlations from both these years and projected them to 2012. The relation is as follows.

Equation 3.2 (US EPA, 1978; US EPA, 1980)

$$\text{Cost (MGD)} = 3 \times 10^{6} \times capacity\ (MGD)^{1.0128}$$

The sewer cost is computed based on the (Los Angeles County Flood Control District, 1983) and the Producer Price Index developed by the Bureau of Labor Statistics, U.S.A. The reported construction cost per unit length of the sewer followed an exponential relation with the diameter (Figure 3.14). The Producer Price Index is a parameter which is used to project the production cost of a commodity to any desired year for which this index is available. (US Department of Labor, 2012). The complete table is in Table 6.2.

We calculated the cost for small treatment plants based on the EPA Report on Biological Nutrient Removal Processes and Costs, (2007) and the EPA cost-flowrate correlations from the years 1978, 1980 and 1992 (US EPA, 1978; US EPA, 1980; Qasim, et al., 1992; United Nations, 2003). We used this relation to compute a construction cost and projected it to 2012. As the decentralized plant belonged to the category of small treatment plants similar to those reported, one value of construction cost was computed using this relation.

Table 3.2 Literature review of relations between construction cost and flowrate of wastewater treatment plants **(US EPA, 1978; US EPA, 1980; Qasim, et al., 1992; United Nations, 2003; US EPA, 2007)**

Reference	Region	Source of data	Type of cost	Unit process	Regression	Variables
(US EPA, 1978)	U.S.A	Winning bids for Construction Grants Program for EPA	Construction cost, piping, excavation	Site work excluding excavation	$C=(1.12 \times 10^5)(3780Q)^{0.97}$	C = cost (dollars) Q=flow rate (m^3/day)
				Preliminary treatment	$C=(5.79 \times 10^4)(3780Q)^{1.17}$	
				Influent pumping	$C=(1.47 \times 10^5)(3780Q)^{1.03}$	
(US EPA, 1980)	U.S.A	Winning bids for Construction Grants Program for EPA	Construction cost, piping, excavation	Equalization	$C=(6.76 \times 10^4)(3780Q)^{0.60}$	C = cost (dollars) Q=flow rate (m^3/day)
				Oxidation ditch	$C=(4.68 \times 10^5)(3780Q)^{0.57}$	
				Rotating biological contactor	$C=(6.09 \times 10^5)(3780Q)^{0.77}$	
(Tsagarakis, et al., 2003)	Greece	National survey of MWTPs	Construction	Conventional ASP (whole plant)	$C=0.116X^{0.954}$	C = cost in 10^6 dollars per 1000 population equivalent X = plant size in 1000 population equivalent
(United Nations, 2003)	U.S.A.	Manufacturers, conceptual design and published data from USEPA report	Construction (1996 dollar values)	Screening and grit removal with bar screens	$CC = 674Q^{0.611}$	CC: Capital cost in dollars Q: average design flow in m^3/day
(Qasim, et al., 1992)				Conventional activated sludge with diffused air	$CC = 72Q + 368{,}043$	

3.3 Results and Discussion

3.3.1 Discussion for Developing Regions

3.3.1.1 Example 1 - Nagpur, Maharashtra, India - Nag River

The main obstacle for Nagpur in wastewater management is lack of land. Processes such as the UASBR or RBC can reduce the plant footprint, resolving land scarcity. The key is to install multiple small plants at economical and feasible locations. Political and corporate financing and endorsement is essential for implementation of wastewater management in such regions. Acquiring land as early as the planning stage may help prevent land disputes in the implementation stage. Acquiring a larger area of land can prove to be difficult due to several issues such as ownership and land cost. With decentralized wastewater management, the required land area for treating a certain demand can be fragmented into smaller pieces of land and can render more flexibility to project planning.

Community participation is a key requirement for wastewater management. This can be achieved by spreading awareness about the spread of disease due to lack of wastewater management. Especially in developing areas, the compromised source water quality compels residents to use expensive household water filtration devices, an inadequate replacement of wastewater treatment (Morrison, 2012). A small fee for installing a reliable treatment plant instead of expensive water filtration devices can be an incentive to install a reliable treatment system. Decentralizing wastewater management and entrusting it to individual residential communities, commercial complexes, universities and industrial sectors can improve community participation due to increased awareness and involvement.

3.3.1.2 Discussion for Example 2 - Gurgaon and Noida, India - Yamuna River

Though the State Government installed new treatment plants in Noida a decade after capacity exhaustion, we predict that the excess capacity will be exhausted in 3-4 years. A very conservative buffer capacity for future demand, the associated capital and dependence on inconsistent government funding are a problem for such cities. The construction and commissioning of utilities such as wastewater collection and treatment must parallel the rapid rate of development.

With decentralization, modularizing capacity expansion can reduce the required initial capital. Smaller treatment utilities or even package plants for individual communities require lesser time and capital at every step to build. With smaller plants, economy of scale becomes less significant, enabling selection of more modular treatment processes. Housing communities and commercial complexes can install 'Design-Build-Operate' treatment units with the occupants contributing to the capital through maintenance fees.

3.3.2 Results and discussion for Los Angeles Example (Developed Region)

We compared the centralized and decentralized configurations for three potential requirements to accommodate reclamation services for Hollywood.

- No Capital or Sewer expansion for centralized system (Only Pump-back energy consumption)
- Sewer expansion but no capital expansion for centralized system
- Both capacity expansion and sewer expansion for centralized system

3.3.2.1 Pumpback and treatment energy costs

The reclaimed water distribution system required an additional pump station for every pipe section for the 100 feet elevation gain, due to frictional losses and pipe pressure ratings. We calculated the pumpback energy required for every station and its location. Figure 3.12 shows the pumpback energy consumption at every lift station. A large part of the pumping energy is required to counter frictional losses. The reclaimed water conveyance over long distances incurs high frictional losses. Both these values correspond to wastewater generated only in Hollywood. The typical energy consumption for treating wastewater for an activated sludge plant is about 4000 kWh per million gallons treated (SBW Consulting, Inc, 2006). The total pumping energy for this scenario is about 7000 kWh per MG. Thus, we can see that the reclaimed water pumpback energy consumption is higher than the treatment energy consumption for the same flow.

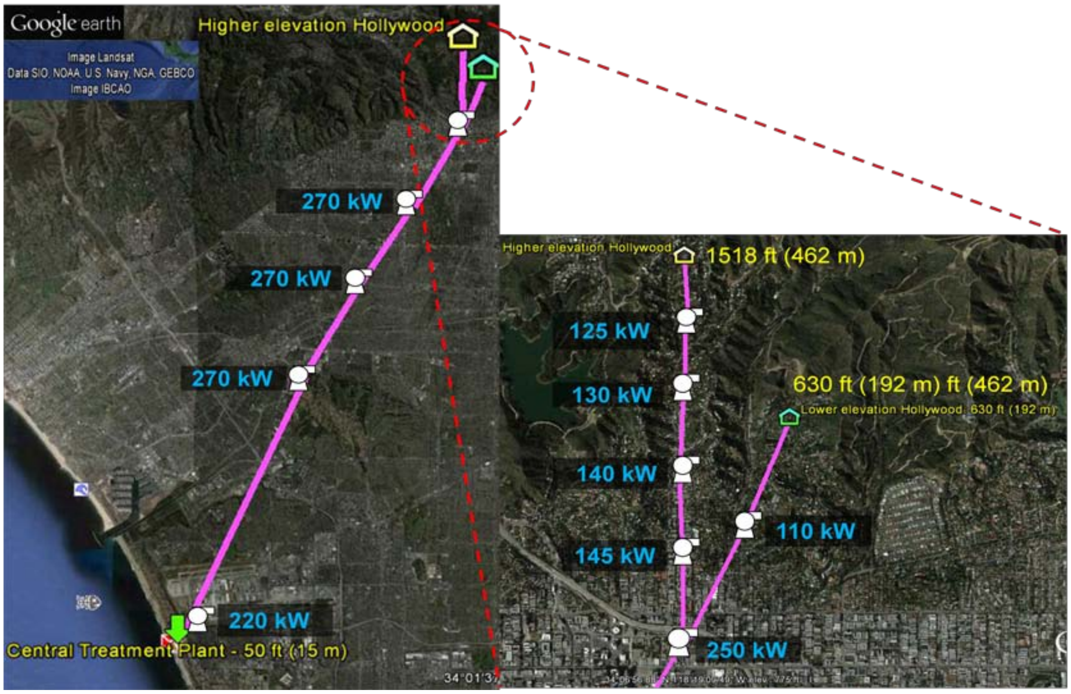


Figure 3.12 Pump-back Energy consumption for Hollywood, CA

We also calculated the cost of installing the reclaimed water pipeline. We referred to the City of Los Angeles reclaimed water installation report (CH:CDM, 2006) and calculated the pipeline cost. This cost includes both material and installation. We converted this cost to 2012 USD. Thus, the total cost for the reclaimed water pipeline is **$12,318,800.** Since we planned to locate the decentralized plant within a 5 mile radius of the Hollywood area, the reclaimed water cost was **$3,850,000.** Both these costs are for the flow from Hollywood only. Thus, the reclaimed water conveyance from the central plant can add to the infrastructure cost as well.

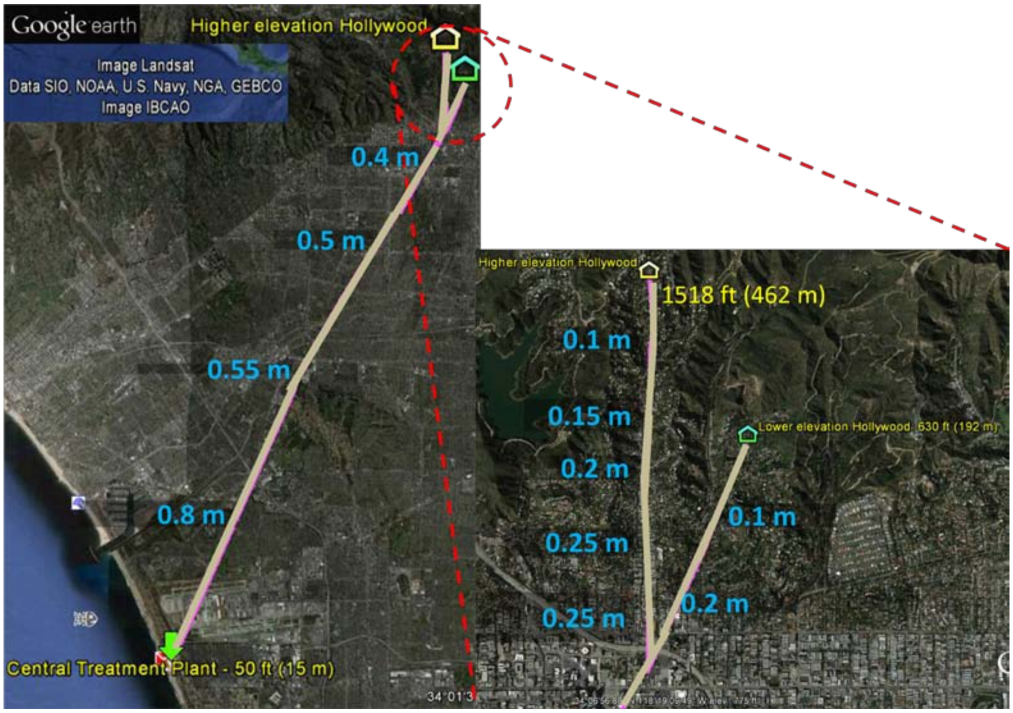


Figure 3.13 Designed sewer size for central collection network

We assumed that the cost of lift stations for reclaimed water distribution is 10% of that of a treatment plant. We considered the cost of multiple lift stations is 30% higher than that of a single station (US EPA, 1976). Thus we computed a total construction cost of all the lift stations as **$18,425,000.**

3.3.2.2 Sewer and reclaimed water pipe construction without capacity expansion

To connect Hollywood to the central treatment plant, the sewer diameter has to be enlarged to accommodate the flow. Figure 3.13 shows the increase in sewer diameter with flow for the same case. Near the central plant, the design diameter approaches **1 meter**. In case of decentralized treatment plant for Hollywood, the design trunk sewer diameter is **0.45 meters.**

Expansion of old sewers is more expensive than building smaller new sewers. The cost for the entire sewer is computed to be **$865,975,000** (Los Angeles County Flood Control District, 1983) and the Producer Price Index developed by the Bureau of Labor Statistics, U.S.A.) (US Department of Labor, 2012). Figure 3.14 shows the relation of construction cost of a sewer with its diameter for extrapolated till 2012. The construction cost for a main sewer trunk connecting the region to a decentralized plant at a radius of 5 miles is calculated to be **$6,004,500.**

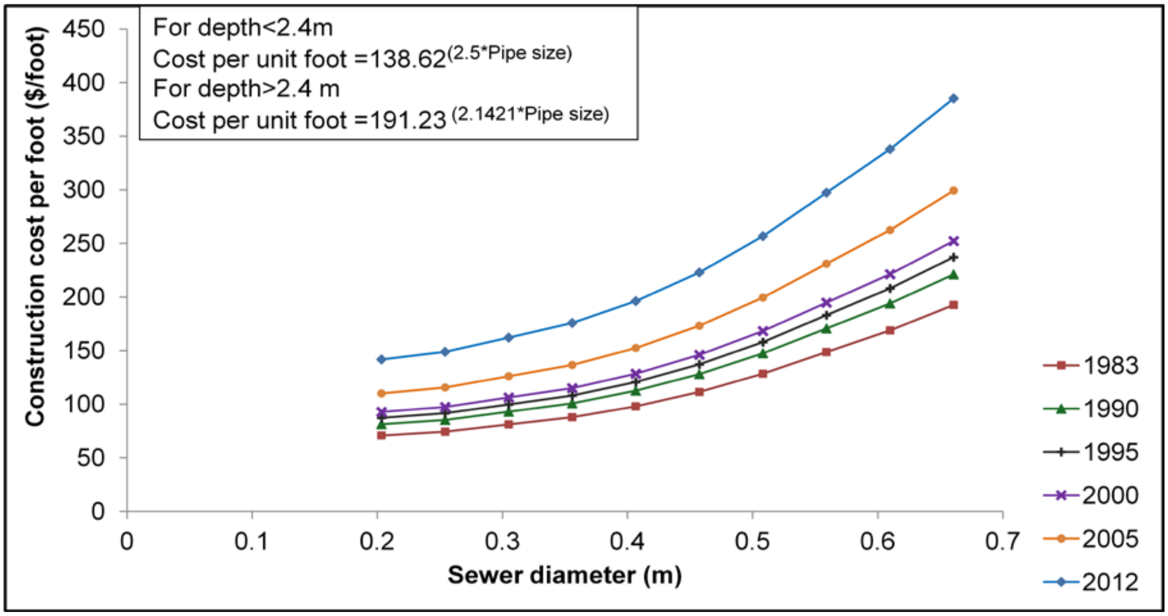


Figure 3.14 Variation of construction cost of sewer per foot with sewer diameter and time **(Los Angeles County Flood Control District, 1983)**

The construction cost of the decentralized treatment plant of the required capacity of 7.4 MGD was calculated to be in the range of **$22,776,000**. The upper limit of this range is a conservative estimate, since it estimates the construction cost of a BNR-based system rather than a conventional ASP-based system. Thus, construction cost for the sewer connecting to the central plant exceeds the combined cost of the decentralized treatment plant and the sewer connecting to it.

3.3.2.3 Comparison using capacity expansion cost for central treatment plant

The capital cost for central plant was computed to be in the range **$141,740,800.** The minimum expansion cost can be assumed to be 50% of the construction cost, i.e. **$70,870,400**. As compared to the combined cost of the decentralized plant **($22,776,000)** and the connected sewer **($6,004,500)**, the combined cost of expanding the sewer connecting to the central plant **($67,839,000)** and expansion of the central plant facilities **($70,870,400)** is much higher.

Table Comparison of decentralized and centralized options for Hollywood's wastewater management

Table 3.3 Comparison of decentralized and centralized options for Hollywood's wastewater management

Factor	**Centralized Plant**	**Decentralized Plant**
Pump-back energy consumption (reclamation)	0.26 MW/MG (1.9 MW totally)	Negligible
Reclaimed water pipeline cost	\$1.7 million per MG (Total: \$12,318,800)	\$0.5 million per MG (Total: \$3,850,000)
Sewer re-construction cost (with excavation)	\$2.86 million per MG (Total: \$128.7 million)	\$2.4 million per MG (Total: \$17.8 million)
Construction cost for WWTP	\$3.15 million per MG	\$3.08 million per MG
Expansion cost (50% expansion)	\$1.6 million per MG	\$1.54 million per MG
Pumpback stations cost	\$0.4 million per MG	\$0.3 million per MG

As we can see from Table 3.3, conveying reclaimed water from the central plant can be expensive in terms of infrastructure and energy. Reclaimed water piping has a relatively higher unit cost as compared to wastewater collection systems. Thus, the shorter the distribution network for reclaimed water, the more cost-effective reclamation can be. Distance from the serviced area can also be a key factor in the change in pumping losses. As the distance from the respective area increases, the reclaimed water distribution system counters significantly larger frictional losses. The probability of encountering more undulating topography increases with increasing distance of conveyance.

We can see in Figure 3.14 the cost per unit length increase with pipe size is higher than that with increased distance of piping. With larger flows of wastewater being conveyed to the central plant, the collection system cost can increase, either due to higher initial capital or expansion costs. With increased wastewater demand, central wastewater treatment facilities also require expansion. To support long reclaimed water distribution networks, pump stations require to be installed which can be a significant part of the capital investment.

For this case, the unit cost for treatment was approximately equal for the centralized and decentralized plant. But due to higher economy of scale in larger facilities, the unit cost of treatment capacity expansion is generally higher for decentralized systems than for centralized. Thus, it narrows down to a tradeoff between the higher economy of shorter wastewater and reclaimed water conveyance distance and that of larger treatment facilities. There are several other factors which can contribute to this tradeoff, such as labor cost and availability, need for reclamation, etc. Figure 3.15 is a simplistic representation of the factors affecting this decision.

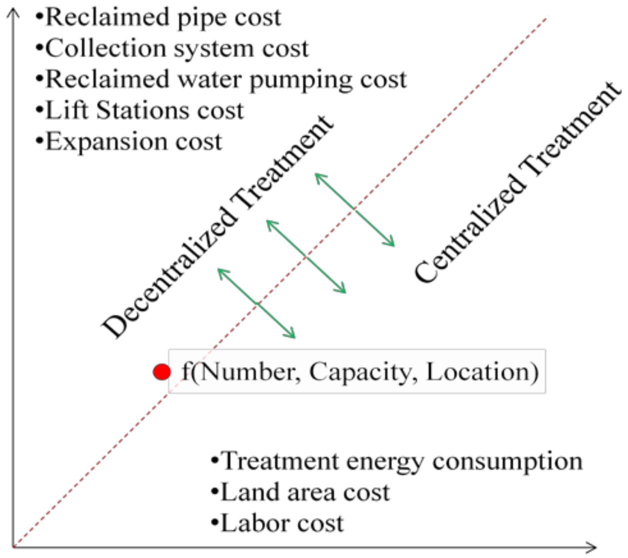


Figure 3.15 Tradeoff between centralized and decentralized treatment

A decentralized treatment system can be optimized and controlled more efficiently by utilizing the central treatment facilities for biosolids treatment, similar to the Los Angeles City D.C. Tillman and Glendale wastewater treatment plants. At these plants and upstream plants operated by the Los Angeles County Sanitation Districts, primary sludge, waste activated sludge, screenings and grit are all returned to the trunk sewers. This simplifies the distributed plant design and construction, and does not overload the trunk sewers, since these flows are typically less than 1% of the treated flow. In this case study, the decentralized plant was assumed to have biosolids treatment facilities.

In areas adjacent to water bodies, the recreational value of the water body can reduce, affecting real estate values and compromising the general well-being of the community. Since, decentralizing wastewater management can protect public health and water sources with reduced impacts to the ambience, it can be a more appealing alternative to residential communities.

There is a tradeoff between dividing the required land area into smaller parts and the acceptability of the distance of the service area from the plant. Smaller treatment systems occupying smaller land areas can be more environmentally benign due to smaller scale construction. Reduced impacts by construction can be more acceptable to isolated residential communities, such as Malibu.

3.4 Conclusions

Different locations have diverse constraints for a wastewater management system, such as lack of capital, land crisis, lack of electricity supply or skilled labor. It is important to tailor the wastewater management process train and network configuration to meet local requirements and choose an economical configuration. Decentralized plants can be modified to suit local needs which can promote complete wastewater collection and treatment and also reclamation. Decentralized plants are generally of small capacity reducing the required capital investment, which can be provided by the residents or occupants of the area. This can eliminate the dependence on funding from the Government which has been observed to be inconsistent in developing regions. In developing regions, this can ensure public health and source water protection thus fulfilling water demands by managing water resources more effectively.

For developed regions with more stringent water quality standards, decentralization can achieve improved energy-efficient reclamation which is advantageous for arid and semi arid regions. It can also be the cost-effective solution to fulfilling non-potable water needs for remote, developed communities. Pump-back power consumption of the recycled water, expansion cost of sewer lines and central treatment plant facilities determine the feasibility of installing a decentralized system for a new/remote region. Pump-back power consumption is a large fraction of the total treatment power consumption and can surpass aeration energy consumption. With the demand for recycled water on the rise, pump-back power consumption has to be controlled to make water reclamation more practical and economical. Thus, decentralized treatment can be an extremely practical and economic alternative for expanding communities and urban areas. Furthermore, it ensures access to wastewater treatment for remote regions. This study establishes the need to model decentralized treatment systems, in terms capacity, number of units and location.

Community participation is the key to implementing decentralization; hence it is necessary to spread awareness about the benefits of adequate wastewater treatment. Efficient wastewater management requires a nexus of public participation, water demand assessment and resource allocation stemming from geographical or local constraints. This study establishes the need to optimize decentralized systems and their planning further. There are several factors which need to be considered to determine the most suitable configuration for a given scenario. The next chapter discusses the methodology of optimizing decentralized systems that we devised, its applicability to certain typical scenarios and the most suitable solutions.

4 Optimizing Integrated Decentralized Wastewater Configurations for Improved Application

4.1 Introduction

In Chapter 2 we quantitatively established the need for access to proper wastewater management for public health protection. In Chapter 3, we discussed wastewater management concerns in developing and developed areas and demonstrated the applicability of decentralized treatment. Decentralization in terms of decisions, capital and reclamation can address wastewater management issues that emerge for remote wastewater sources or spatially expanding urban areas and can be more cost-effective, energy-efficient and reliable than centralized treatment. But we also inferred that effective decentralization requires the optimization of network and treatment facilities configuration. In this chapter, we formulated a detailed hydraulic and network design model using the Genetic Algorithm for decentralized configurations. We studied several typical configurations and devised suitable solutions for them. We also discussed several optimization algorithms and previous attempts at optimizing various components of a wastewater management system.

4.2 Previous studies for optimizing decentralized systems

Several optimization/planning algorithms have been developed for both centralization and decentralization of the system. Some of these have been included in Chapter 1 (Adams & Gemmel, 1973; Yao, 1973; Rossman & Liebman, 1974). Converse (1972) used dynamic programming to evaluate the minimum cost solution for a linear system of sources discharging to a river system. Conagha and Converse (1973) applied a heuristic algorithm to a specific example which involved a decomposition mechanism to optimize subsystems. The algorithm makes cost-based decisions between treating or piping the generated flow for each point. It checks each step for consistency in decisions for each point and then proceeds. Joeres (1974) devised a planning methodology for minimum cost using simplified cost and flow assumptions for collection and treatment units. They used a piece-wise linearized cost curve for varying demand. The authors deduced from the results that the lowest linear cost curve estimates would not be exceeded, although linearizing collection network costs must decrease accuracy. Their results indicated that a certain degree of decentralization for part of the region is more economical than the centralized option.

Whitlatch Jr. and Revelle (1976) developed a heuristic algorithm to regionalize (centralize) a wastewater system with two effluent quality constraints, namely at plant level and an integrated level. This algorithm adopted a weighted distance approach for network optimization with linear waste sources and unidirectional (no bypass) assumptions for wastewater flow. For plant location they used linear programming to compare with local decentralized alternatives for minimum cost and best effluent quality. To assess the cost-effectiveness of regionalization, they evaluated the cost of each plant at each step in the algorithm, and consolidated ineffective plants. Brille Jr. and Nakamura proposed a branch and bound method in (1978) and (1979)to resolve the same problem and extended it using a matrix index system to compare two alternatives which can achieve varied objectives.

Ocanas and Mays (1981) devised a minimum cost algorithm to supply fresh and reused water to a region with quality and source availability constraints using the Large-Scale Generalized Reduced Gradient method. This method involves a condensation of multiple variables into a few basic variables, eventually forming a one directional search to find the optimum solution in the “super-basic” constraints. They applied this method to a hypothetical example for three different effluent water quality scenarios involving three freshwater sources, two water treatment plants, four users, and two wastewater treatment plants. Zhu and Revelle (1988) proposed the Balinski Siting Model to resolve optimal siting for proposed linearly located treatment plants without bypassing and a fixed level of treatment and unknown and unconstrained effluent quality. Though it has the advantage of being a linear model, it can only be reliable as a preliminary siting model; the wastewater source and the treatment facility must have a one-to-one relation, since intermediate treatment points are not allowed. Chapter 1 describes the approach by Deininger and Su (1973) to compare individual solutions to regional solutions.

4.3 Applicability of Optimization Algorithms

Many of the algorithms used to optimize decentralized configurations for a given problem area rely on branching from a good approximation for an initial point. A more randomized approach, independent of the initial point can be more capable of arriving at the optimal degree of decentralization. This randomization can be applied to determining the treatment plant locations and capacities, and network layout. The following section reviews the nature of the algorithm.

4.3.1 The Genetic Algorithm

The Genetic algorithm is a heuristic method that is analogous to the concept of natural selection. Table 4.1 describes the terminology that this algorithm uses. It randomly generates a set of chromosomes called a population, denoting values for the decision variables. It passes the decision variables specified by each chromosome through the user-defined fitness function which calculates the objective to be minimized or maximized. The chromosome can be constrained for feasibility by providing various conditions ("environmental constraints"). On evaluating the fitness function for the given set, the algorithm ranks the set from the best ("fittest") to the worst.

Table 4.1 Terminology for the Genetic Algorithm **(Langdon, 1998)**

Chromosome	A bit string which represents and describes a candidate solution composed of "genes" or bits representing various decision variables. In a binary genetic algorithm, the '1's represent the existence of a certain component , whereas '0's represents its non-existence.
Population	A group of interbreeding "chromosomes" or candidate solutions
Generation	Sequential evolutionary stages of "populations" developed from "breeding" or combinations within the "populations".
Fitness Function	Function which evaluates a "chromosome" or candidate solution
Mutation	Random change in characteristics of a "gene" or bit
Mating	Creating a new "chromosome" for the new generation by combining parent chromosomes or "crossing over" various parts of the parent chromosomes
Convergence	Tendency towards a static, optimal "population" of identical "chromosomes" or candidate solutions

For the next iteration of candidate solutions, the algorithm selects a fraction of the best candidate solutions, based on a user-defined selection rate (which is generally 50%). The algorithm then uses the threshold selection to generate the next set. This method selects candidate solutions that exceed a certain threshold value in performance. It uses "mutation" and "crossover" to generate new chromosomes to combine with some of the fittest "parent chromosomes" to create a new "population". It pairs the fittest chromosomes to form new chromosomes relying on several pairing methods, such as top-bottom, random, weighted random pairing and tournament selection.

A description of various pairing techniques is given below. The algorithm continuously uses these techniques until it finds a new set of parent chromosomes based on the fraction selection.

- Top-bottom method: This technique pairs even and odd pairs sequentially from top to bottom.
- Random method: This technique pairs randomly picked chromosomes.
- Weighted random/Roulette Wheel method: This technique assigns mating probabilities to the parent chromosomes depending on associated weighted costs. There are different types of weighted pairing methods.
    - Rank weighting: This method calculates the probability of mating from the rank of the parent chromosome using the following relation.

$$P_n = \frac{N_{keep} - n + 1}{\sum_{n=1}^{N_{keep}} n}$$

P_n = Probability of chromosome ‘n’ being selected for mating

N_{keep} = Number of parent chromosomes from previous generation

    - Cost weighting: This technique calculates the cost of each chromosome normalized by the lowest cost of the discarded chromosomes in the population and ranks the chromosomes accordingly. The probability is given by the following relation.

$$P_n = \frac{C_n}{\sum_{m}^{N_{keep}} C_m}$$

P_n = Probability of chromosome ‘n’ being selected for mating

N_{keep} = Number of parent chromosomes from previous generation

C_n = Cost of each chromosome normalized by lowest cost of discarded chromosomes

- Tournament selection: This technique selects the fittest chromosomes from smaller subsets of the population. This technique paired with threshold pairing for large population sizes.

The algorithm goes through several "generations" of "populations" to seek a global optimum. The global optimum cannot be guaranteed to be an absolute optimum, as it is a heuristic method. Yet, this algorithm has produced sufficiently accurate results in previous studies which are discussed further.

After pairing the parent chromosomes, the algorithm randomly selects a crossover point to divide the bit string of each parent chromosome to create two different offspring chromosomes. Also, the algorithm changes parts of the bit strings of the parent chromosomes to create new chromosomes. This technique is called "mutation". Mutations introduce newer components to a pre-defined part of the next generation, independent of parent chromosome characteristics and avoid inadequate number of iterations. These do not occur in the final iteration or on the best chromosomes, thus rendering this algorithm "elitist".

The algorithm stops after converging, that is, producing new generations when it arrives at a population composed of the same chromosomes. We used the Binary Genetic Algorithm for our study. A binary genetic algorithm follows the same procedure as the other type of genetic algorithm, the continuous type, but stores its chromosomes in binary bits. The continuous genetic algorithm stored its chromosome bits in floating point numbers. The binary genetic algorithm is more suited to this particular problem as the decision variables denote the existence of collection system components or treatment facilities. Figure 4.1 summarizes the flow of the Genetic algorithm. The Genetic Algorithm requires a feasible initial population to proceed to convergence.

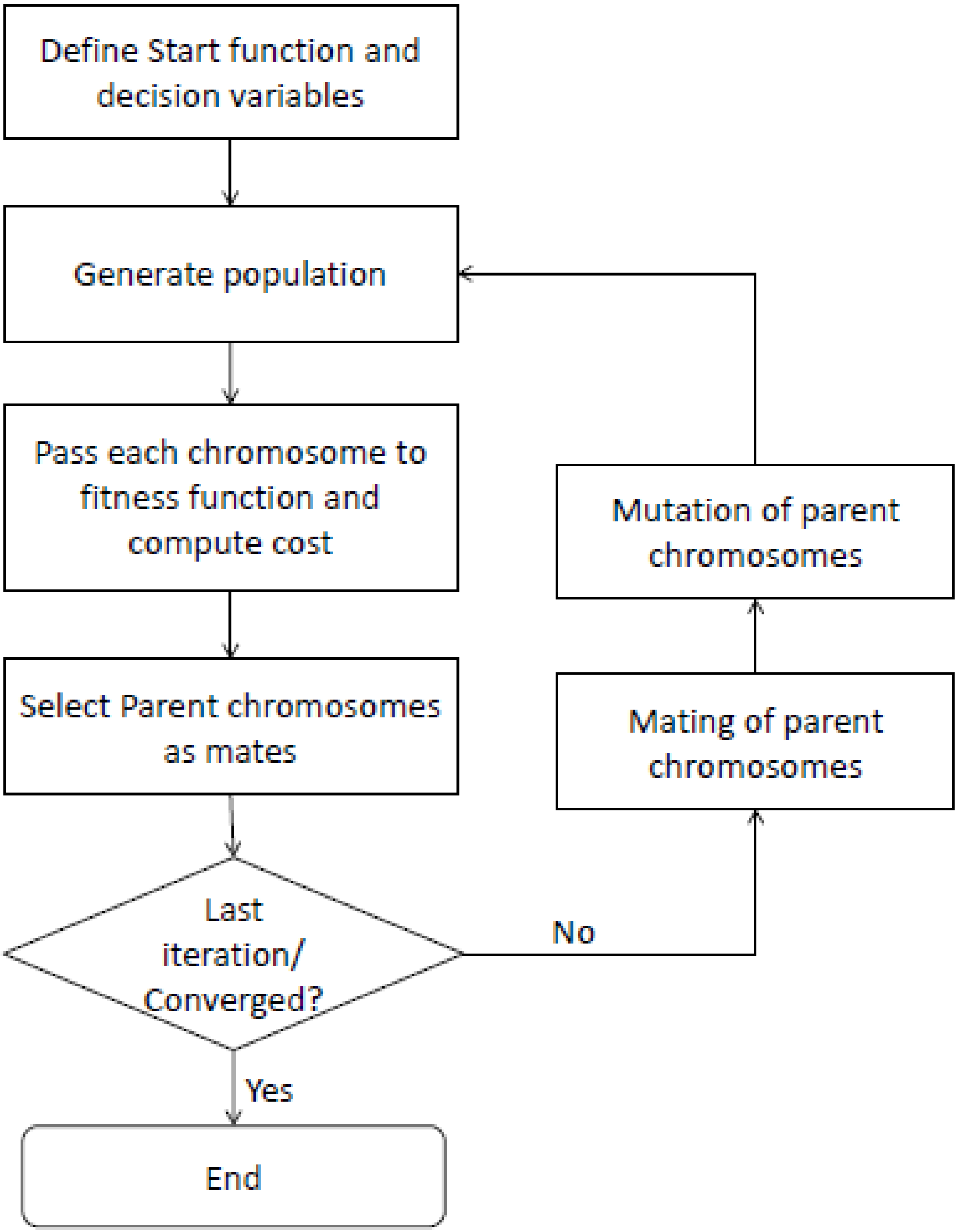


Figure 4.1 Flowchart for Genetic Algorithm

Several studies applied the Genetic Algorithm (GA) to wastewater management problems. Guo et al. combined the genetic algorithm with cellular automata to design sewer collection systems with only collection, no reclamation and one outfall in (2007) and storm sewer collection systems in (2008) respectively. The Cellular automata method addition to the genetic algorithm used a grid of distinct cells, with corresponding characteristics which vary in every generation according to previous states and neighboring cells. Their objectives were to minimize flooding within a sewer system and the capital cost. They used the Non-Dominated Sorting Genetic Algorithm II in which populations were generated by a dominance factor chosen by Pareto principle (the 80-20 rule). A large population of preliminary solutions from the cellular automata algorithm is fed to the GA to obtain a good initial point.

Pan and Kao (2009) used the GA with quadratic programming for cost functions, which is simpler to execute than piece-wise linearization of cost, which the older studies used. The algorithm was constrained for a minimum pipe size for flow transfer and sequential increase in pipe size based on flow patterns. In addition to collection pipes, they provided pumping stations in the design, wherever necessary. The selection criterion for a chromosome to the next generation depends on the significance of the fitness function value with respect to other chromosomes. The QP function considers the excavation, manhole, pumping station and pipe costs. Haghighi and Bakshipour (2012) used the Adaptive Genetic Algorithm to hydraulically design the collection system by varying the pipe size and slope subject to the constraints used by Pan And Kao (2009). They applied the method to an existing sewer network of 79 pipes and 80 manholes with and without pump stations. If the genetic algorithm is used to perform the entire hydraulic design, such as choosing pipe diameters, the number of constraints significantly increases and complicate the generation of an initial population.

Sewer network with wastewater treatment plants:

Several studies used the GA to optimize collection networks with treatment facilities. Chapter 1 discusses Converse (1972) as a study on heuristic optimization methods to study the impact of linearly discharging systems and Conagha et al. (1973) used the decomposition algorithm to solve a problem involving seven treatment plants more efficiently.

Leitao et al. (2005) focused on remote communities with low population densities, which is an interesting decentralization problem. They inferred that using distance models which maximize coverage that a single facility location can provide (measured by maximum weighted distances from the location) can be uneconomical for such remote locations.

They applied two "greedy type" algorithms, the “Add” and “Drop” algorithms, which select local optima in treatment facility location to eventually reach the global optimum. The Add algorithm begins with locating a treatment facility optimally for minimum overall collection and treatment cost and continues till the overall cost begins to increase. The Drop algorithm removes the treatment facility which reduces the overall cost most significantly and continues until the cost no longer decreases. They developed a model for design of linear structures to locate collection systems conveying flow from each community to the facility, aided by the Digital Terrain Model (for topographical data).

They applied this model to an agglomeration of 87 rural areas in Portugal of 2000 inhabitants each, comparing to a control case of one treatment facility per village. The Drop algorithm provided a more economical solution in this scenario with 21 treatment facilities, reducing the degree of decentralization from the control case. This method has a potential disadvantage in that choosing the local optima can mask a possible global optimum, especially for a large problem area.

Diogo and Graveto (2006) discussed the applicability of the Enumeration model and the Simulated Annealing Model to the collection network problem with a central treatment facility. This algorithm starts with a network layout, followed by shifting the network in its immediate vicinity in several steps to obtain an optimum. The algorithm progresses to the neighboring solution based on the difference in the cost for each candidate solution and the "temperature" or the size of step for each progression. The Simulated Annealing Algorithm is stochastic and computationally faster than the enumeration, with a reasonable approximation of the global optimum as compared to the brute force of the enumeration method.

Cunha et al (2009) applied the simulating annealing algorithm to a completely decentralized configuration to three case studies involving 38 population centers with rivers crossing them for varying topography and water quality requirements. There were 8 possible linear locations for treatment plants. The algorithm provided solutions for all 3 cases within reasonable computational time. Yet, the results were highly dependent on the initial network selection and were at the risk of not varying significantly from the initial design depending on the number of iterations.

Brand and Ostfeld (2011) used the Genetic algorithm to minimize network cost using collection system sizes, slopes and the demand as decision variables. They applied this technique for proof of concept to a simplistic example of two cities with options of three possible treatment plants followed by a central collection point with corresponding collection pipes. Increasing the problem size and complexity will complicate the applicability of the genetic algorithm due to added constraints. Also, decentralized collection systems generally carry smaller flows which cannot ensure a flow ratio of 80%, which this study assumes. The increased iterations needed to perform the hydraulic design of a smaller collection system can complicate the optimization further.

4.4 Methodology

The base setup for a region is a grid made up of cells with associated local characteristics and decision and solution variables. The resolution of the cells and grid is variable based on the expanse of the area and its division into individual cells. The division of the region is orthogonal, thus creating a road network which can possibly be a combination of orthogonal or diagonal roads. The wastewater collection network can potentially be along the road network. The algorithm designs the individual links of the collection network and connects them to form the optimal network. Figure 4.2 shows the grid, cells, possible road/sewer network, and individual characteristics.

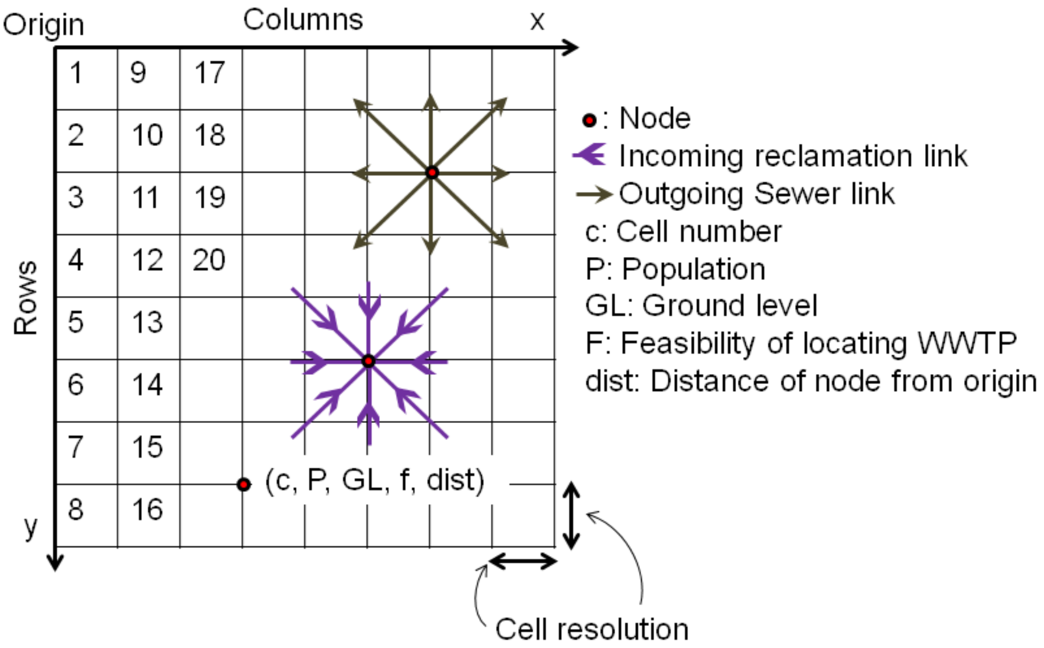


Figure 4.2 Schematic showing components of the local grid

4.4.1 Characteristics

Each cell in the grid has a corresponding set of input characteristics, decision variables and solution variables, which are described in Table 4.2. These are user-defined variables which define the various scenarios for that particular grid in terms of rows and columns.

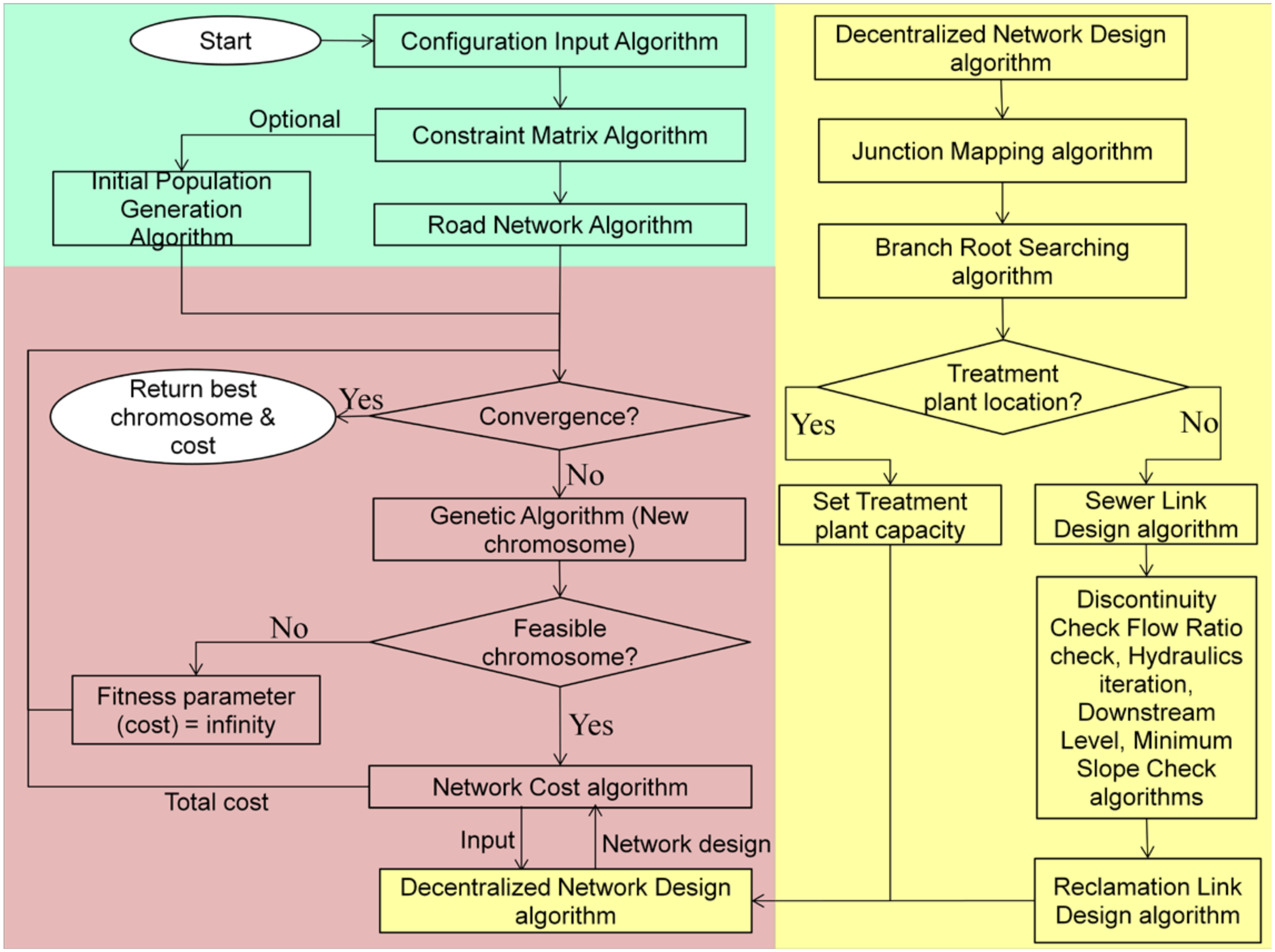
Table 4.2 Types of variables corresponding to each cell in the grid

Variable/component	Description
Cell number (Input)	The number allotted to each cell. The cell number increases vertically downward for each column as shown in fig.
Demand (Input)	Population in each cell
Resolution (Input)	Size of each cell
Coordinates (Input	Cartesian coordinates of each cell in the grid as shown in fig.
Feasibility (Input)	Feasibility of locating a treatment facility in a cell
Sewer variables (Intermediate and Output)	All variables for a designed sewer pipe for a node are stored here: size, invert levels, slope, cumulative flow, lift station, flushing station, drop manhole, flow ratio, depth of flow ratio, partial velocity and full flow and velocity
Reclamation variables (Intermediate and Output)	All variables for a designed reclamation pipe for a node are stored here: size, pumping head, slope, cumulative flow, velocity
Wastewater treatment facility variables (Intermediate and Output)	The capacity of a wastewater treatment facility is stored here

These input variables are passed to the genetic algorithm. The fitness function for the genetic algorithm is a cost calculation algorithm. The hierarchy, sequence and function of the various algorithms nested in the fitness function are described as follows. The nesting sequence specifies the calling (parent) function of each algorithm and their order of appearance. All the symbols used in equations describing the methodology are described in the List of symbols section in the beginning of the dissertation.

4.4.2 Algorithms

All these algorithms are implemented in Matlab 2013a. We converted the general genetic algorithm toolbox function to a binary genetic algorithm function by restricting the chromosome to binary bits by using the integer constraining option. In Matlab 2013a, this allows usage of inequality constraints but not of equality constraints to define feasible chromosomes. Fig. shows the outline of the optimization using the genetic algorithm of the entire decentralized configuration .



4.3 Optimization of decentralized configurations using the genetic algorithm (Different colors represent he functionality: Light green (top): Grid characteristics and input matrices; Pink(left bottom): Optimization; Yellow(right): Hydraulic and network design

4.4.2.1 Configuration Input Algorithm

This algorithm sets up the size of the grid and the user-defined input variables for the grid. It also calls the Road Network algorithm to set up the potential road network and chromosome length for the grid. It uses the chromosome length, grid size and infeasibility specifications to call the Constraint Matrix function to set up the inequality and equality constraints for the grid. Using these constraints it calls the Initial Population Generation matrix to define and initial population to seed the genetic algorithm. Since we used the binary genetic algorithm, we defined [0, 1] as the possible chromosome bits. It sets various options for the genetic algorithm such as the population type (double), the population size (generally 500, subject to convergence) and the initial population. The algorithm then passes the Network Cost Algorithm as the fitness function to the genetic algorithm.

4.4.2.2 Constraint Matrix algorithm

This algorithm includes several feasibility and network constraints in the form of equality and inequality constraints. There are one equality and two inequality constraints (A_{ineq}, A_{eq}). This algorithm creates a matrix representing the bits in the chromosome which can be combined to constitute the infeasible condition. Each bit in a chromosome represent a network component, and a bit value of '1' represents its existence, whereas a bit value of '0' represents its nonexistence. Multiplying the chromosome with this matrix checks if the existing network components create an infeasible condition. To restrict the chromosomes to feasible conditions only, this algorithm defines a matrix of boundary values for products of the chromosome and the constraint matrices (b_{ineq}, b_{eq}). The constraints take this general form.

Equation 4.1

$$A_{ineq} \times chromosome \leq b_{ineq}$$

Equation 4.2

$$A_{eq} \times chromosome = b_{eq}$$

The constraints are described as follows and are represented in Figure 4.3.

1. No circular links in pairs: This is an inequality constraint that ensures that two links do not form a collection feedback loop with one another, so that wastewater from all nodes is collected effectively to convey to a treatment facility.
2. No treatment plants at infeasible locations: This is an inequality constraint. We can define infeasible locations for treatment facilities in the grid based on land use patterns and land costs in the Configuration Input Algorithm. This constraint restricts the location of any treatment facility to feasible cells according to user-defined conditions.
3. One outgoing sewer link or treatment plant at each node: This is an equality constraint which ensures that every node is included in the network by the chromosome. This is achieved if the node has either a sewer link originating from it or a treatment plant located at it. A treatment plant located at a node treats the wastewater generated in the cell represented by the node itself. This constraint also restricts the node to only one outgoing sewer link. Integer constrained genetic algorithms (in this case, binary genetic algorithms) in Matlab 2013a do not accept equality constraints. Hence, we defined the equality constraint using two inequality constraints.

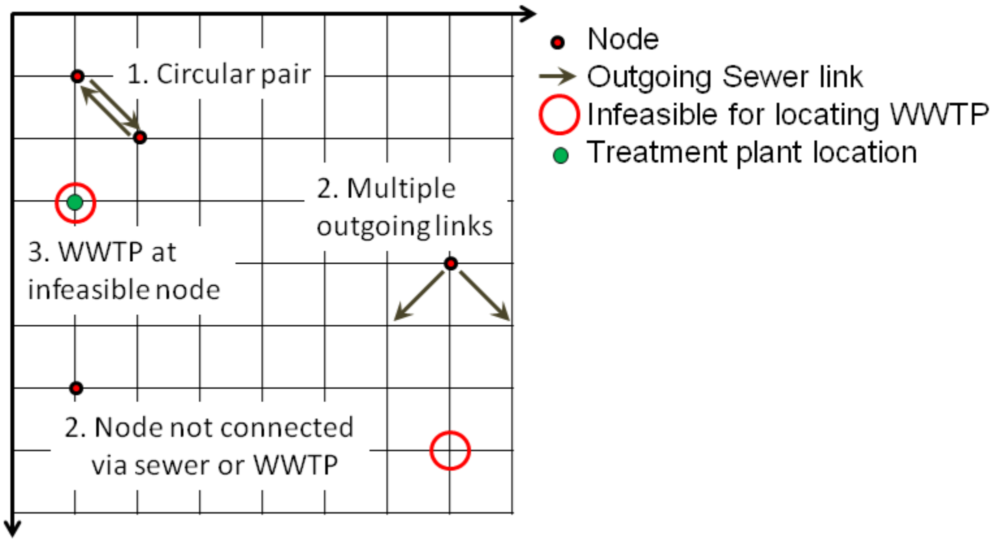


Figure 4.4 Infeasible conditions rejected by the Constraint Matrix Algorithm

4.4.2.3 Road Network algorithm

The collection network is assumed to be parallel to the road network. This algorithm creates the potential road network for a given grid. The road network for each node is built using immediately adjacent cells. This network also stores the feasibility of locating a treatment plant at particular node using user-defined feasibility conditions. Figure 4.4 describes the algorithm.

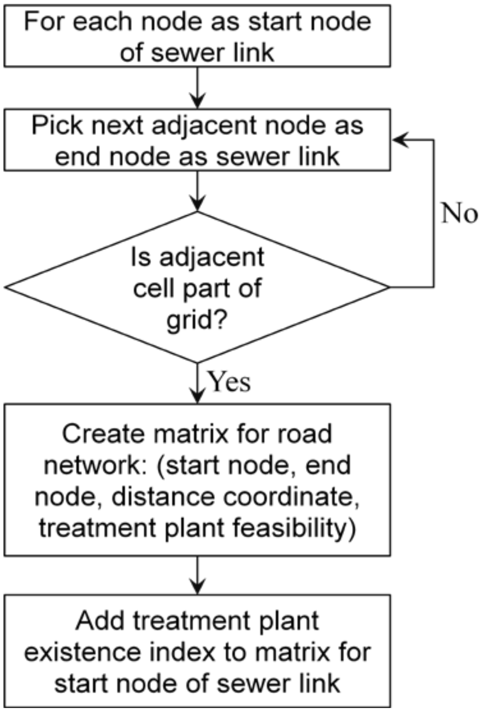


Figure 4.5 Procedure of Road Network algorithm

Initial Population Generation algorithm

The genetic algorithm requires a feasible initial population to converge. Due to the size of the grid and the number of possible chromosomes, the genetic algorithm can fail to select a population which fits the constraints. Hence we created the constraint matrices outside the genetic algorithm to create a feasible initial population to seed the genetic algorithm. This directs the genetic algorithm towards feasible chromosomes. This algorithm randomly generates a population of chromosomes subject to the feasibility constraints used in the constraint matrix algorithm. We stored this initial population and used it to seed the genetic algorithm for the corresponding grid to economize on computational time.

4.4.2.4 Network Cost algorithm (fitness function)

This algorithm is the fitness function that calculates the capital, energy and operation maintenance cost for a network configuration specified by a particular feasible chromosome. If the generations consequent to the initial population pass an infeasible chromosome to the network algorithm, the algorithm returns the total cost as infinity, forcing the genetic algorithm to search for better chromosomes.

If the genetic algorithm passes a feasible chromosome, this algorithm calls the Decentralized Network Optimization algorithm to design the network specified by the chromosome. The cost algorithm then receives the designed network from the called function to compute its cost. Table 4.3shows the various cost and energy computation relations and their sources that the algorithm uses. Cost relations specified for particular years were converted to 2013 costs using the appropriate producer price indices.

Table 4.3 Relations for capital and operating cost and energy consumption estimation

Type of cost	**Mathematical relation**	**Reference**
Wastewater/Reclamation lift station energy consumption	$\frac{(\rho \times g \times flow_{cumu} \times z)}{\eta}$	
Sewer link cost	$138.62^{2.5 \times dia} \times l$ for invert level ≤ 2.4m $191.23^{2.1421 \times dia} \times l$ for invert level > 2.4m	(Los Angeles County Flood Control District, 1983)
Wastewater treatment facility cost	$3 \times 10^6 \times (flow_{mgd})^{1.0128}$	(US EPA, 1978; US EPA, 1980)
Wastewater/Reclaimed water lift station cost	$10\%\ of$ wastewater treatment facility	(US EPA, 1976)
Reclamation link cost	Survey: USD per foot (for various pipe sizes)	(SBW Consulting, Inc, 2006)
Electrical rates	\$0.15 per kWh	(US Energy Information Administration, 2013)
Net Present Value (operation and maintenance, pumping energy consumption,	$\frac{1}{(1+i)^n} \times A$	
Annual operation and maintenance cost	$(1.03 \times 10^5 \times cap^{0.776})$ $\dots for\ year$ 1981	(US EPA, 1981)

4.4.2.5 Decentralized Network Design Algorithm

This algorithm is called by the Network Cost Algorithm to design the network according to a given chromosome. The fitness function passes the grid characteristics and the road network to this algorithm. Figure 4.5 shows the procedure followed by this algorithm. The algorithm then returns the designed network to the Network Cost algorithm. This algorithm calls many sub algorithms to design the network. The following sections describe these algorithms.

4.4.2.6 Junction Mapping algorithm

The Decentralized Network Design algorithm calls this algorithm to map out junction nodes, primary nodes and dead-end nodes. Junction nodes have multiple branches intersecting at one point. Primary nodes are the beginning nodes of a particular network branch which do not have any upstream nodes. Dead-end nodes are ending nodes of network branches which do not have any downstream nodes. This algorithm uses a basic counting algorithm to categorize all the nodes in these categories. It also returns the number of upstream branches intersecting at a particular junction.

4.4.2.7 Branch Root Search algorithm

The Decentralized Network Design algorithm calls this algorithm when it encounters a junction node. It returns the upstream primary node of each branch connecting to a particular junction. The Decentralized Network Design algorithm then starts designing the network from that primary node, going downstream after each node. If it encounters a junction again, it follows

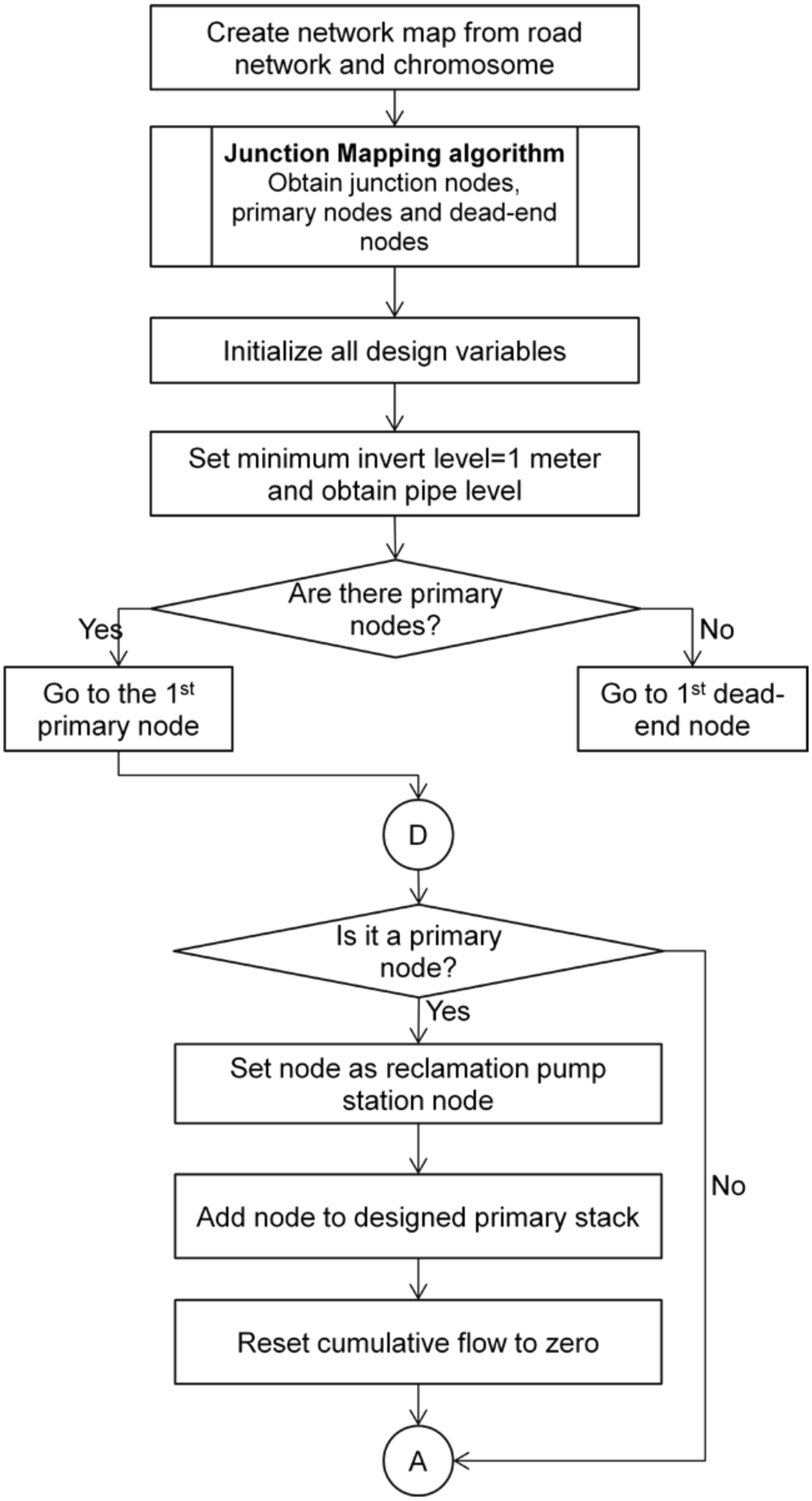


Figure 4.6 Decentralized Network Design Algorithm (Part I)

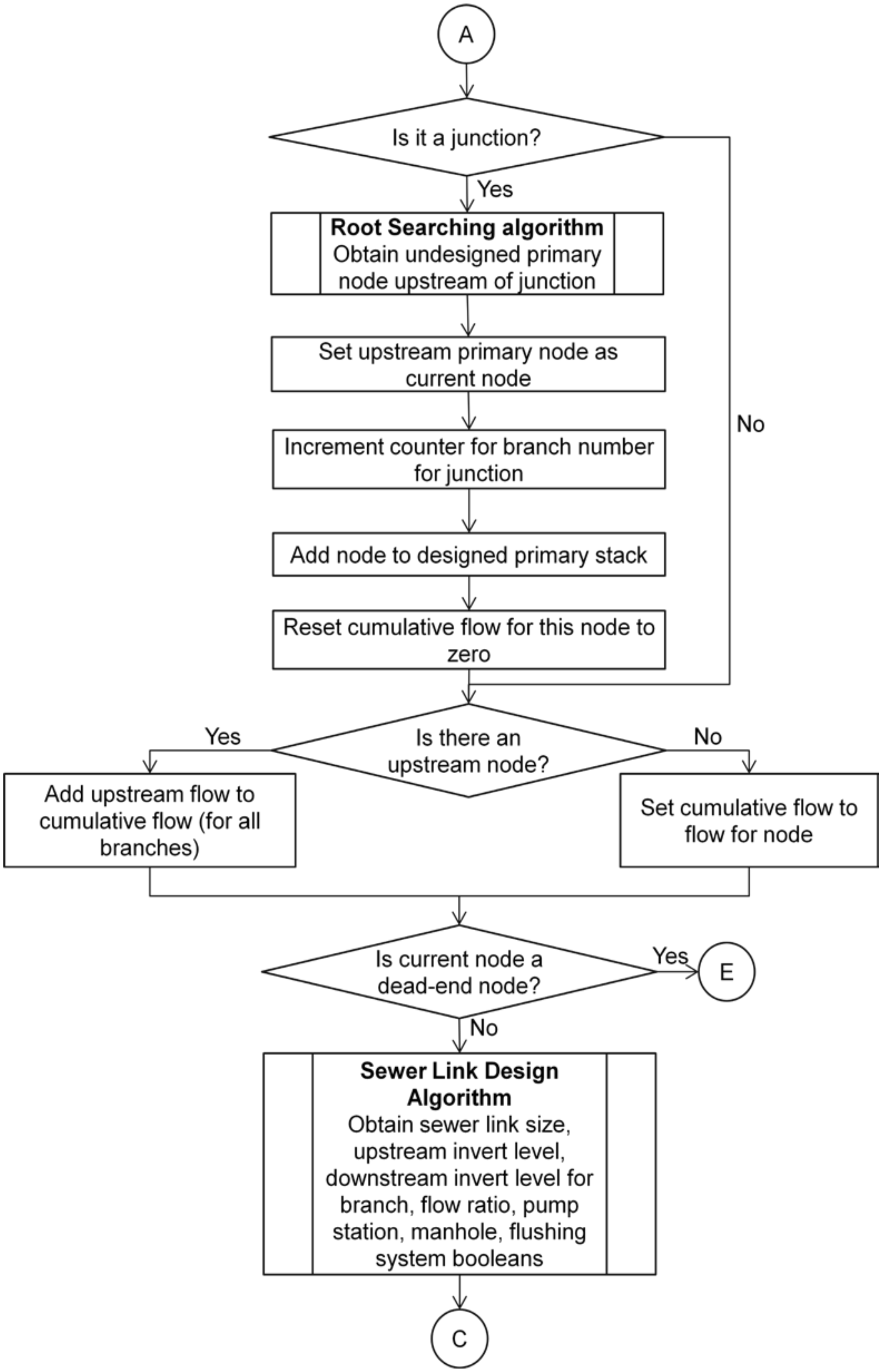


Figure 4.7 Decentralized Network Design Algorithm (Part II)

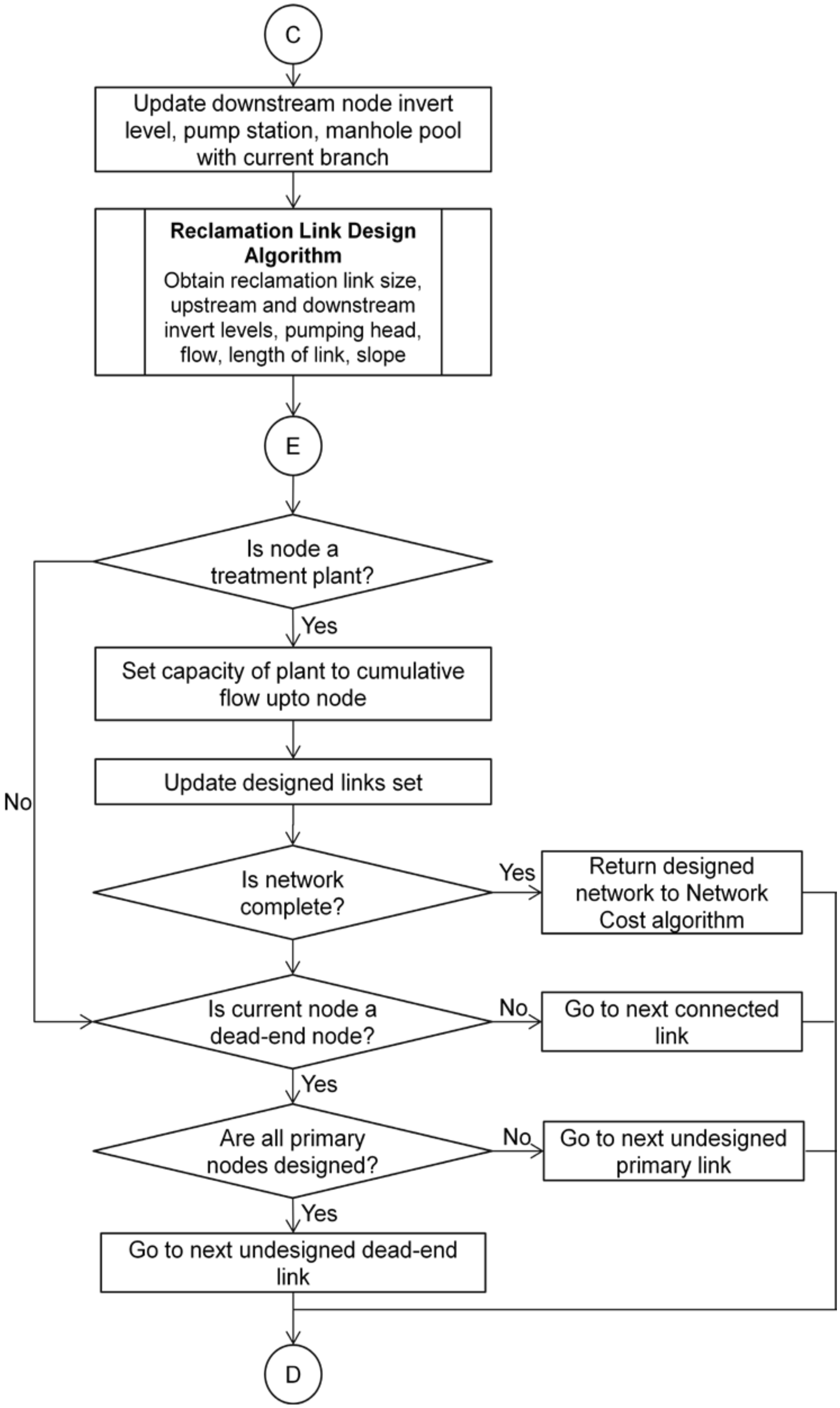


Figure 4.8 Decentralized Network Design Algorithm (Part III)

the same procedure to find the upstream primary node of that junction and branch. Figure 4.6 shows the procedure that this algorithm follows.

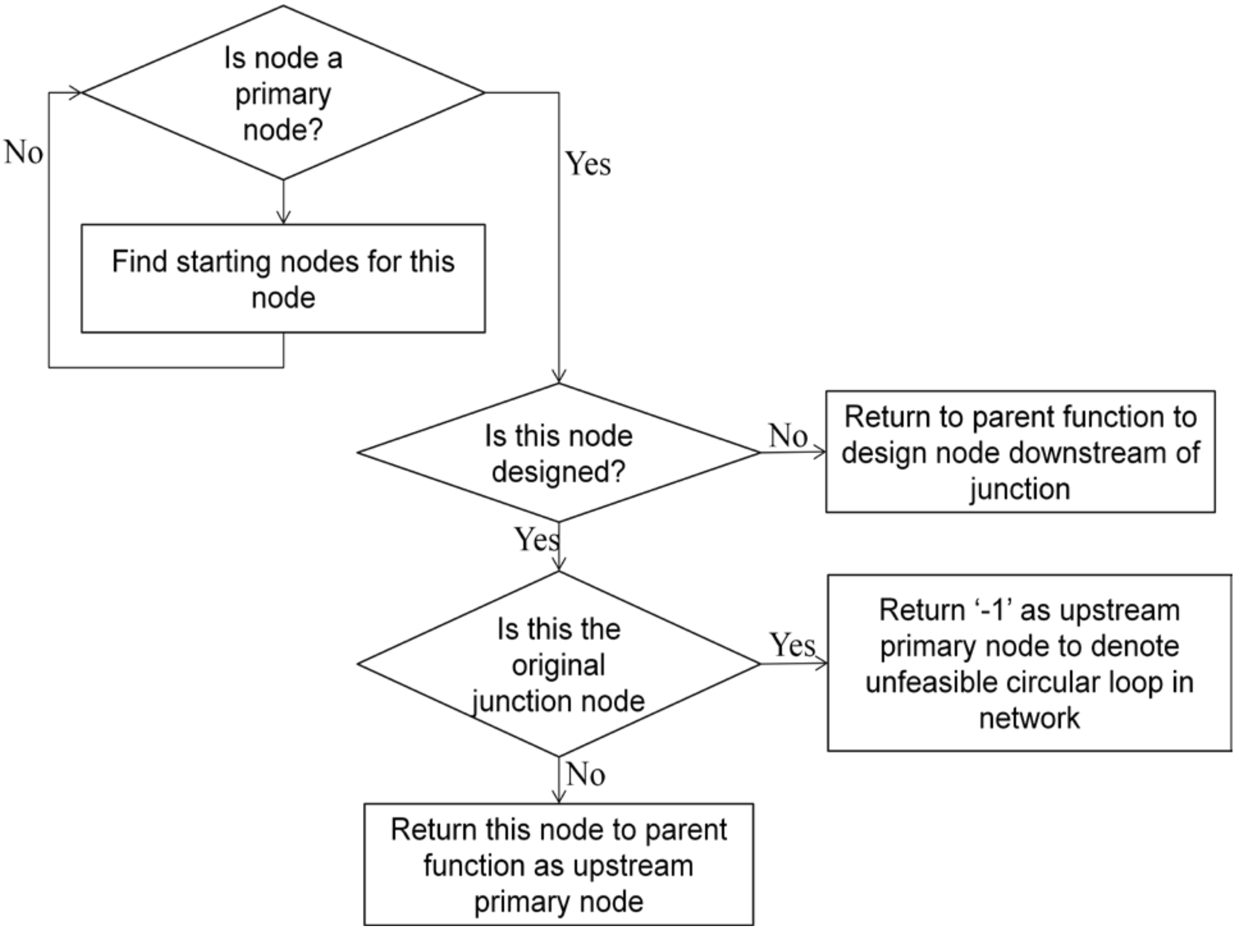


Figure 4.9 The Branch Root Search algorithm

4.4.2.8 Sewer Link Design Algorithm

If the Decentralized Network Design algorithm encounters a node which has a connecting sewer link, it calls this algorithm to design it. This algorithm considers the flow to be conveyed, the upstream sewer size, the upstream and downstream ground levels, distance and previously designed links intersecting the given node to design the sewer link. It returns the pipe size, new invert levels, pump station, manhole, and flushing system Booleans to the parent algorithm. Figure 4.7 describes the procedure of this algorithm.

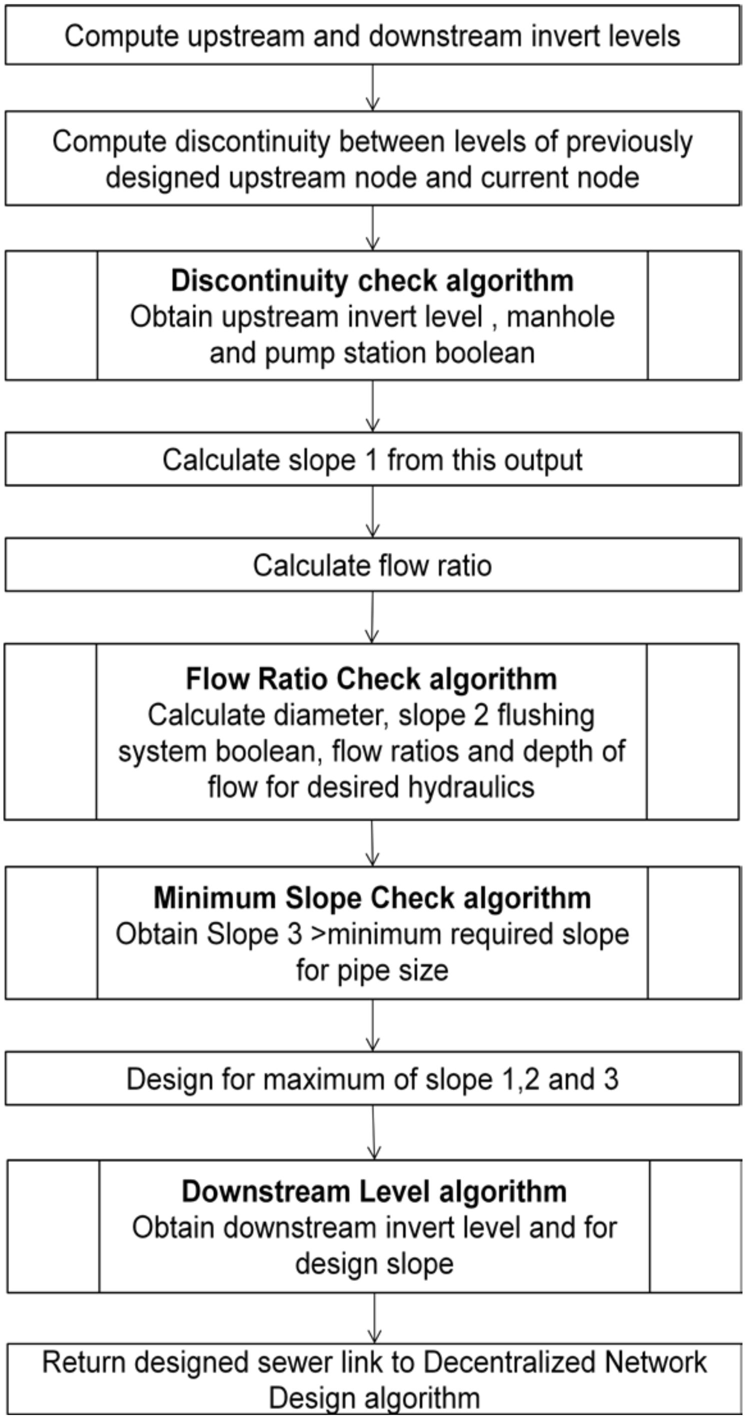


Figure 4.10 Sewer Link Design Algorithm

4.4.2.9 Discontinuity Check algorithm

The Sewer Link Design algorithm calls this algorithm to check for disconnects between the level of the ending node of the upstream sewer link and that of the current node. For designed upstream links, if the downstream sewer link begins at a lower level than the upstream level, the algorithm provides a manhole at the downstream node, whereas if it is higher, it provides a lift station. For undersigned links, it adjusts the level of the downstream link. Figure 4.8 shows the procedure followed by this algorithm.

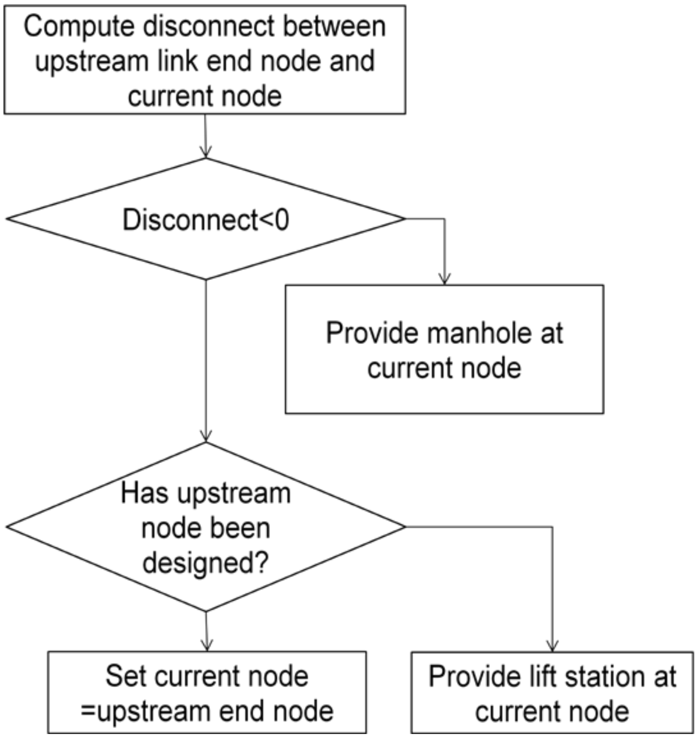


Figure 4.11 Discontinuity check algorithm

4.4.2.10 Flow Ratio Check Algorithm

The Sewer Link Design algorithm calls this algorithm to constrain the flow ratio to less than 1 and partial flow velocity to a range of 0.7 to 5 m/s. As this algorithm designs for a decentralized system, the design flows are generally expected to be low. Hence, the flow ratio cannot be constrained to have a lower limit. Figure 4.9 shows the procedure followed by this algorithm.

4.4.2.11 Hydraulics Iteration Algorithm

The Flow Ratio Check algorithm calls this algorithm to design the Sewer pipe size for the adequate flow and appropriate flow ratios based on the explicit equations by Ott and Jones (1988). Table 4.4 describes these explicit design equations. We modified the design procedure by Ott and Jones for faster and definite convergence. Figure 4.10 shows the procedure of this algorithm.

Table 4.4 Theoretical equations for Sewer Design Model **(Ott & Jones, 1988)**

Equation (d/D) ≤ 0.5	**Equation (d/D) > 0.5**	**Variables**
$\frac{d}{D} = \frac{\left[1 + \cos\left(\frac{\theta}{2}\right)\right]}{2}$	$\frac{d}{D} = \frac{\left[1 - \cos\left(\frac{\theta}{2}\right)\right]}{2}$	d: Depth of flow D: Pipe size θ: Angle subtended at center (refer to Fig. 2) α: (2π- θ) R_{PF}: Hydraulic radius of wetted area A_{PF}: Wetted area of pipe Q_{PF}: Partial flow rate Q_F: Flow for completely filled pipe V_{PF}: Velocity at partial flow
$\theta = 2\arctan\left\{\frac{\sqrt{1-\left[2\left(\frac{d}{D}\right)-1\right]^2}}{\left[2\left(\frac{d}{D}\right)-1\right]}\right\}$	$\theta = 2\arctan\left\{\frac{\sqrt{1-\left[1-2\left(\frac{d}{D}\right)-1\right]^2}}{\left[1-2\left(\frac{d}{D}\right)-1\right]}\right\}$	
$R_{PF} = \frac{D}{4}\left[\frac{2\pi - (\theta - \sin\theta)}{(2\pi - \theta)}\right]$	$R_{PF} = \frac{D}{4}\left[\frac{(\theta - \sin\theta)}{\theta}\right]$	
$A_{PF} = \frac{D^2}{8}\left[2\pi - (\theta - \sin\theta)\right]$	$A_{PF} = \frac{D^2}{8}(\theta - \sin\theta)$	
$\frac{Q_{PF}}{Q_F} = \left[\frac{(\theta - \sin\theta)^{5/3}}{2\pi(\theta)^{2/3}}\right]$	$\frac{Q_{PF}}{Q_F} = \left[\frac{(\alpha - \sin\alpha)}{2\pi(\alpha)^{2/3}}\right]$	
$V_{PF} = \left[\frac{8Q_{PF}}{D^2\left(\theta - \sin\theta\right)}\right]$	$V_{PF} = \left[\frac{8Q_{PF}}{D^2\left(\alpha - \sin\alpha\right)}\right]$	

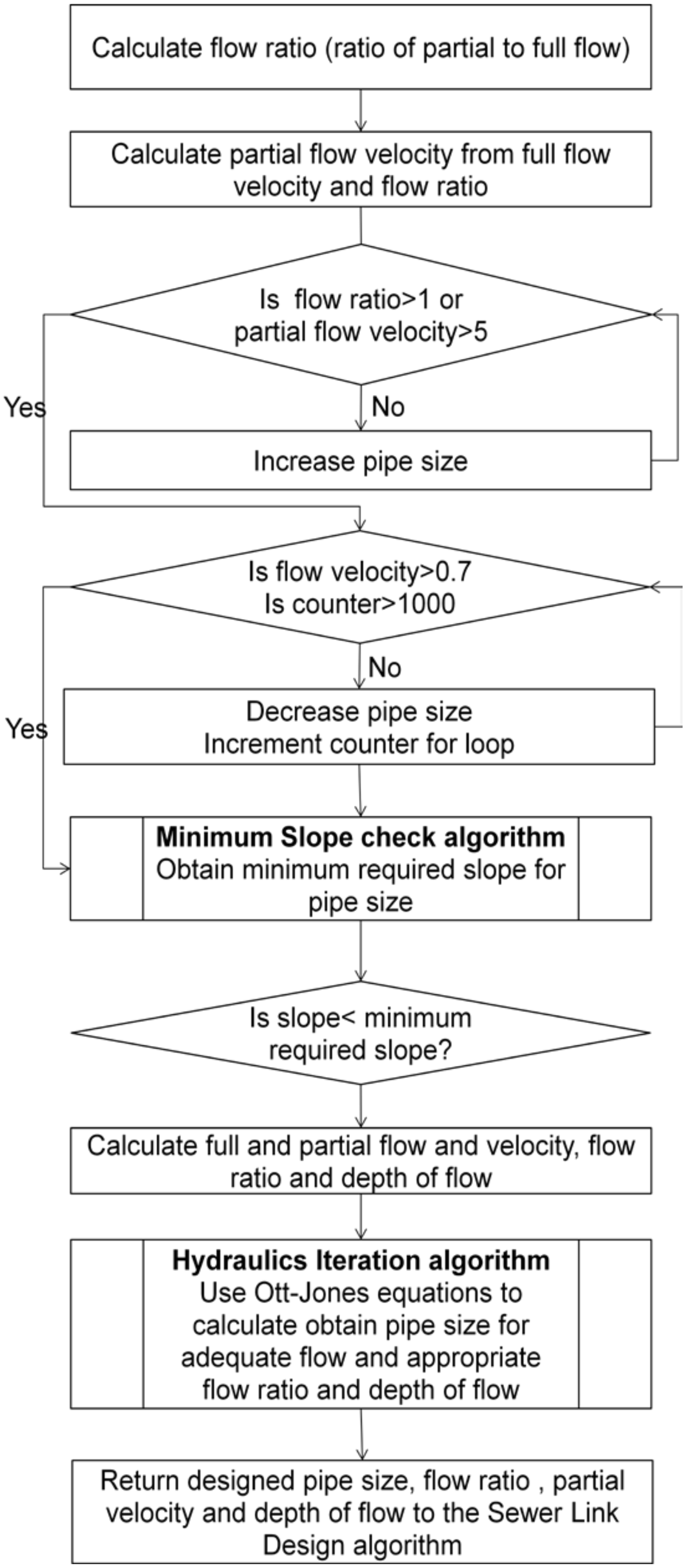


Figure 4.12 Flow ratio check algorithm

4.4.2.12 Downstream Level algorithm

This algorithm is called by the Sewer Link algorithm to adjust the node downstream of the current node based on the newly designed pipe size and slope. It constrains the invert level to a maximum depth of excavation of 3 m to economize the collection system and keep a distance from the water table. Figure 4.11 shows the procedure of this algorithm.

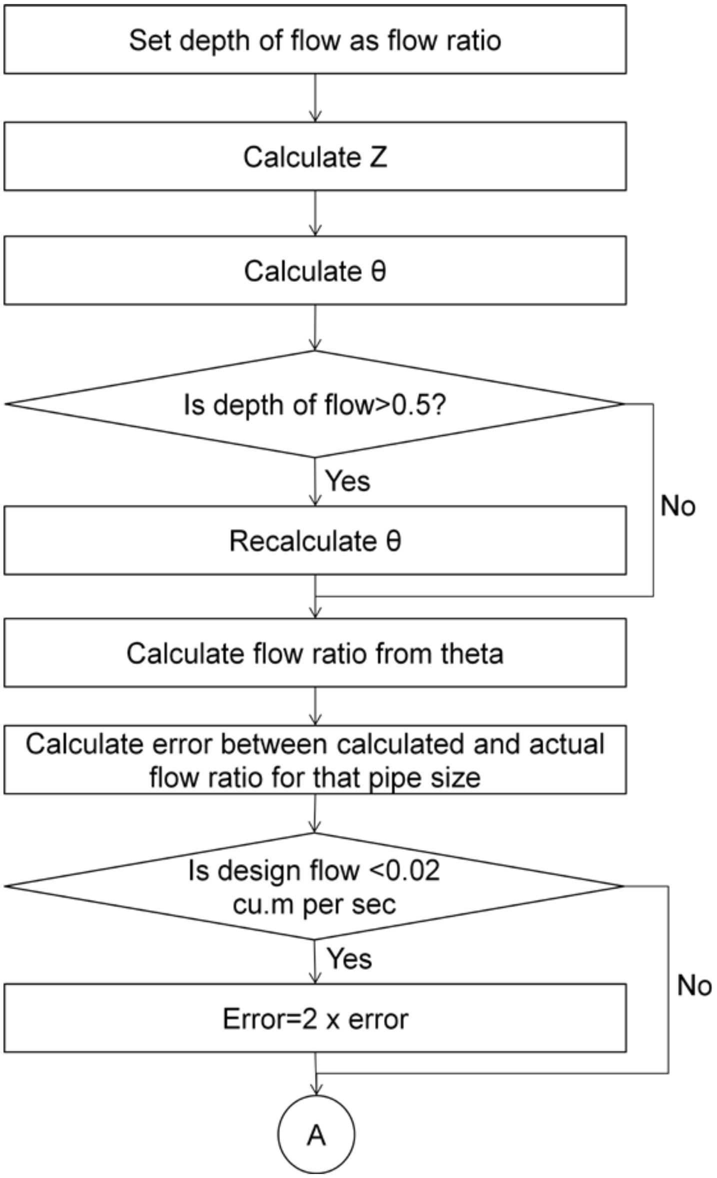


Figure 4.13 Hydraulics Iteration Algorithm (Part I)

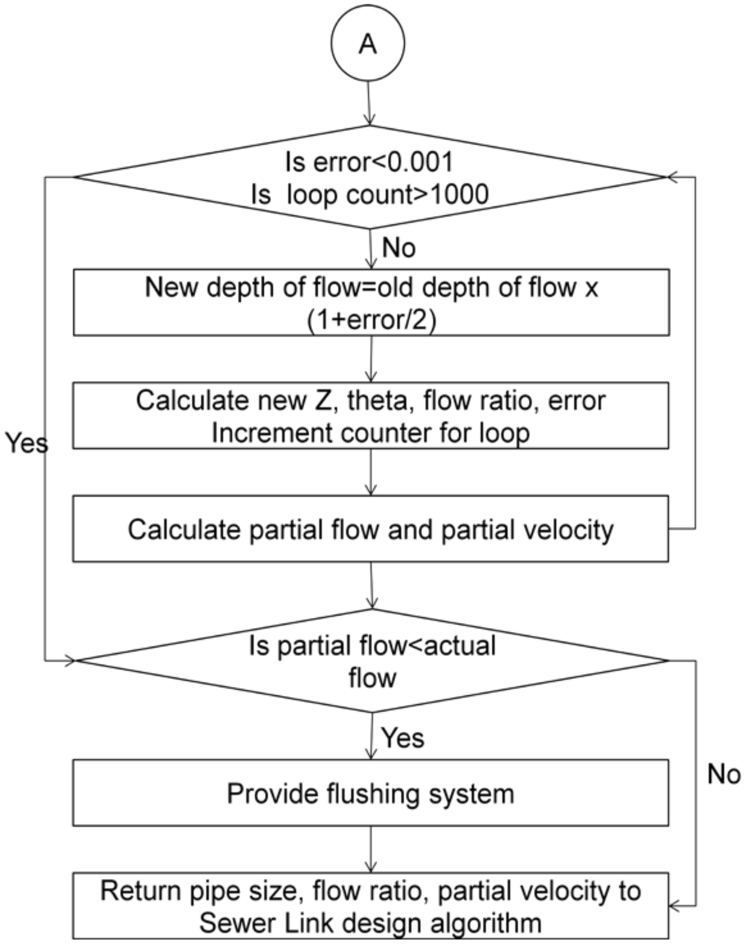


Figure 4.14 Hydraulics Iteration Algorithm (Part II)

4.4.2.13 Minimum Slope check algorithm

This algorithm is called several times in the Sewer Link Design algorithm. The algorithms check is the minimum slope requirement is met each time the slope is updated.Table 4.5 summarizes the slope requirements for various pipe sizes.

Table 4.5 Minimum slope requirements for different pipe sizes

Pipe Size (m)	Minimum Slope (1 in 1 m)
0.25	0.0042
0.25-0.3	0.0031
0.3-0.35	0.0024
0.35-0.6	0.0022
0.6-0.75	0.00088
>0.75	0.0007

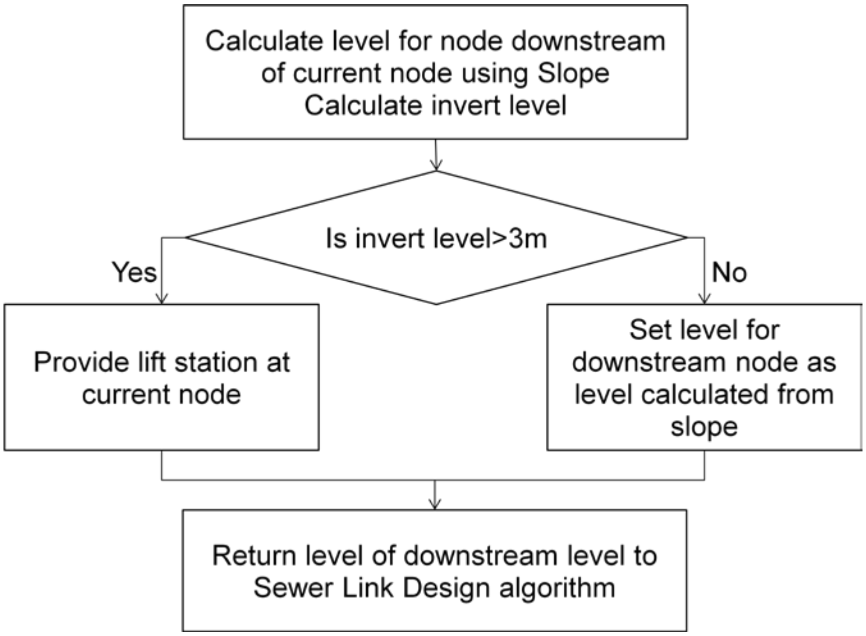


Figure 4.15 Downstream level algorithm

4.4.2.14 Reclamation Link Design algorithm

The Reclamation design algorithm is called by the Decentralized Network Design algorithm. It calculates the levels of the reclamation pipe and calculates the required pipe size based on flow for 90% reclamation. It uses the Hazen-Williams equation to calculate the pipe size from the flow and design flow velocity.

4.5 Applications and Discussion

This algorithm is more complex in terms of the number and design of network components and reclamation implications as compared to previous applications of the genetic algorithm in wastewater management. It is also more flexible with respect to potential locations of plants (non-linear), direction of collection and reclamation networks, addition of wastewater and reclaimed water pump stations. As a result, applying the genetic algorithm to the complete network for optimal design is currently computationally intense.

We considered a grid of 16 cells (4 rows and 4 columns). We assumed a typical urban residential scenario with multi-story family homes. Figure 4.12 shows the characteristics of the hypothetical grid.

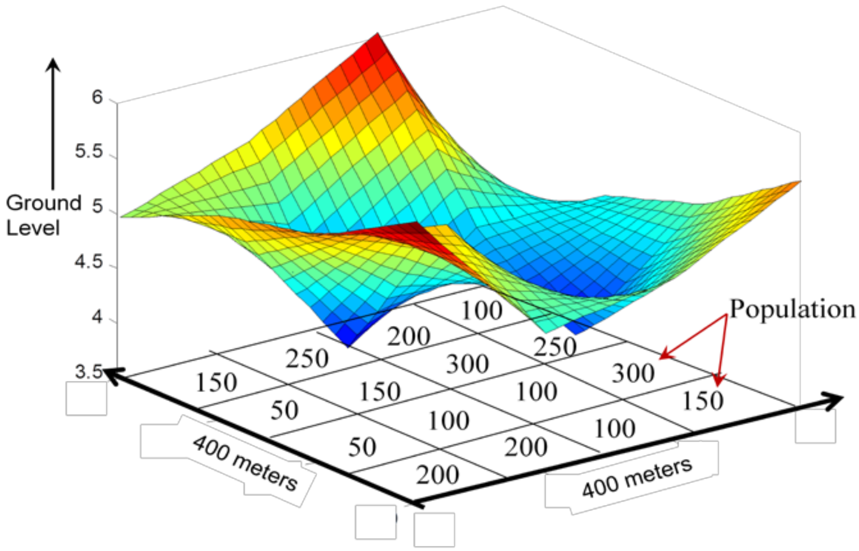


Figure 4.16 Characteristics of hypothetical example grid

To obtain an initial feasible point for the algorithm, we developed an initial feasible population to "seed" the algorithm. The algorithm then goes through a series of chromosomes, both feasible and infeasible, creating generations to arrive at a minimum fitness value chromosome. We used this "seeding" technique to generate different configurations by changing local characteristics or feasibility constraints.

4.5.1 "Favorite" node infeasibility – Finding the global optimum

The genetic algorithm being a random and a "brute-force" method, makes obtaining the global optimum easier. Yet, we tested the algorithm for any tendency to confuse a local optimum as the global optimum. We selected "favorite" nodes of the algorithm for the grid, that is, the nodes which were frequently selected as locations for treatment plants for a given problem by the algorithm. We marked each of them as infeasible in the feasibility matrices for inputs to the algorithm and generated a solution for each run. Selection of certain nodes as treatment plant locations may restrict the algorithm to a local optimum. Local optima were identified if a new solution converged to a better fitness function after marking previously identified optimal nodes as infeasible. We considered all the "favorite" nodes and marked them as infeasible. For this case, eliminating any of the "favorite" nodes did not provide a better solution. This result did not guarantee that a global optima was obtained, but increased the confidence that the obtained solution was a global optimum.

In case of favorite nodes, we propose the following approach. If the algorithm generated a lower cost than the original simulation, we can use this solution chromosome to seed the algorithm without any infeasible locations. We can then run the algorithm with this seeded initial population, corresponding to a new initial best cost, which the algorithm then tries to improve. We can run the algorithm with the favorite node infeasibility matrix multiple times to obtain the next favorite node, if any. We can continue this procedure till the cost does not reduce further. Figure 4.13 shows the procedure.

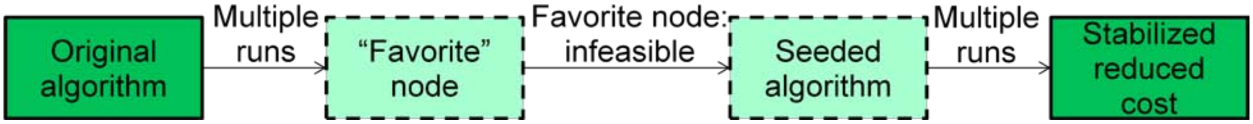


Figure 4.17 Procedure for finding global optimum by the favorite node infeasibility iteration

4.5.2 Applications

The optimization technique was used to determine optimal solutions for three primary cases: optimal solution with no constraints; best case constrained to a centralized treatment plant and cases with growth scenarios.

4.5.2.1 Optimal solution

We marked all nodes as feasible locations of the treatment plant. We did not restrict the algorithm for any constraint other than the basic feasibility constraints. We then ran the algorithm to obtain the best cost solution for the hypothetical grid. Figure 4.14 presents the optimal solution with the optimum centralized solution for comparison. Detailed description of simulating a centralized solution are given in the next section.

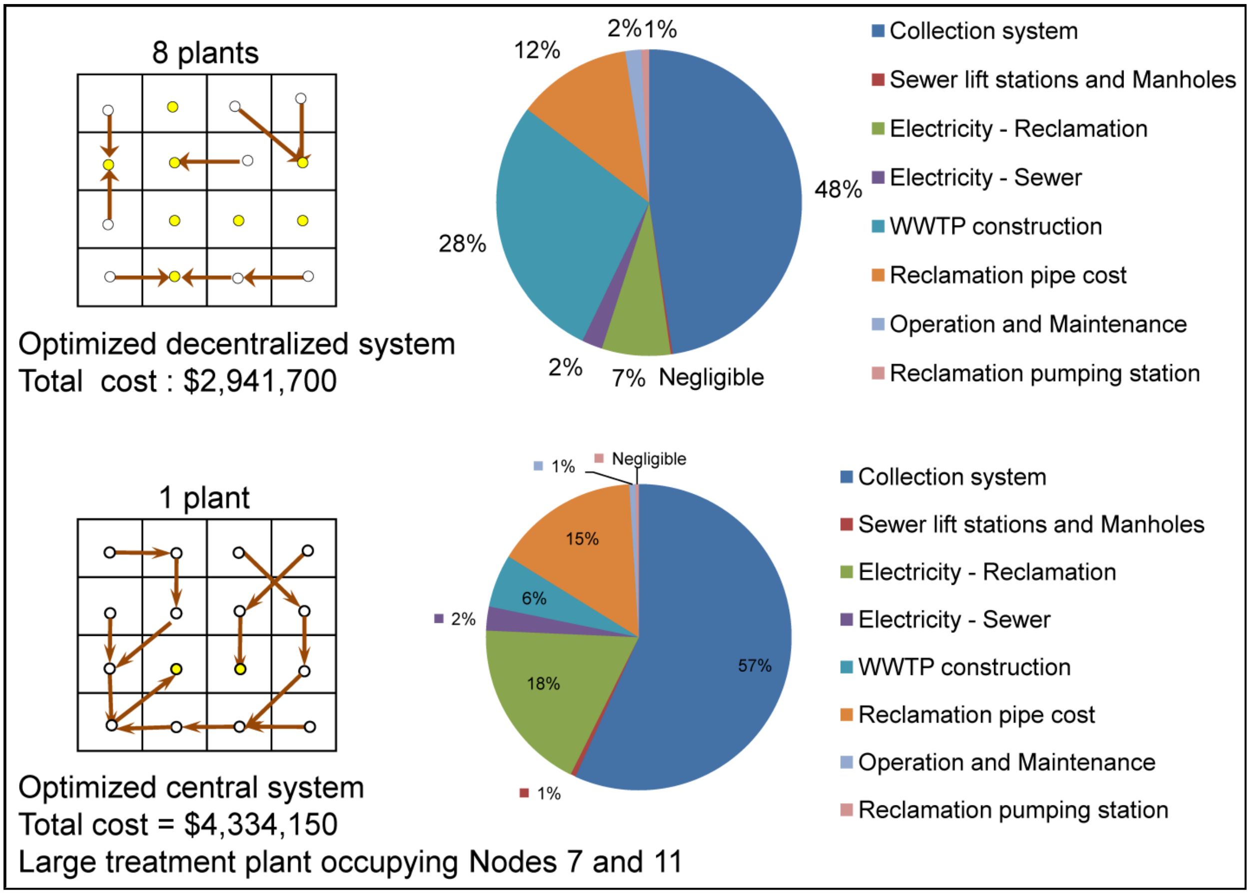


Figure 4.18 Comparison of overall optimal and optimized centralized solution

4.5.2.2 Centralized solution

We simulated a centralized configuration with the algorithm. We considered a few nodes as possible candidates for the central plant location, with criteria such as low ground level (minimum number of lift stations) and centered location in the grid (minimum number of large size pipes). We marked these as feasible and the rest of the matrix as infeasible to direct the algorithm towards a centralized solution.

We also set up layouts of collection networks manually (without the algorithm) for the same candidate nodes to obtain single chromosomes and calculated the costs for these networks. Figure 4.15 presents the networks and their costs.

4.5.2.3 Demand Growth

This simulation explored our methodology to evaluate modularized capacity expansion with conservative capacity expansion. We simulated an increase in population for the grid, both spatially even and uneven, but constant over time. Our objective was to compare a basic two time step approach with the conservative one time step approach for the configuration upgrade. We then compared the cost of the 10 year solutions provided by each approach at 5 years after construction to determine the feasibility of the solution in terms of capital investment and interest accumulated. Fig. a and b show the comparison between both the approaches for even and uneven population growth respectively. We assumed a population growth rate of 10% overall for the even growth, and an additional 10% growth for nodes 13-16 for uneven growth.

4.5.2.3.1 Even Growth

- Direct jump in capacity to accommodate 10 years of growth.

  We predicted a full time step solution for after 10 years. We seeded the algorithm with the original (0 years) best chromosome. Figure 4.16 shows the results of the time studies (step-wise and jump).

- Step-wise capacity increase (5 and 10 years)

We predicted an intermediate solution for after 5 years and then a full time-step solution for after 10 years. Though both these solutions had different networks, we

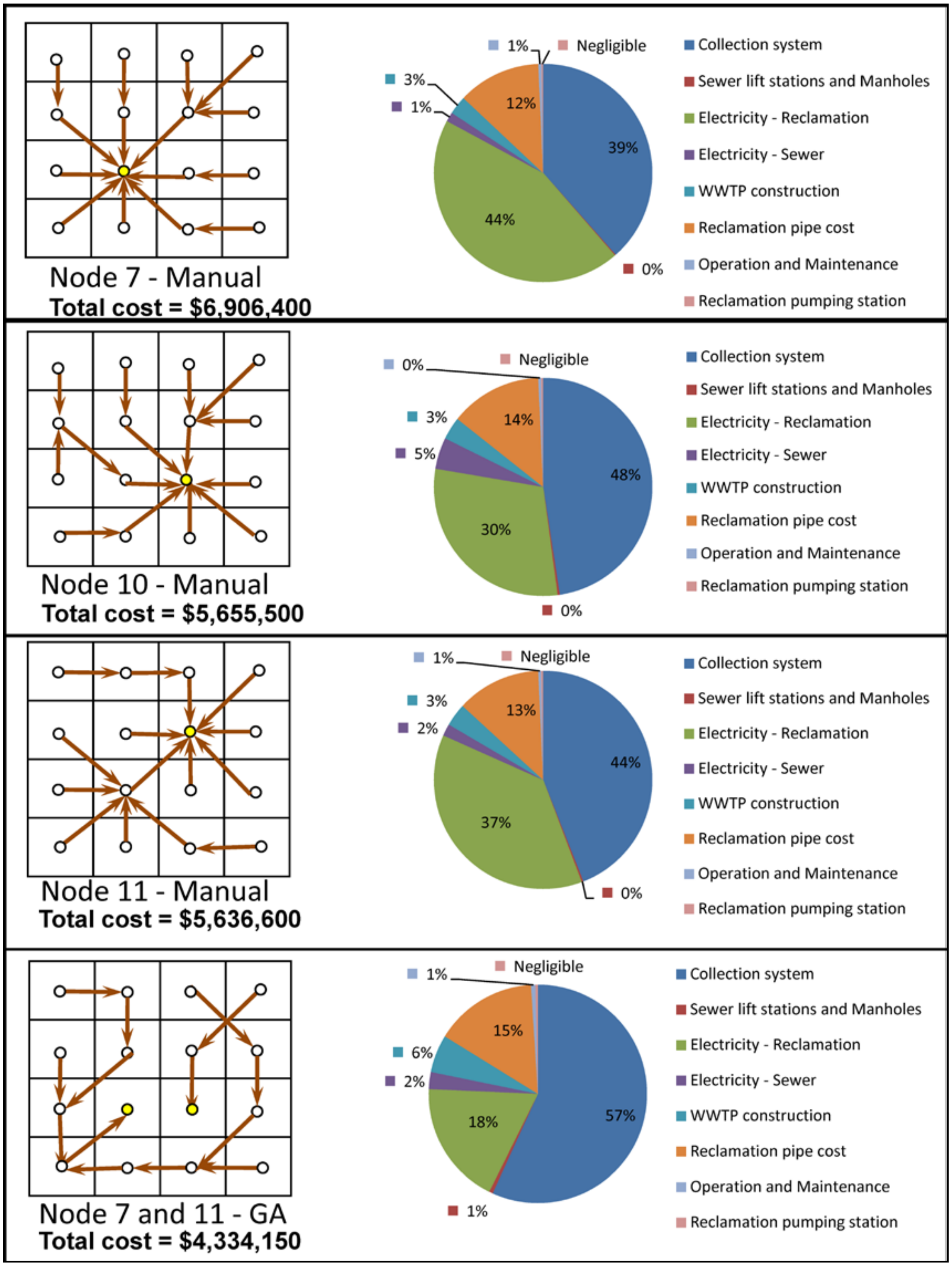


Figure 4.19 Comparison of manually designed and optimized centralized configurations

seeded the initial population of the 5 years simulation algorithm with the original (0 years) solution chromosome and 10 years simulation algorithm with the 5 years growth solution chromosome. This simulated a step-wise approach.

4.5.2.3.2 Uneven Growth

We simulated uneven growth in the grid by using a growth matrix. We set the input growth for the last 4 cells as twice the rest of the grid. We also applied the step-wise and direct jump growth approach to the partial growth scenario. Figure 4.17 shows the results of the analysis.

- Direct jump capacity increase (10 years)
- Step-wise capacity increase (5 and 10 years)

4.5.3 Discussion

While comparing solutions for the various scenarios, we observed that there were certain links which were alternatives of each other, that is, interchanging one link for the other in the solution did not change the solution, in terms of direction or cost. This is true of the genetic algorithm, as the branch or network formation is not sequential, but a randomization at the beginning of the run. Since the genetic algorithm can sometimes provide the best encountered chromosome in all the generations as the solution, convergence of the mean solution and best solution is not necessarily achieved. Thus, in implementing the solution in the practical sense requires an interface of translation. For example, if replacing a sewer link by its alternative simplifies the solution; such a change should be considered by the user. Such a concept is only observed for the conveyance links and not usually for treatment plants.

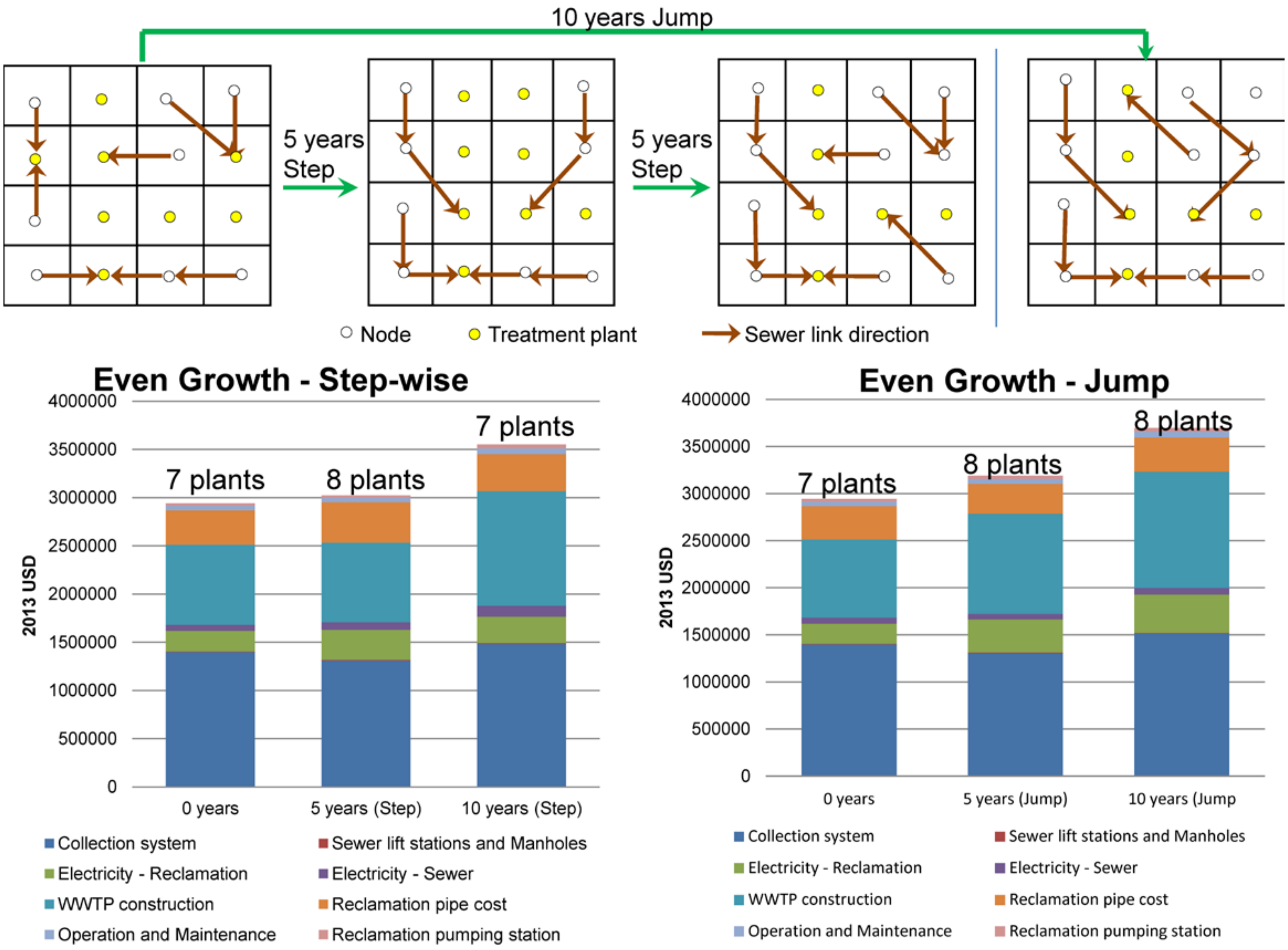


Figure 4.20 Application of the Step and Jump approach – Even growth

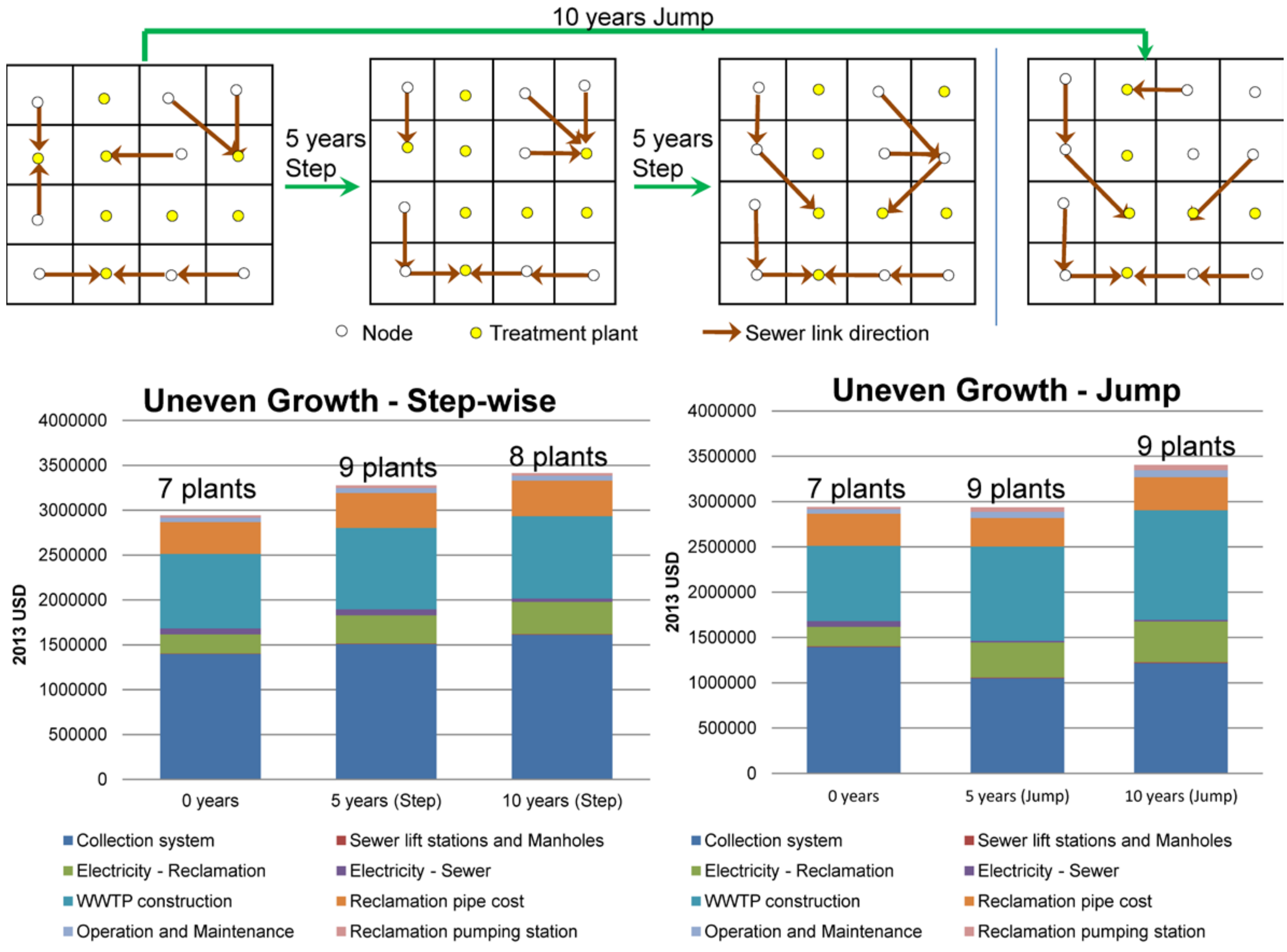


Figure 4.21 Application of the Step and Jump approach – Uneven growth

4.5.3.1 Centralized solution

The centralized solution provided by the genetic algorithm was more economical than the manually designed alternative central configurations. The manually designed solutions were based on commonly used engineering practices such as, feasibility of the location, least conveyance distance and maximum wastewater flow by gravity. The genetic algorithm obtained the most economical solution for a highly constrained situation such as a centralized configuration.

4.5.3.2 Optimal Solution

The optimal solution that we obtained from the genetic algorithm was a decentralized solution with 8 plants. The cost of this solution was about 1.5 million USD less than that for the optimal centralized system. This emphasizes the collection system cost increase with flow or distance. Though the grid was of a relatively small size, the optimal solution still produced smaller collection system by adding multiple plants.

4.5.3.3 Time progression study

We applied the step-wise time progression approach to seed the algorithm with the best case scenario in 5 years to obtain a better optimum more rapidly. The cost that we obtained with the step-wise approach for overall growth returned a lower cost with one less treatment plant, whereas that for partial growth returned a higher cost than the jump approach. This is a demonstration of an application of this algorithm for capacity expansion studies. Further research is required to provide more constraints to restrict the flow network for smooth transitioning between phases.

4.6 Conclusion

The proposed algorithm can successfully obtain an optimal solution even when conforming previously designated collection system details, such as lift stations, reclamation distribution system, electrical costs, operation and maintenance and the treatment facilities for a given situation. The algorithm considers today's emerging need for reclamation and includes its implications in terms of design, energy consumption and capital investment. The algorithm has adequate flexibility to assume various types of scenarios and compare the optimum solutions. The applied genetic algorithm was robust, avoiding local optima to attain the global optimum. We also used an approach to verify a global optimum solution by eliminating "favorite" nodes and showing that no better solution could be obtained. The algorithm has the flexibility of adapting the cost estimates to any geographical region. The algorithm can be used to study capacity expansion, but it requires some added constraints. It can be used to study and apply modularized expansion which is the key advantage of decentralized treatment that developing regions might find suitable.

In a test case of the algorithm it chose a decentralized configuration as the lowest cost alternative; the cost was lower than an optimal central solution. This various decisions made by the optimization provide insight to the user about various configurations, how the decisions were related to specific situations and in some cases, the reasons for counterintuitive results.

The algorithm can also be used without optimization. In this case the user provides a starting point and the algorithm provides the cost and other characteristics of the treatment system. This can in turn aid the user to modify an optimal solutions in order to comply user defined constraints that are not site-specific or contrary to typical design decisions. The flexibility of the algorithm makes it a practical methodology, applicable to a wide range of problem cases.

In the process of evaluating the algorithm it was used to create a central treatment system which was lower cost than several different manually designed central systems, using common engineering concepts. It was able to obtain a lower cost solution than best case manual design. This was a second validation of the utility of the algorithm.

5 Conclusions and Future Research

This dissertation addresses the need and benefits of wastewater treatment. Chapter 2 showed that improved wastewater treatment results in improved public health. Developing countries tend to have less wastewater treatment at present and therefore will benefit the most from new treatment technologies. There are numerous difficulties in providing wastewater treatment and in developing countries, cost is a major problem. Also the lack of existing infrastructure makes wastewater treatment, and in particular collection systems, difficult to build. An approach of reducing overall cost and avoidance of complicated collection systems is decentralized treatment. Chapters 3 show how decentralized treatment represents an opportunity to construct new treatment plants at lower cost and improved benefits. Decentralized treatment also has benefits to developed countries and to arid lands where water reclamation may be needed. Chapter 4 described an algorithm using a genetic optimization technique and several design procedures to produce an optimal solution of a hypothetical 16 cell square grid residential neighborhoods. In the following pages, the major conclusions of each section are presented.

5.1 Need for Wastewater Treatment

Wastewater collection and treatment improves public health independent of the economic standing of a region (Naik & Stenstrom, 2012). Contaminated water bodies can compromise the overall health of a population. In Chapter 2, we quantitatively established that proper wastewater management improves public health, by conducting a paired analysis between wastewater management and health statistics for 39 nations. Incidences of diarrheal diseases and inadequate wastewater treatment were positively correlated and the correlation was shown to be independent of indicators of economic standing. Rates of tuberculosis and malaria were not well correlated with wastewater treatment rates but did show reductions with improved economic standing.

Rates of diseases not considered typically waterborne were not tested in our work, but the chronic poor health caused by water born diseases is a suspected cause of the shorter incubation time and higher mortality of diseases such as HIV and tuberculosis (McCormick, et al., 1996). Therefore the damage caused by inadequate wastewater treatment may be greater than observed in controlled studies.

After the results of Chapter 2 were published (2012), further studies found additional links between increased risk due poor wastewater management and several diseases. Jin et al. (Jin, et al., 2013) reviewed literature relating health risks to wastewater management. They reviewed several other studies analyzing trends such as the effect of urbanization on source water quality, the relation between diseases such as digestive cancer and water quality, metallic bioaccumulation and sewage farming, emerging contaminants such as endocrine disrupters and their bioaccumulation, epidemics and compromised wastewater collection systems or lack of treatment, etc. Lack of wastewater treatment or infiltration of wastewater into water distribution systems can put water sources at risk. Samples of urban rivers were tested positive for enterovirus genes in Philippines (Apostol, et al., 2012), for Cryptosporidium oocysts in Turkey (Avci, 2012). This restates that poor wastewater management increases the spread of diseases irrespective of the economic status.

5.2 Need for Decentralization

Some developing regions lack access to wastewater collection and treatment. The high capital investment and long term construction make wastewater management impracticable. Murray and Dreschel (2011) surveyed the existing treatment systems in Ghana and their inadequacies due to the direct impact on public health. Only 30% of the plants had sufficient capacity, and the effluent quality was inadequate for environmental or public health protection.

About 13% of the treatment facilities performed up to the design standards. These plants were highly decentralized belonging to private luxury hotels. The total treatment capacity in Ghana served only 10% of the population. Many other regions have similar shortfalls in treatment capacity, especially developing regions.

Certain regions that lack wastewater management infrastructure do not have the capital for large capacity collection systems and treatment facilities. In most of these cases, it so appears that the State or National Government does not assign a high priority to wastewater management. Such regions can only afford small multiple investments decentralized to smaller communities or authorities for better management. Dividing the total wastewater treatment capacity into smaller fragments by decentralizing collection and treatment can be the only alternative for these regions. In India, many newly developed suburban communities are relying on smaller treatment systems or package treatment plants as permanent solutions for the lack wastewater collection or treatment (Naik, 2011). In Chapter 3, we analyzed wastewater management issues of two Indian cities: capacity management of wastewater infrastructure and source water protection in the face of rapid urbanization. We described the problems faced by these cities and recommended measures to resolve them. Decentralized wastewater management is a suitable alternative for cases similar to these cities. Fragmenting land allocation can make planning of decentralized systems more applicable. The construction impacts of these smaller systems are less, making them more appealing to the serviced community.

In regions with intense urbanization or agriculture, reclamation has emerged as a solution to high water demand and water scarcity. In arid regions such as the Middle-east and Southern California, local water supply authorities are developing wastewater reclamation to overcome shortfalls in supply. Reclamation has two main expenditures: increased treatment costs, and reclaimed water distribution costs, divided between capital cost and energy for pumping. In Chapter 3, we analyzed the energy intensity and capital cost for water reclamation and reclaimed water distribution for Hollywood using a distant central reclamation plant. We observed that the pumpback energy consumption was higher than the treatment energy consumption for that region. Centralized treatment also added to the pumping stations cost for reclaimed water distribution. The large flows associated with centralized treatment require a large collection network, which incurred a higher cost.

5.3 Optimizing Integrated Decentralized Collection and Treatment Systems

We observed that the cost implications of wastewater collection and reclaimed water distribution systems spanning long distances can be too high for reclamation to be a viable option. We also observed that decentralizing wastewater reclamation can reduce these costs due to reduced pipe size, lengths and elevation gain encountered during distribution. The knowledge of the configuration and added cost implications of decentralization for a large region can be complicated. Therefore in Chapter 4, we devised a methodology to optimize decentralized configurations consisting of collection and reclaimed water distribution networks and treatment facilities using a Genetic Algorithm coupled with several design algorithms with feasibility constraints. We adopted the Genetic Algorithm to minimize the capital, operating and pumping energy costs and to determine the optimal configuration for the given local constraints. The solution provides details such as the network layout, collection system pipe sizes, invert levels, lift stations, drop manholes, flushing systems, reclaimed water pipe sizes, pump stations, treatment plant locations and capacities, operating costs including electrical expenses and wastewater pumping and reclaimed water pumping electrical costs.

The methodology could also be used to evaluate various alternatives for the centralized treatment to determine the optimum design. Examples using the methodology were more economical than manually designed solutions based on typical planning criteria such as topography, distance of wastewater conveyance and location feasibility. On evaluating various alternatives without the centralized constraint for the same situation, the algorithm provided a decentralized solution which was $1.5 million less costly than the optimal centralized solution.

We applied the methodology to various scenarios, such as step-wise and direct projection solutions for even and uneven population growth and centralized treatment. We analyzed and compared the suitability of modularized expansion and conservative planning. We proposed a methodology to avoid restricting the algorithm to a local optimum, by marking "favorite" nodes as infeasible during the "seeding" of the initial population of the algorithm. We analyzed various cost components for each solution and their corresponding trends and biases. To summarize, this study provides a tool capable of feasibility analysis, planning, design, cost analysis and capacity expansion analysis for wastewater management.

5.4 Future Research

Treatment, collection and distribution system design is complex and few tools exist to optimize the process. Our research on decentralized wastewater management can be continued with efforts to develop other aspects of the model. These possible improvements are described as follows:

- Existing Networks and Facilities

The model can determine a decentralized solution for an unsewered area. Decentralization can be applicable to areas with existing wastewater infrastructure faced with rapid increase in demand. The prime motivation behind decentralizing in urban areas with established wastewater infrastructure is to avoid expensive enlargement of collection networks or upgrading treatment facilities for a conservative population growth estimate. The primary objective of this setup will be to minimize changes to the collection network by increasing the number of treatment facilities near the sub-areas that anticipate relatively more population growth.

- Solids processing – Central or Satellite

For this model we have assumed that each treatment facility has its solids processing facility. Though the capital and operating cost corresponding to this assumption is believed accurate, decentralizing the operation and maintenance of solids processing can be cumbersome and unacceptable to the serviced community due the potential of odors and increased truck traffic. Most decentralized facilities convey solids to the central plant, making the decentralized plant cleaner and more compact, and hence more appealing to neighboring communities. Conveying solids to a central facility increases dependence on the central system, which might not be an option for many developing regions. Currently, developing areas which depend on package treatment systems truck these solids to landfills or composting locations. This can be studied as a separate problem and then adapted to this model.

- Potable water savings and Reclaimed water revenue

Computing potable water savings is a straightforward addition which depends on the usage patterns of the reclaimed water and the potable water demand. Reclaimed water revenue can be determined using the overall cost, the potable water cost, the reclaimed water demand and thus the potable water saving.

- Processing speed and resolution

To improve the resolution of the problem, it is necessary to improve the computational speed of the algorithm. We partially resolved this issue by supplying a predetermined initial population to the algorithm using the pre-defined feasibility constraints. This improved the speed and the probability of convergence significantly. To improve the algorithm speed, it is necessary to reduce the number of populations in a generation required to possibly obtain the global optimum.

- Modularized expansion

The algorithm is capable of evaluating methods for expansion/upgrading the treatment and collection systems- step-wise or conservative. It is necessary to provide constraints to ensure smooth transitioning from an initial phase to the expanded phase of the configuration.

- Frictional losses in collection and reclaimed water pipes

For larger grids, frictional losses become more significant. In the next iteration of the model, energy consumption due to frictional losses in collection and reclaimed water distribution systems should be added. With this the model can be used to provide more energy-efficient configurations.

- Land use patterns

  Land use patterns are crucial in determining the cost of land and its practicability to install a treatment facility. Decentralizing wastewater treatment implies possible proximity locations of various types of land use patterns. The infeasibility matrix in the algorithm encompasses land use allowances partially for locating treatment facilities. But preferences for a certain type of land can be considered by using weighting factors. There is some literature on factors assigned to these patterns (EPA, 1982), but these can be updated to accommodate more recent land use patterns.

6 Appendix

Table 6.1 Dataset for analysis of relationships between indicators

Columns (1), (2), (3), (4), (5) and (6) are ‘percent wastewater treatment’, ‘percent sanitation’, ‘percent collection’, ‘disease mortality by tuberculosis per million’, disease mortality by diarrhea per million’ and disease mortality by malaria per million’ respectively (United Nations National Accounts Main Aggregates Division, 2010, United Nations Development Program, 2010, World Health Organization Statistical Information System, 2010, United Nations Environment Statistics, 2010, United Nations Social Statistics, 2010).

Country	HDI	(1)	(2)	(3)	(4)	(5)	(6)	GNI
Chad	0.295	0.0	9	0	56.8	162.2	170	530
Zambia	0.395	0.0	49	29	1520	4247	5059	950
Haiti	0.404	0	17	0	57.6	70.1	4.6	660
Yemen	0.439	3.3	52	31.9	2.2	16.6	1.0	950
Kenya	0.470	4.9	31	4.9	28.1	26.7	25.8	770
India	0.519	27.0	31	-	309.0	515.5	15.9	1070
Morocco	0.567	80.0	69	87.2	2.7	4.9	0.3	2580
South	0.597	57.0	77	60	41.5	14.1	0.3	5820
Indonesia	0.600	2.8	52	-	100.4	36.1	3.4	2010
Egypt	0.620	23.5	94	-	2.2	11.6	0.5	1800
Botswana	0.633	56.4	60	-	0.7	1.0	0.0	6470
China	0.663	32.5	55	45.7	218.0	62.3	0.4	2770
Dominican	0.663	12.0	83	31.4	1.5	1.5	0.0	4390
Turkey	0.679	42.0	90	72	5.4	10.5	0	9340
Jordan	0.681	52.0	98	97.7	0.5	9.6	0	3310
Tunisia	0.683	51.8	85	55.3	0.3	0.9	0.0	3290
Brazil	0.699	26.0	80	48	13.2	28.9	1.0	7350
Costa Rica	0.725	2.4	95	24.8	0.1	0.1	0.0	6060
Bulgaria	0.743	42.0	100	70	0.3	0.0	0.0	5490
Mexico	0.750	35.0	85	67.6	2.8	5.1	0	9980
Panama	0.755	55.0	69	-	3.3	8.9	0	6180
Romania	0.767	28.0	72	43	9.7	0.5	0	7930
Argentina	0.775	42.5	90	42.5	2.1	0.1	0.8	7200
Poland	0.795	62.0	90	60	0.9	0.0	0.0	11880
Portugal	0.795	68.0	100	74	0.4	0.0	0.0	20560
Hungary	0.805	62.0	100	62	0.3	0.0	0.0	12810
Slovenia	0.828	51.0	100	63	0.6	0.2	0	24010
United	0.849	97.5	100	97.7	0.5	1.5	0.0	45390
Austria	0.851	92.0	100	92	0.0	0.0	0.0	46260
Spain	0.863	100.0	100	100	0.5	0.4	0.0	31960
Belgium	0.867	60.0	100	86	0.1	0.1	0.0	44330

Israel	0.872	89.0	100	100	0.0	0.1	0.0	24700
France	0.872	80.0	100	82	0.9	1.0	0.0	42250
Switzerland	0.874	97.0	100	97	0.0	0.0	0.0	65330
Japan	0.884	67.0	100	67	4.2	1.5	0.0	38210
Germany	0.885	94.0	100	97	0.5	0.9	0.0	42440
United	0.902	71.0	100	71.4	0.8	4.6	0.0	47580
Australia	0.937	80.0	100	87	0.0	0.0	0.0	40350
Norway	0.938	78.0	100	83	0.0	0.1	0.0	87070

Table 6.2 Literature review of capital costs of wastewater treatment plants

Reference	**Region**	**Source of data**	**Type of cost**	**Unit process**	**Regression**	**Variables**	**Significance**
Year: 1968							
EPA	U.S.A.	Dorr-Oliver Inc. sales estimates	Construction	Comminutor	Log(Cost)=0.14Log(MGD)+1.76	C= Cost in 100 dollars	
				Grit removal	Log(Cost) = 1.58 –0.65*log(MGD)	Cost in 100 dollars per MGD	
				Detritus removal	Log (Cost) = 1/(0.211*Log(Area)+0.073)	Cost in dollars per sq.ft Settling area in sq. ft	
				Primary sedimentation	Log (Cost) = 1/(0.233*Log(Area)+0.758)	Cost in dollars per sq.ft Settling area in 1000 sq. ft	
				Digestion	Log (Cost) = 1/(0.31*Log(Vol)+0.37)	Tenths of dollars/cu.ft Vol = 1000 cubic feet	
				Activated sludge (Concrete + mechanical	Log(Cost) = 0.806*Log(Vol)+0.306	Cost in 1000 dollars Vol = 1000 cu. ft.	

				aerator cost)			
				Blower capital cost	3.58*capacity +2.53	Cost in 1000 dollars Capacity in 1000 scfm	
				Trickling filter	Log(Cost) = 1/(0.18*log(Area)+0.78)	Cost in dollars per sq. ft Area in 1000 sq. ft.	
				Final clarification	Log(Cost)= 1/(0.2*Log(area)+0.57)	Cost in dollars per sq. ft. Area in 100 sq. ft.	
				Primary digested sludge	9 dollars/Ton dry solids		
				Primary, digested, elutriated	4.5 dollars/Ton of dry solids		
				Primary, digested (using polymers)	4.5 dollars/ton of dry solids		
				Vacuum filtration	Log(Cost)=0.65 -0.66*log(Area)	Cost in 100 dollars/sq.ft Area in 100 sq. ft	
				Dewatering by Centrifugation	Log(Cost) = 2.5 - 0.193log(Influent solids)	Cost in dollars per pound per hour	

						Influent flow in lbs per dry solids per hour	
				Sludge drying beds (including comminution and dewatering, combustion, stack gas treatment, electrical, piping, pumping requirements)	Log(cost)= 1/(1.14*log(influentflow)-1.64) [22% solids feed] Log(cost)=1/(2.18*log(influent solids)-4.38) [40% solids feed]	Cost in 100 dollars per lb dry solids per hour Influent solids as lbs of dry solids per hour	
				Sand filtration	Log(Cost)=0.631*log(influent flow) +0.305	Cost in 1000 dollars Influent flow in 1000 gallons per day	
				Carbon adsorption	Log(Cost)=0.839-0.495*log(Influent flow)	Cost in cents per thousand gallons Influent flow in MGD	
Year : 1978							

EPA	U.S.A	Winning bids for Construction Grants Program for EPA	Construction cost, piping, excavation	Sitework excluding excavation	$C=(1.12 \times 10^5)Q^{0.97}$	C = cost (dollars) Q=flow rate (MGD)	
				Sitework excluding excavation	$C=(1.71 \times 10^5)Q^{1.17}$	C = cost (dollars) Q=flow rate (MGD)	
				Exacavation	$C=(1.38 \times 10^5)Q^{0.97}$	C = cost (dollars) Q=flow rate (MGD)	
				Pilings, Special foundations and dewatering	$C=(3.68 \times 10^4)Q^{1.12}$	C = cost (dollars) Q=flow rate (MGD)	
				Yard Piping	$C=(9.96 \times 10^4)Q^{1.03}$	C = cost (dollars) Q=flow rate (MGD)	
				Preliminary treatment	$C=(5.79 \times 10^4)Q^{1.17}$	C = cost (dollars) Q=flow rate (MGD)	
				Influent pumping	$C=(1.47 \times 10^5)Q^{1.03}$	C=cost in dollars Q in MGD	
				Equalization	$C=(1.09 \times 10^5)Q^{0.49}$	C=cost in dollars	

						Q in MGD	
				Primary sedimentation	$C=(6.94 \times 10^4)Q^{1.04}$	C = cost (dollars) Q=flow rate (MGD)	
				Activated sludge	$C=(2.27 \times 10^5)Q^{0.87}$	C = cost (dollars) Q=flow rate (MGD)	
				Rotating biological contactor	$C=(3.19 \times 10^5)Q^{0.92}$	C = cost (dollars) Q=flow rate (MGD)	
				Clarification	$C=(1.09 \times 10^5)Q^{1.01}$	C = cost (dollars) Q=flow rate (MGD)	
				Filtration	$C=(1.85 \times 10^5)Q^{0.84}$	C = cost (dollars) Q=flow rate (MGD)	
				Stabilization ponds	$C=(9.05 \times 10^5)Q^{1.27}$	C = cost (dollars) Q=flow rate (MGD)	
				Aerated lagoon	$C=(3.35 \times 10^5)Q^{1.13}$	C = cost (dollars) Q=flow rate (MGD)	
				Chlorination	$C=(5.27 \times 10^4)Q^{0.97}$	C = cost (dollars)	

						Q=flow rate (MGD)	
				Land treatment	$C=(3.67 \times 10^{5})Q^{1.02}$	C = cost (dollars) Q=flow rate (MGD)	
				Aerobic digestion	$C=(1.47 \times 10^{5})Q^{1.14}$	C = cost (dollars) Q=flow rate (MGD)	
				Anaerobic digestion	$C=(1.12 \times 10^{5})Q^{1.12}$	C = cost (dollars) Q=flow rate (MGD)	
				Air drying - sludge	$C=(9.89 \times 10^{4})Q^{1.35}$	C = cost (dollars) Q=flow rate (MGD)	
				Sludge incineration	$C=(8.77 \times 10^{4})Q^{1.33}$	C = cost (dollars) Q=flow rate (MGD)	
				Flotation thickening	$C=(2.99 \times 10^{4})Q^{1.14}$	C = cost (dollars) Q=flow rate (MGD)	
				Gravity thickening	$C=(3.28 \times 10^{4})Q^{1.10}$	C = cost (dollars) Q=flow rate (MGD)	
				Mechanical	$C=(3.44 \times 10^{4})Q^{1.61}$	C = cost	

				dewatering		(dollars) Q=flow rate (MGD)	
				Heat Treatment - Sludge	$C=(1.51 \times 10^{5})Q^{0.81}$	C = cost (dollars) Q=flow rate (MGD)	
				HVAC	$C=(3.10 \times 10^{4})Q^{1.24}$	C = cost (dollars) Q=flow rate (MGD)	
Year : 1980							

EPA	U.S.A	Winning bids for Construction Grants Program for EPA	Construction cost, piping, excavation	Equalization	$C=(6.76 \times 10^{4})Q^{0.60}$	C = cost (dollars)
						Q=flow rate (MGD)
							n=11;
							r=0.86;
							F=25.59

				Influent pumping	$C=(1.31 \times 10^{5})Q^{0.63}$	---- “ “ ------	n=70; r-0.77; F=102.50
				Comminutors	$C=(1.98 \times 10^{4})Q^{0.56}$	-----“ “ --------	n=9; r=0.72; F=102.50

				Preliminary treatment (bar screen and/or comminutor and/or grit removal	$C=(6.43 \times 10^{4})Q^{0.76}$	----- “ “ --------	n=61;
							r=0.80;
							F=104.58

				Primary	$C=(1.20 \times 10^{5})Q^{0.70}$	------ “ “ ----	n=36;

				sedimentation		----	r=0.83; F=77.59

				Activated sludge	$C=(5.19 \times 10^5)Q^{0.75}$	------- “ “ ------	n=43;
							r=0.84;
							F=97.36

				Oxidation ditch	$C=(4.68 \times 10^5)Q^{0.57}$	-------“ “ --------	n=17;
							r=0.81;
							F=29.12

				Rotating biological contactor	$C=(6.09 \times 10^5)Q^{0.77}$	-------“ “ --------	n=10;
							r=0.92;
							F=46.73

				Trickling filter	$C=(3.66 \times 10^5)Q^{0.46}$	--------“ “ -------	n=8;
							r=0.78;
							F=9.32

				Stabilization pond	$C=(7.08 \times 10^5)Q^{0.67}$	--------“ “ -------	n=18;
							r=0.76;
							F=22.25

				Aerated lagoon	$C=(6.87 \times 10^5)Q^{0.79}$	--------“ “ -------	n=12;
							r=0.82;
							F=20.03

				Chemical additions	$C=(5.46 \times 104)Q^{0.91}$	--------“ “ -------	n=22;
							r=0.72;
							F=21.73

				Secondary microscreens	$C=(1.22 \times 10^5)Q^{0.58}$	--------“ “ -------	n=5;
							r=0.97;
							F=44.98

				Mixed media filters	$C=(2.42 \times 10^5)Q^{0.79}$	--------“ “ -------	n=4;
							r=0.97;
							F=29.40

				Sand filters	$C=(2.14 \times 10^5)Q^{0.61}$	--------“ “ -------	n=15; r=0.72;

							F=13.98

				All filtrations	$C=(2.15 \times 10^{5})Q^{0.74}$		n=47;
							r=0.89;
							F=13.98

				Chlorination	$C=(6.33 \times 10^{4})Q^{0.65}$		n=92;
							r=0.82;
							F=192.50

				Land treatment of secondary effluent	$C=(3.98 \times 10^{5})\ Q^{0.71}$		N=17; r=0.87; F=45.33

				Lab maintenance building	$C=(1.93 \times 10^{5})\ Q^{0.58}$		n=73;
							r=0.78;
							F=111.1

				Gravity thickening	$C=(6.91 \times 10^{4})\ Q^{0.70}$		n=20;
							r=0.82;
							F=38.33

				Sludge drying bed	$C=(6.94 \times 10^{4})\ Q^{0.73}$		n=42;
							r=0.75;
							F=53.94

				Sludge lagoons	$C=(6.69 \times 10^{4})\ Q^{0.72}$		n=7;
							r=0.86;
							F=13.63

				Anaerobic digestion	$C=(2.69 \times 10^{5})\ Q^{0.92}$		N=9; r=0.93; F=48.01

				Aerobic digestion	$C=(1.99 \times 10^{5})\ Q^{0.78}$		n=21;
							r=0.86;
							F=55.68

				Heat treatment	$C=(3.22 \times 10^{5})\ Q^{0.53}$		n=5;
							r=0.83;
							F=6.64

				Incineration	$C=(2.64 \times 10^{5})\ Q^{1.00}$		n=11;
							r=0.87;
							F=29.33

				Site-work including excavation	$C= (1.96 \times 10^{5})\ Q^{0.66}$		N=43; r=0.82; F=84.64

				Site-work without excavation	$C=(1.11 \times 10^{5})\ Q^{0.57}$		n=118;
							r=0.76;
							F=163.16

				Excavation	$C=(1.33 \times 10^{5})\ Q^{0.64}$		n=90;
							r=0.79;
							F=150.46

				Pilings, dewatering, special foundation	$C=(6.60 \times 10^{4})\ Q^{0.57}$		n=22;
							r=0.73;
							F=22.94

				Electrical	$C=(1.67 \times 10^{5})\ Q^{0.73}$		n=155;
							r=0.86;
							F=434.16

				Controls and instrumentation	$C=(7.78 \times 10^{4})\ Q^{0.78}$		n=45;
							r=0.81;
							F=83.03

				All Piping	$C=(2.23 \times 10^{5})\ Q^{0.77}$		n=75;
							r=0.81;
							F=144.36

				Yard piping	$C=(1.15 \times 10^{5})\ Q^{0.71}$		n=81;
							r=0.82;
							F=161.45

				Process piping	$C=(1.51 \times 10^{5})\ Q^{0.82}$		n=43;
							r=0.77;
							F=57.94

				Equipment	$C=(5.96 \times 10^5) Q^{0.60}$		n=73;
							r=0.69;
							F=63.86

				Concrete	$C=(5.02 \times 10^5) Q^{0.79}$		n=79;
							r=0.83;
							F=173.84

				Steel	$C=(8.22 \times 10^4) Q^{0.90}$		n=47;
							r=0.79;
							F=73.97

				HVAC	$C=(4.83 \times 10^4) Q^{0.81}$		n=83;
							r=0.82;
							F=165.79

Year 2002							
Tsagarakis, P. et al.	Greece	National survey of MWTPs	Construction	Conventional ASP (whole plant)	$C=0.116X^{0.954}$	C is cost in 10^6 dollars per 1000 population equivalent X is plants size in 1000 population equivalent	$R^2=0.935$ p.e.range: 40,000-180,000 Number of plants: 9
				Extended Aeration and Mechanical dewatering (whole plant)	$C=0.206X^{0.775}$	C is cost in 10^6 dollars per 1000 population equivalent X is plants size in 1000 population equivalent	$R^2=0.829$ p.e.range: 5,000-120,000 Number of plants: 35

				Extended aeration with air drying (whole plant)	$C=0.153X^{0.727}$	C is cost in 10^6 dollars per 1000 population equivalent X is plants size in 1000 population equivalent	$R^2=0.808$ p.e.range: 1550-72,000 Number of plants: 32
Years 1992 and 2003 [1996 dollar values]							
United Nations (2003), Qasim et al.(1992)	U.S.A.	Manufacturers, conceptual design and published data from USEPA report: analyzed by PLOTIT	1996 dollar values	Screening and grit removal with bar screens	$CC = 674Q^{0.611}$ $O\ \&\ M = 0.96Q + 25{,}038$	CC: Capital cost in dollars O&M operation and maintenance cost in dollars Q: average design flow in m^3/d	
				Screening & grit removal without bar screens	$CC = 531Q^{0.616}$ $O\ \&\ M = 0.96Q + 25{,}038$		
				Primary sedimentation with	$CC = -0.00002Q^2 + 19.29Q + 220{,}389$ $O\ \&\ M = 1.69Q + 11{,}376$		

				sludge pumps			
				Ferric chloride addition	$CC = 0.000002Q^2 + 3.6Q + 44{,}624$ $O \& M = 9.68Q + 22{,}392$		
				Conventional activated sludge with diffused air	$CC = 72Q + 368{,}043$ $O \& M = 4.58Q + 36{,}295$		
				Activated sludge with nitrification in single stage	$CC = 90Q + 612{,}777$ $O \& M = 93Q^{0.834}$		
				Final clarifier with aeration basin	$CC = 2941Q^{0.609}$ $O \& M = 3.32Q + 5{,}842$		
				High rate trickling filter	$CC = -0.00007Q^2 + 56.89Q + 244.791$ $O \& M = 278Q^{0.505}$		
				Clarifier for highrate trickling filter	$CC = -0.00005Q^2 + 44.77Q + 323{,}702$ $O \& M = -0.000003Q^2 + 5.2Q + 5733$		
				Gravity filtration	$CC = 2903Q^{0.656}$ $O \& M = 194Q^{0.693}$		

				(dual media)			
				Activated carbon adsorption	$CC = -0.0002Q2 + 156Q + 796.55$ $O \& M = -0.00001Q^2 + 14Q + 229{,}458$		
				Chlorination	$CC = 795Q^{0.598}$ $O \& M = -0.000001Q2 + 2.36Q + 24{,}813$		
				Dechlorination using sulfur dioxide	$CC = 1170Q0.598$ $O \& M = -0.000001Q^2 + 0.97Q + 15{,}058$		
				UV disinfection	$CC = -3\times10^{-5}Q^2 + 11.85Q + 142{,}439$ $O \& M = -3\times10-6Q^2 + 1.038Q + 4585$		
				Sludge pumping	$CC = -0.00005Q^2 + 44.77Q + 323{,}702$ $O \& M = -0.000003Q^2 + 5.2Q + 5733$		
				Gravity thickener	$CC = 177Q^{0.68}$ $O \& M = -0.0000003Q^2 + 0.18Q + 4136$		
				Aerobic digester	$CC = -0.00002Q^2 + 23.7Q + 208{,}627$ $O \& M = 8.54Q^{0.916}$		
				Two-stage anaerobic digesters	$CC = -0.00002Q^2 + 21.28Q + 471{,}486$ $O \& M = 0.67Q + 26{,}784$		
				Sludge drying beds	$CC = 89Q^{0.854}$ $O \& M = -0.00002Q2 + 2.57Q + 8003$		
				Filter press or belt filter	$CC = 10{,}255Q^{0.481}$ $O \& M = 3165Q^{0.348}$		
				Miscellaneous structures	$CC = 1438Q^{0.567}$ $O \& M = -0.000003Q^2 + 1.97Q + 57{,}349$		
United Nations	NEED TO			Aerated pond (Partial mix	600-1200 dollars/m^3/d		

(2003), Reed, S.C. et al. (1990)	CHECK			aeration; No pretreatment; flowrate ~ 400 m^3/d)			
				Hyacinth pond (Pretreatment included; flowrate ~ 400 m^3/d; crop harvest included)	500-1000 dollars/m^3/d		
				Constructed wetland (Free water surface type; pretreatment, flowrate ~ 400 m^3/d; no harvest)	500-1000 dollars/m^3/d		
				Dewatering of sludge	0.175 dollars/10,000 capita 0.117 dollars/100,000 capita		
				Anaerobic stabilization and dewatering of sludge	0.200 dollars/10,000 capita 0.158 dollars/100,000 capita		
				Dewatering and incineration of sludge	0.292 dollars/100,000 capita		

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